TECHNICAL INFORMATION

AN EXPLORATION OF LEAKAGE CURRENT

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Abstract:

Leakage currents of commercial capacitors are notoriously difficult to analyze because they are the sum of several independent current flow mechanisms and because they are history dependent.

A test procedure has been established for investigation of background current in solid tantalum capacitors and to deduct it from the total current. The "excess current" can then be investigated in more detail so establishing its dependence on time, voltage, and temperature. This excess current is seldom related to total surface area of the dielectric and is most likely localized in discrete regions or flaws.

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Introduction

Although it is normal to discuss the leakage current (DCL) of an electrolytic capacitor, this term is not commonly used when describing the same types of mechanism in other capacitor technologies. Instead the term insulation resistance (IR) is adopted. However the two terms are directly related and a low IR is the same as a high DCL. To give an example of this relationship a DCL of 0.01 nA/µFV (readily achieved with a good solid tantalum capacitor) equates to 100,000 megohm µF. Furthermore, the minimum IR limit of some present ceramic capacitors (100 megohm µF) is identical to the maximum limit for many tantalum capacitors (0.01 µA/µFV).

Therefore although the experimental results in this paper are based on tantalum capacitors, many of the considerations apply equally well to other capacitor technologies.

Before going further, the units for reporting DCL measurements need some explanation. It is usual to normalize the current in terms of the size of the capacitor, hence the use above of the unit nA/µFV. This is sometimes expressed in terms of coulombs instead of µFV but this has no real logic: this thinking might just as well be taken to its logical conclusion and so express it in reciprocal seconds (0.01 nA/µFV = 10 µA/C = 0.1 Ms-1) a measurement unit which has no physical meaning in this context. Rather than convert µFV to µC there is more justification in conversion to surface area. As an approximation 4 µFV is obtained from 1 cm^2 of anodized tantalum surface. Consequently, a DCL of 0.01 nA/µFV approximates to a current density of 0.4 µA/m^2. When dealing with one CV rating of capacitor this variation with size is irrelevant and the DCL is expressed in µA or nA.

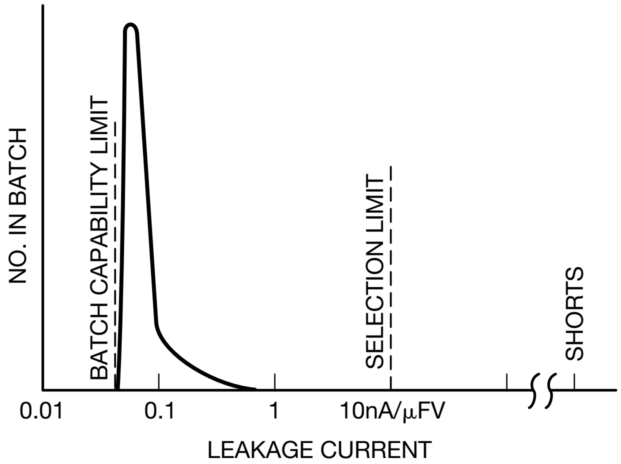

Figure 1. Batch Distribution

TABLE 1.
DCL readings from low leakage 47/35 capacitors.

Time (mins.)	DCL (nA) @ 35 V & 23 C #1	#2	#3	#4
1	249	350	300	881
2	152	250	192	775
3	110	213	146	733
4	93	195	128	710
5	80	175	112	690
6	72	170	105	681
7	60	160	92	675
8	54	154	85	670
9	50	148	83	660
10	52	148	83	658
11	46	143	77	659
12	42	140	73	655
13	44	140	78	649
14	38	134	71	650
15	37	134	68	645
16	35	132	66	644
17	36	132	67	640
18	33	128	64	644
19	29	124	61	641
20	29	124	61	641
21	29	124	60	643
22	28	124	57	644
23	26	120	57	640
24	24	119	56	640
25	26	121	56	640
26	28	124	59	640
27	26	120	56	640
28	26	120	56	640
29	24	118	54	640
30	22	116	53	640

Low DCL Capacitors

The distribution of DCLs in a batch of capacitors has a definite lower limit (see Fig. 1) usually with a high proportion of samples near that limit but with a tail extending to very much higher levels. The low limit needs to be understood in order to analyze the high values. This is because the high DCLs are the sum of the contribution from several conduction mechanisms one of which is the same as that found in the best capacitor of the batch.

By way of an example, Table 1 shows the leakage current from 4 representative capacitors in a batch of 47 µF 35 V solid tantalum capacitors. The DCL values were recorded at rated voltage at intervals up to 30 minutes. The values drop more or less continuously with time apart from some slight fluctuations. These fluctuations are probably due to a combination of small variations in room temperature and measuring voltage rather than instabilities within the capacitors as all the readings appear to deviate at the same time interval. Of these 4 samples, No. 1 displays the lowest DCL. Its values are made up from the fundamental background level plus the minimum of other contributions. They can therefore be used to subtract the background out of the other readings to allow analysis of the “excess current”. Table 2 shows that the resultant values are essentially independent of time. This indicates that the DCL of these samples is made up from a time-variable component which is identical from one capacitor to another plus a time-invariant component which is different for each capacitor.

From many other measurements the background current is found to closely follow an inverse relationship with time, i.e., Ixt = constant. If it is assumed that the DCL for sample 1 is itself composed of this constant Ixt component plus another lesser current then for at least the period between 10 and 30 minutes the readings accurately divide into an Ixt constant of 27 μC and an excess current of 7nA.

If the test voltage is now reduced to zero, the charge on the capacitor plates is removed within a few seconds and yet current continues to flow for periods greater than the charging time. This discharge current approaches that of the background current and again follows an Ixt = constant relationship. Table 3 shows the values for sample 1 but in fact the same level of discharge current is observed for all the capacitors in the batch. The Ixt product for the discharge is less than that for the background current but then the duration over which it flows is greater: the charging is truncated after a certain time (in this case 30 minutes) but the discharge current would flow for very much longer times. To make a direct comparison, both currents would need to be integrated from zero time to either the end of charging or to infinite time. However integrating Ixt from zero time or to infinite time yields a total charge transfer of infinity! The Ixt relationship must break down at both short and long time periods.

TABLE 2.
Excess Current
(background current removed by subtracting #1)

Time (mins.)	Excess current (nA) #2	#3	#4
1	101	51	632
2	98	40	623
3	103	36	623
4	102	35	617
5	95	32	610
6	98	33	609
7	100	32	615
8	100	31	616
9	98	33	610
10	96	31	606
11	97	31	613
12	98	31	613
13	96	34	605
14	96	33	612
15	97	31	608
16	97	31	609
17	96	31	604
18	95	31	611
19	95	32	612
20	95	32	612
21	95	31	614
22	96	29	616
23	94	31	614
24	95	32	616
25	95	30	614
26	96	31	612
27	94	30	614
28	94	30	614
29	94	30	616
30	94	31	618
Average	97	33	614

TABLE 3.
Discharge current from #1

Time (mins.)	Discharge current (nA)	I * t (μC)
1	510	31
2	116	14
3	72	13
4	53	13
5	42	13
6	36	13
7	31	13
8	27	13
9	24	13
10	21	13
11	19	13
12	18	13
13	16.2	13
14	15.6	13
15	14.5	13
16	13.9	13
17	12.5	13
18	12	13
19	11.9	14
20	11	13
21	10	13
22	10	13
23	9.6	13
24	9	13
25	8	12
26	8	12
27	8	13
28	8	13
29	8	14
30	7.6	14

Examination of a large number of capacitors shows that both the background current and the discharge current are directly proportional to the test voltage and are roughly proportional to the CV product of the capacitor. The overall impression is that they are both manifestations of dielectric absorption and that probably all the background current is recoverable during discharge. In other words it flows into but not through the dielectric.

Other methods of estimating dielectric absorption (such as recovery voltage measurements) lead to levels of charge transfer compatible with the discharge currents when carried out over the same time intervals.

Product from different manufacturers show similar levels of these currents although variations of several fold can sometimes be observed. There are indications that these differences are related to processing conditions during anodization and during high temperature treatments. However within the normal product range the background currents tend to be around 0.1 nA/µFV after 1 minute at rated voltage and the discharge currents around 0.06 nA/µFV.

Analysis of High DCL

Once it is accepted that the DCL is the sum of several component parts and that one, which is present in all capacitors, can be identified and quantified separately, considerable progress can be made in categorizing the excess current. Normally the leakage current is spoken of as if it were one value. If it were, there would be little chance of establishing its cause. However the different causes of high DCL have characteristic relationships with time, temperature, and voltage which can be used to fingerprint particular mechanisms. In this context high DCL does not just mean high with respect to the specification limit, it covers any value above that found for the best units in a batch.

A procedure has been developed which allows a considerable amount of data to be obtained both on low and high DCL capacitors. Individual capacitors are charged for 1 minute at 20% of rated voltage (0.2 U_R) during which time current readings are taken at 10 second intervals. The capacitors are then discharged with current readings again taken at 10 second intervals for 1 minute. In some instances, when dealing with low current samples, it is necessary to extend the discharge time to 5 minutes before the next step. The test voltage is increased in 0.2 U_R steps up to rated voltage again with 10 second readings of current. Results from a typical run are shown in Table 4.

The test voltage rises to its set value in less than one second but due to circuit limitations in the present system the reduction of the voltage to zero on discharge is much slower. Consequently the discharge currents at the 10 and 20 second intervals must be discounted in the present work.

TABLE 4.
Typical measurement run.
100 µF 6.3 V tantalum capacitor (currents in nA)

Time (s)	Test voltage				
(charge)	1.26	2.52	3.78	5.04	6.3
10	220	419	645	844	1120
20	58	98	148	196	249
30	35	60	90	125	161
40	26	44	70	92	123
50	21	36	54	74	99
60	19	31	46	65	86
(discharge)					
10	-5800	-10000	-14650	-18960	-22100
20	-859	-1650	-3512	-4312	-5110
30	-176	-330	-500	-660	-836
40	-46	-89	-136	-181	-228
50	-20	-37	-56	-76	-96
60	-12	-22	-34	-47	-59

Whereas low DCL capacitors display an ohmic relationship for both the charge and the discharge currents, high DCL units can display a wide variety of responses. The true characteristics of the high DCL units are often masked by the presence of the background current and so the latter should be established separately, by measuring a low leakage unit of the same type, and the excess current obtained by deducting the background from the total. The effect of doing this can be seen from Fig. 2 - 4. While the total current for sample B appears to decrease with time, the excess current is found to be relatively insensitive, if anything tending to increase slowly with time. The excess current is markedly nonohmic. By replotting this part against voltage its voltage coefficient can be obtained. Sometimes this plot has a distinct kink in it indicating that more than one fault mechanism is occurring. In such cases additional information can be obtained by repeating the run

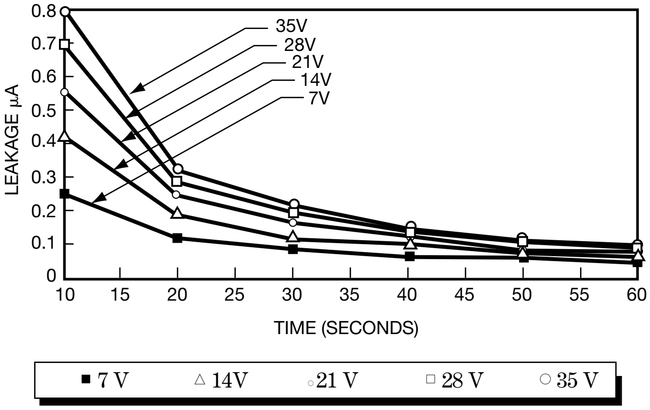

Figure 2. Low Leakage 22/35 (Sample A)

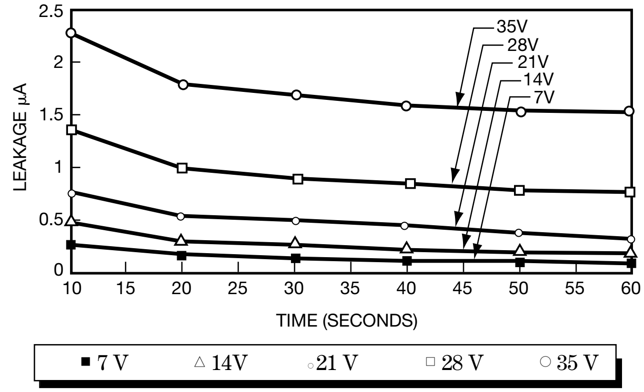

Figure 3. High Leakage 22/35 (Sample B)

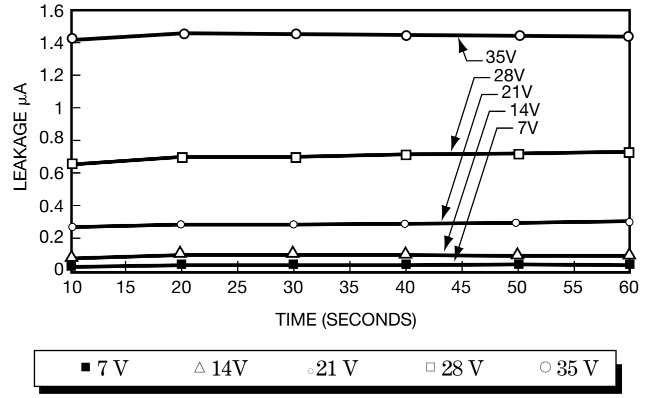

Figure 4. Excess Current (For Sample B)

using either higher or lower voltage ranges than the one recommended above.

By repeating the tests at higher temperatures the temperature coefficient is obtained and this can be converted to an activation energy. These need to be assessed for the different voltage levels as they are voltage sensitive. It is possible for the readings to show distinct differences from high to low voltages again indicating a mixture of fault mechanisms. All of the necessary processing of raw data is readily performed with simple computing programs. One important aspect that must be observed is adquate discharge between voltage steps. For an increasing voltage regime the discharge time must be at least as long as the charge and may in some cases be at least 5-fold longer. The situation is even more critical for decreasing voltage steps. Consequently if the run needs to be repeated, the capacitors should be discharged for at least 10 times the charge period at the high voltage. In the same way, it is preferable to carry out a temperature run with increasing temperature steps because more charge is stored at the higher steps and it therefore takes longer for that charge to dissipate.

There are other reasons for starting with the lowest stress level. Firstly self-healing sometimes occurs and this can be readily distinguished with increasing voltage: it could be masked altogether if the higher voltages were applied first. Secondly, when the leakage paths involve moisture tracks they can be removed at the high temperatures. It is possible for the DCL at 85°C to be less than that at room temperature when such tracks are dried out. Such effects are easily detected if the temperature is raised from normal ambient through intermediate steps of say 50 and 70°C, up to 85°C.

An appropriate sequence of measurements for most investigations is therefore as set out below, taking readings at 10 second intervals for the first 1 minute of charge or discharge, and covering both the high DCL units and a low DCL unit for comparison.

- Charge at 0.2 U_R for 1 minute at room temperature (record actual temperature)
- discharge for 1 minute minimum
- increase the charging voltage in 0.2 U_R steps up to U_R
- repeat the discharge between each step
- discharge for a further 10 minutes
- repeat the above sequence at the higher temperatures.

If any unusual features are observed (self-healing, further deterioration, or drying out) repeat the sequence after a minimum discharge time of 20 minutes. Note that the discharge must be with the capacitor short-circuited and not just left open-circuit for the charge to dissipate itself.

The readings from the low DCL sample are subtracted from those of the high DCL units.

As all these stages can be programmed such an investigation need not involve much engineer support in the collection of data. The engineer is in more demand for the interpretation of the data!

Application Example

An example of the use of this procedure will show how it can be applied. A large number of 22 µF 35 V solid tantalum capacitors were submitted to a Highly Accelerated Stress Test (HAST) and some DCL failures were found. These were subjected to the above procedure at room temperature only. After subtracting the background current the voltage and time characteristics were found to fall into two distinct groups (Fig. 5 and 6). One group had ohmic characteristics and the other was distinctly non-ohmic. This immediately showed conclusively that two separate failure mechanisms were operating. From the behavior patterns it was immediately possible to postulate mechanisms for each sample before the start of destructive failure analysis procedures.

Behavior Patterns

The main causes of high DCL for solid tantalum capacitors can be categorized as follows:

- Electrical breakdown of the dielectric
- mechanical breakdown of the dielectric
- conductive paths due to impurities
- conductive paths due to poor anodization
- bypassing of dielectric due to excess manganese dioxide
- bypassing of dielectric due to moisture paths
- bypassing due to other conductors (silver, carbon, etc.).

A similar list could be prepared for all the other

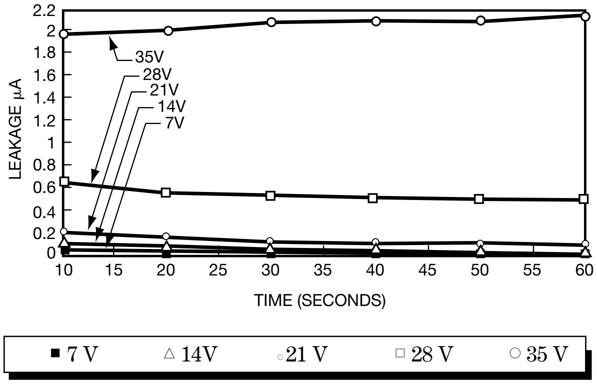

Figure 5. Non-Ohmic Example from HAST

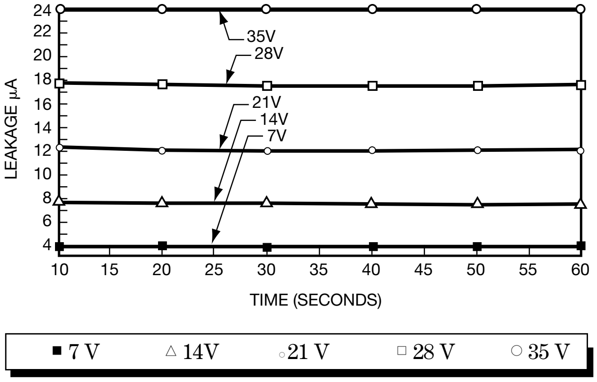

Figure 6. Ohmic Example from HAST

capacitor technologies. Each of the above fault mechanisms has its own characteristic behavior but in some cases they have a band of voltage or temperature coefficients rather than one single value. Also some change with time due to the effect of the measurement itself.

TABLE 5.
Capacitor dielectric disrupted by temperature cycling (current in nA)

Time (s) (charge)	Test voltage 7	14	21	28	35
10	609	1940	4800	2047	4800
20	247	1230	3613	940	2181
30	170	1095	2240	701	1875
40	139	1000	2280	600	1740
50	112	920	2240	560	1630
60	98	880	2070	515	1600

TABLE 6.
Capacitor from Table 5 after repeated measurements

Time (s) (charge)	Test voltage 7	14	21	28	35
10	578	990	1390	1779	2241
20	224	360	498	643	855
30	138	230	320	420	580
40	99	171	240	330	480
50	78	137	196	280	409
60	63	115	168	240	364

If a particular fault can be generated in a controlled manner its characteristics can be established for use in this type of analysis. For instance dielectric breakdown may be induced by application of overvoltage. Mechanical breakdown may be induced through temperature cycling. The use of inappropriate anodization conditions can generate several different types of fault mechanisms. Assembly faults can be simulated to produce other bypass situations. The information obtained from such deliberate deterioration of the capacitors is not always conclusive as the degree of severity of the fault can modify the results. However the following example is given to show the type of data which might be observed.

A number of 47/35 tantalum capacitors were measured for DCL and then subjected to temperature cycling until one showed a sudden increase in DCL indicating that the dielectric had been mechanically disrupted. Table 5 shows the charging current after the cycling. The 28 V and 35 V readings are lower than those at 21 V showing conclusively that self-healing can occur to partially clear the contact at the disrupted area. Remeasuring the DCL showed that the readings at the lower voltages were also improved and after several repeat runs the DCL values were as shown in Table 6. These leakages are similar to those obtained before the temperature cycling. A fault had been generated but had self-healed as a result of the application of the test voltage. If the DCL had been measured as is normal, just rated voltage and at one period of time, this fault would have been missed. However in service the capacitor might never see rated voltage and so could remain as a suspect high DCL device until tested at rated voltage when it would self-heal and be diagnosed as a satisfactory factory unit.

One more example will be given to show how this procedure can yield information that is not obtainable by normal measurement techniques. When a 1 µF 35 V capacitor with high DCL was tested the discharge currents were completely at variance with the normal levels and were sometimes positive instead of negative (Table 7). Even when they were negative the values were much lower than usual. The explanation for this behavior was that there was direct contact between the manganese dioxide and tantalum which generated a battery current opposing the discharge current. This conclusion is compatible with the very high level of DCL and also its instability as seen in the charging currents.

TABLE 7.
Measurements from an unstable 1/35 (currents in nA)

Time (s) (charge)	Test voltage 7	14	21	28	35
10	3010	8180	15400	28400	52750
20	3010	8000	19500	30100	54000
30	3040	7800	18400	30000	54200
40	3010	6750	18700	32400	52000
50	3010	7010	18800	32000	54000
60	3000	6900	18800	30000	51000
(discharge)					
10	-74	-210	-112	-640	-35
20	2	-9	4	-29	-12
30	2	-2	5	-5	0
40	2	-1	4	-3	0
50	2	-1	4	-2	2
60	2	0	3	-1	0

Activation Energies

Measurements at different temperatures allows activation energies for current flow to be estimated. Table 8 lists a selection of values obtained using the 1 minute readings at the rated voltage or after discharge from rated voltage. Observations on these results are:

- the values drop with increasing rated voltage
- they tend to decrease with increasing temperature range
- the values for discharge currents are lower than for DCL.

The last of these observations is probably the easiest to explain. Activation energies are normally reduced by the field across the dielectric and while

TABLE 8.
Activation energies (eV)

Temperature range (C)	47/6.3		22/16		47/35	
	DCL	Disch.	DCL	Disch.	DCL	Disch.
24 - 50	0.25	0.32	0.23	0.26	0.13	0.16
24 - 70	0.25	0.32	0.22	0.28	0.12	0.16
24 - 85	0.25	0.30	0.21	0.27	0.11	0.14

the field is present during the DCL measurement it diminishes to near zero during discharge. There are problems in providing a satisfactory explanation of the other two observations and it may be that the simple concept of activation energy used here is inappropriate.

Relationship to DF

Leakage current is a form of dielectric loss which can be expressed in terms of power factor or dissipation factor (DF). The difficulty is in the interpretation of a set time after the application of a voltage step as an equivalent frequency in an AC measurement. The mathematics for this is complicated and will not be attempted here. However the following outline of the relationship is given to show that the background current has the same characteristics as the low frequency DF.

The best quality anodic tantalum dielectric has a DF of 0.4% over a very wide frequency range, possibly down to at least 10^{-6} Hz. If this is expressed in the form of an equivalent circuit of a parallel combination of resistance and capacitance, the equivalent parallel resistance is 40/f Mohms/µF, i.e., the resistance is inversely proportional to frequency or, put in another way it is directly proportional to the time interval.

The equivalent resistance due to the background current is also directly proportional to time. As shown earlier, the background current after 1 minute is of the order of 0.1 nA/µFV. This converts to a resistance of 10^4 Mohms/µF at 60 seconds.

For the resistance from the DF calculation to equal that from the current it would be necessary to assume an equivalent frequency for the 60 second current of 10^{-4} Hz, i.e., a periodicity of 250 seconds. This is close to the expected relationship between the DC and AC conditions.

Therefore as the DF and DCL have the same relationship with respect to time and the calculations indicate a close link in parametric value it is tempting to conclude that they are both manifestations of the same fundamental behavior.

Conclusions

A simple programmable sequence of measurements has been devised which allows classification of leakage currents of capacitors based on their time, temperature, and voltage characteristics. The method adopts the concept that the measured current is the sum of independent flow mechanisms, one of which is present to a consistent extent in all the capacitors. By removal of this part from the total, the true behavior pattern of the excess current can be determined.

The inherent characteristics of different current flow mechanisms can be established separately by creating known types of fault in initially good capacitors.

This approach is capable of exposing instances of self-healing which would otherwise be missed in the normal DCL measurements. Also recording the discharge current can produce new evidence of the existence of fault mechanisms by indicating the presence of battery effects where two dissimilar materials such as manganese dioxide and tantalum are in direct contact.

The techniques described can be adapted to the investigation of other capacitor technologies.

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