Effect of Circuit Resistance and Inductance on Surge Current Testing of Tantalum Capacitors with Different Capacitance

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Abstract. Since tantalum capacitors are used in low-impedance circuits, where they are exposed to surge current impact, it is important to have the special technique to evaluate the performance of tantalum capacitors in such conditions. For these purposes surge current testing according to ESA/SCC Generic Specification №3012 and MIL-PRF-55365 standards is used. But even slight variations of testing parameters in allowable range can significantly change testing conditions. This article is devoted to analysis of the relationship between surge current testing circuit parameters and surge current conditions during testing of tantalum capacitors with different capacitance. The influence of circuit resistance on amplitude of current spike and overvoltage at different capacitor values and circuit inductance is evaluated.

Keywords: tantalum capacitor, surge current testing, surge current failure, transients, breakdown, overvoltage

INTRODUCTION

Tantalum capacitors are widely used as filters, bypass capacitors, coupled capacitors and so on. They have much better characteristics in comparison with their analogs. For example, they have solid electrolyte, which increases reliability against electrolytic aluminum capacitors, and they have larger values of capacitance and rated voltage with the same size, which is the strongest trait of tantalum capacitors and outweighs some disadvantages of this capacitors. Because of their properties, tantalum capacitors are used in military and aerospace applications. That's why requirements of reliability of tantalum capacitors are very high. The worst mode of failure of tantalum capacitor is the short-circuit failure. If current through broken capacitor is not restricted, capacitor may ignite due to exothermic reaction of Tantalum with Oxygen and damage surrounding equipment. Such type of failures is often observed in low-impedance circuits.

The main hypothesis of a relatively high failure rate of tantalum capacitors in low-impedance applications is that self-healing mechanisms in unlimited current conditions don't occur [1]. From the other hand, in low-impedance circuits, tantalum capacitors are exposed to high surge currents impact, which can lead to so-called surge current or turn-on failures. And, according to the results in [1], surge current breakdown voltages are significantly lower than breakdown voltages in steady-state conditions, or scintillation breakdown voltages. It can be assumed, that the fast rise of voltage on the capacitor, dV/dt, is the major reason of surge current failure. As a consequence of the fast rise of voltage, capacitor is exposed to impact of high surge current spike, $i = CdV/dt$. Unfortunately, there is still not theory, which can clearly explain a mechanism of surge current failure, and different hypothesis was suggested by different researchers [2].

For evaluating the capability of tantalum capacitors to withstand high surge current impact, a specific method, called surge current testing (SCT), is used. This method is regulated by ESA/SCC Generic Specification №3012 and MIL-PRF-55365 standards. During this testing, capacitors are exposed to a certain number of charge-discharge cycles from the power supply with very low impedance. To simulate such power supply a battery of aluminum electrolyte capacitors are used. But, surge current failure events are still observed among the tested capacitors. This may be due to that the present SCT method doesn’t simulate the worst surge current conditions and needs to be improved.

As shown in [3], circuit inductance and resistance has a significant effect on transients during SCT and surge current conditions in different testing equipment can be different. In this case reliable and reproducible evaluation of performance of tantalum capacitors in surge current conditions can’t be obtained. The problem is complicated by the fact that tantalum capacitors have the wide range of rated capacitance – from 0.1 μF to 2500 μF. The main goal of this work is to evaluate the influence of circuit inductance and resistance on the surge current conditions at different capacitance of tested capacitors.

Discussion of Model

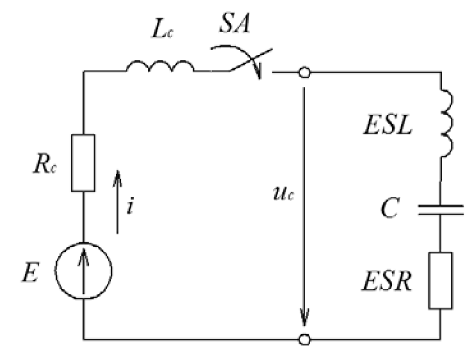


Figure 1. RLC equivalent circuit of tantalum capacitor

As shown in [3], the RCL model of transients during SCT gives a reasonable agreement with the experimental data (Fig. 1). But it is well-known that equivalent series resistance (ESR) and capacitance C of the tantalum capacitor depend on frequency. Thus, for accurate calculations it will be better to use the RC-Ladder equivalent circuit of tantalum capacitor (Fig. 2). In [4] was shown that in the most of cases, difference between results of calculation of transients by using RCL and RC-Ladder model is negligible. So, to simplify the calculations, in this work RCL model is chosen.

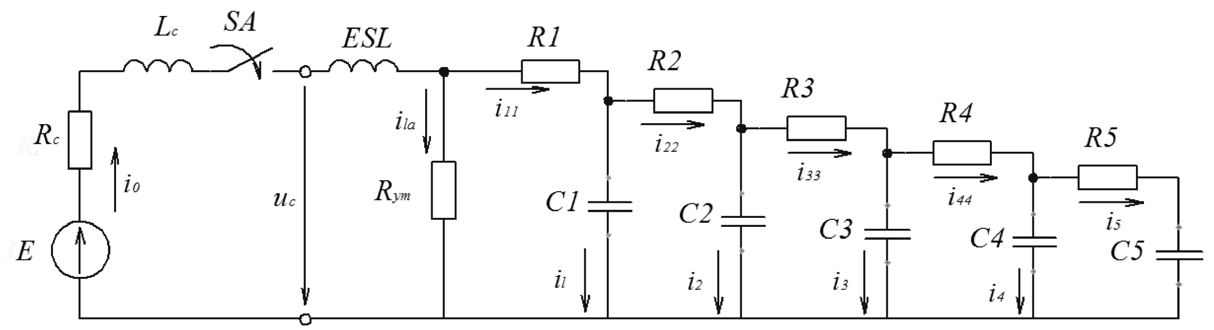


Figure 2. *RC*-Ladder equivalent circuit of tantalum capacitor

Transients during charging of capacitor according to Fig. 1 can be described by system of differential equations:

$$\begin{cases} (L_c + ESL)\dfrac{d^2u(t)}{dt^2} + C(R_c + ESR)\dfrac{du(t)}{dt} + u(t) = E, \\ i(t) = C\dfrac{du(t)}{dt}. \end{cases} \tag{1}$$

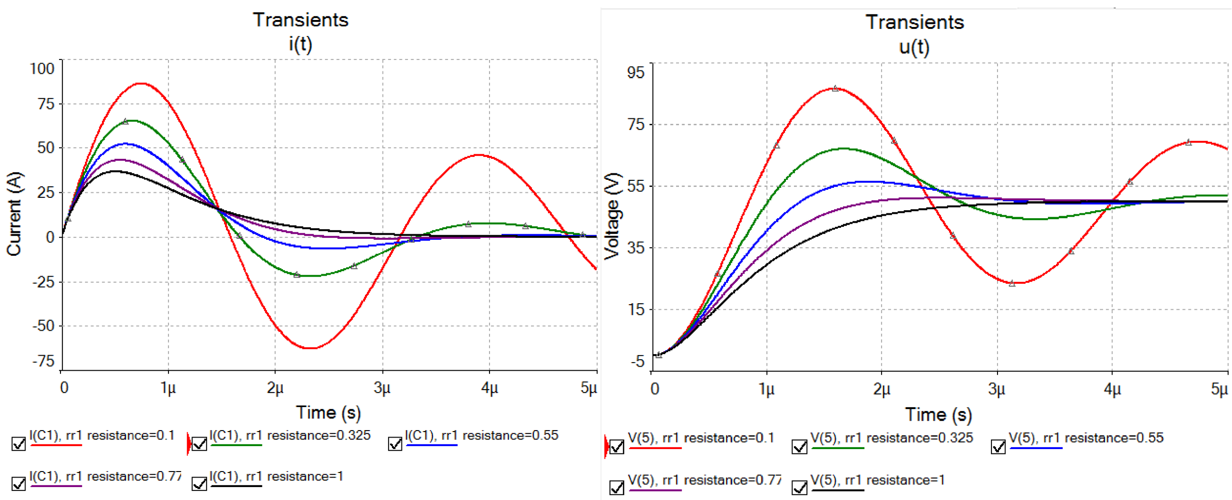
Initial conditions for system (1) are follows:

$$\begin{aligned} &u(0) = 0, \\ &\frac{du(0)}{dt} = 0. \end{aligned} \tag{2}$$

For all calculations it was be assumed, that ESR = 0.1 Ohm and equivalent series inductance ESL = 10 nH.

Calculation and Discussion

According to [3], total external inductance of circuit used for surge current testing, L_c, may vary from ~150 nH to ~1500 nH. According to MIL-PRF-55365 the version of December, 2012, the maximum allowable total external direct current resistance of the test circuit is equal to 1 Ohm. Hence, for calculations in this work, circuit resistance R_c was varying from 0.1 Ohm to 1 Ohm, circuit inductance was varying from 100 nH to 1500 nH. The range of rated capacitance was chosen from 1 μF to 1000 μF. Since that current through the capacitor is directly proportional to the rate of voltage rise on the capacitor, for analyzing the influence of circuit inductance and resistance on transients, it would be enough to analyze only current's changings with this parameters. All conclusions for current dependencies will be similar for the rate of voltage rise dependencies. The exception is the overvoltage on the capacitor, which may develop at underdamped conditions of transients. The value of overvoltage should be analyzed separately.



(a) (b)

Figure 3. Current through capacitor (a) and voltage across the dielectric (b) during surge current testing of 1 μF 50 V Capacitor with different resistance of the circuit at L_c = 250 nH

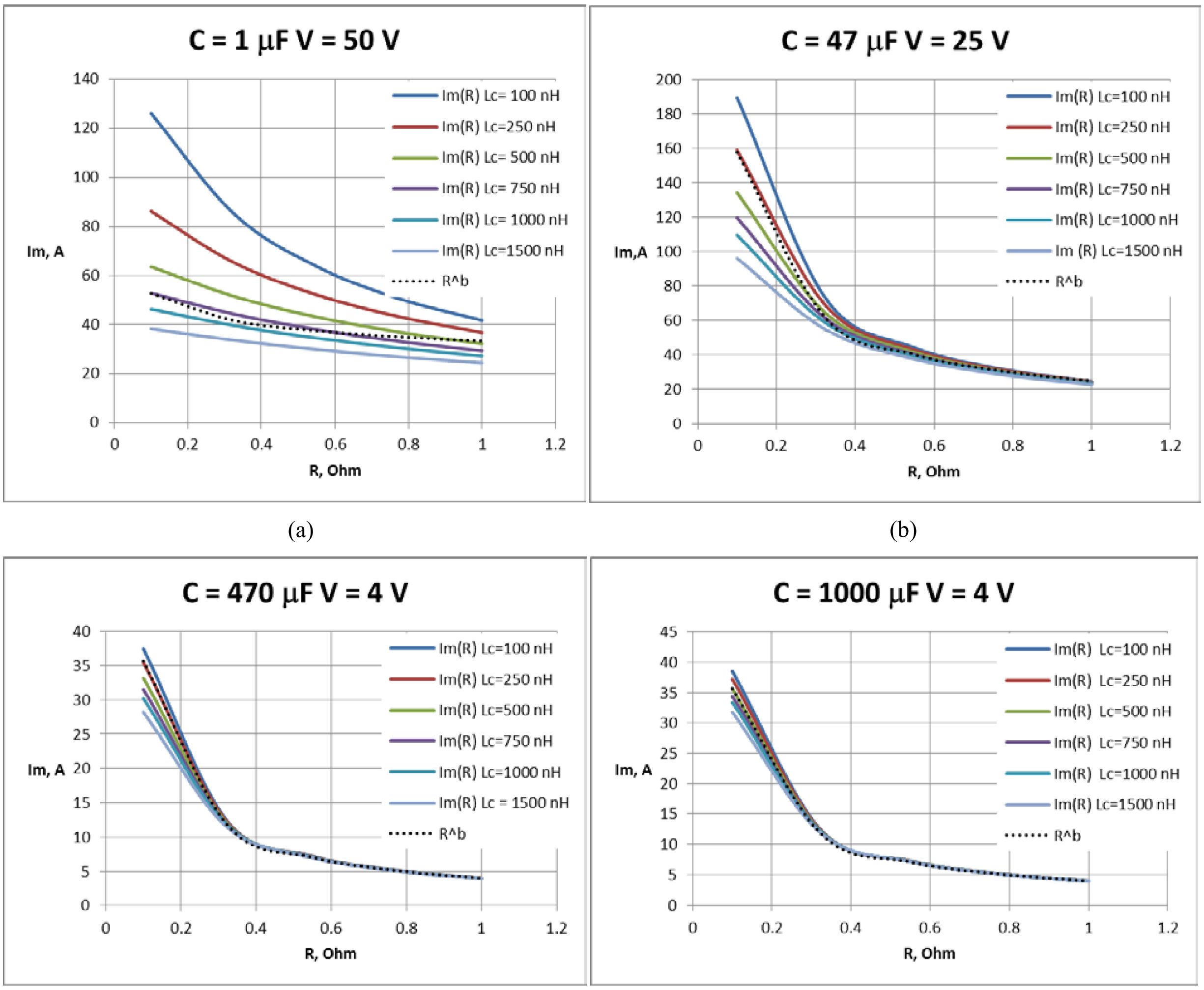
The example of calculation of transients for 1 μF 50 V capacitor with different resistance of external circuit is shown on Fig. 3. Calculation was made for external inductance L_c = 250 nH. The range of external resistance is from 0.1 Ohm to 1 Ohm. As it can be seen, changing of external resistance in allowable range per MIL-PRF-55365 lead to significant varying of amplitude of current spike, duration of current spike and the rate of voltage rise across the dielectric. For example, with increasing external resistance of the circuit from 0.1 Ohm to 1 Ohm, the amplitude of current spike decreases from 86.3 A to 36.8 A. Note that although the time to maximum increases along with increasing resistance, the rate of current rise decreases. Since that the cathode of tantalum capacitor, manganese dioxide MnO_2, has a semi-conductor properties, it can be assumed that tantalum capacitors are sensitive to the rate of current rise di / dt. The character of transients changes from the underdamped to the overdamped conditions while the external resistance decreases. At underdamped conditions capacitor may suffer from overvoltage up to $2 \cdot V_0$. In this example overvoltage across capacitor was $1.73 V_0$ at $R_c = 0.1$ Ohm. Hence, all this variations significantly change the surge current testing conditions.

It is reasonable to assume that influence of circuit resistance will be different at different circuit inductance and capacitance of tested capacitors. To analyze this influence, dependencies between the amplitude of current spike I_m and circuit resistance R_c at different circuit inductances L_c was calculated. Results of calculations are shown on Fig. 4.

It is seen, that the effect of circuit resistance decreases while the circuit inductance increases and capacitance decreases. For example, increasing of circuit resistance from 0.1 Ohm to 0.5 Ohm for 1 μF capacitor at circuit inductance $L_c = 100$ nH leads to decreasing the amplitude of current spike from 126 A to 70 A. The same changing of circuit resistance at $L_c = 1500$ nH leads to decreasing the amplitude of current spike from 38 A to 30 A. For 47 μF capacitor this changes leads to decreasing I_m from 190 A to 50 A at $L_c = 100$ nH and from 96 A to 30 A at $L_c = 1500$ nH. It can also be seen that almost all curves have the inflection point at $R_c \sim 0.4$ Ohm, after which the slope of relationship $I_m(R)$ decreases. At the low capacitance this effect is less strongly expressed. It may be due to that transients become underdamped and current exhibit oscillations. It is seen that at circuit inductance L_c = 1500 nH and capacitance $C = 1$ μF relationship $I_m(R)$ is almost linear.

Note that all curves can be approximated by the power law $I_m = I_1 R^{-\beta}$, where I_1 is the amplitude of current spike at circuit resistance $R_c = 1$ Ohm and β depends on circuit inductance and vary from 0.2 to 0.95. The same dependencies were obtained by Reed and Paulsen in [5] between the breakdown voltage and circuit resistance. The value of β in their research was ~ 0.2. The similar results were obtained by Teverovsky in [3] for dependencies between overvoltage across the dielectric and circuit resistance for 1 μF and 15 μF capacitors. But overvoltage may appear only at relatively low capacitance. For 220 μF and 330 μF capacitors overvoltage almost never observed in practice, because it is need to have the circuit inductance $L_c \sim 20$ μH. From the other hand, difference between β in present work and β of Reed and Paulsen is too significantly to claim that breakdown voltage depend only on circuit resistance. Many researchers hold hypothesis that the rate of voltage rise has a significant influence on probability of surge current failure. It can also be mentioned here that the rate of current rise through capacitor also is of value.

The effect of circuit inductance increases while the circuit resistance and capacitance decreases. Increasing of circuit inductance from 100 nH to 1500 nH at $C = 1$ μF and $R_c = 0.1$ Ohm leads to decreasing the amplitude of current spike from 126 A to 38 A. The same changing of circuit inductance at $R_c = 1$ Ohm leads to decreasing the amplitude of current spike from 42 A to 24 A. For higher capacitance the influence of circuit inductance on I_m at $R_c > 0.4$ Ohm tends to zero and can be neglected in most cases. But for $R_c < 0.4$ Ohm this effect is still significant. Along with decreasing of I_m the pulse width increases, but the rate of current rise di / dt and the rate of voltage rise decrease. The influence of circuit inductance on the pulse width and the rate of voltage rise is significant at small resistance and capacitance. Whereas the effect of circuit inductance on the rate of current rise di / dt is observed at all range of capacitance from 1 μF to 1000 μF. It can be assumed that the fast rise of current can lead to local overheating of the MnO_2 cathode and local breakdowns. In this case variations of circuit inductance even in relatively narrow range between 150 nH and 1500 nH for big capacitance can change the surge current condition and probability of failure.



(a) (b) (c) (d)

Figure 4. Relationship between amplitude of current spike and circuit resistance at different circuit inductance during surge current testing of 1 μF (a), 47 μF (b), 470 μF (c) and 1000 μF (d) capacitors. The black dotted line shows approximations with the power law

It should be mentioned here that at small capacitance transients can be underdamped and current and voltage can exhibit oscillations. The critical inductance, at which transients became underdamped can be find from following equation [3]:

$$L_{cr} \leq \frac{C(R_c + ESR)^2}{4} - ESL. \quad (3)$$

The results of calculations of L_{cr} at different capacitance are shown on Fig. 5.

It is seen that at small circuit resistance and capacitance it is almost impossible to achieve underdamped conditions of transients. For example, at circuit resistance R_c = 0.1 Ohm and capacitance C = 1 μF the critical inductance L_{cr} = 10 nH. In practice, testing circuits more often would have circuit inductance $L_c > 150$ nH [3]. The relationship between the overvoltage across the capacitor and circuit resistance at different capacitance and circuit inductance are shown on Fig. 6. As the relationship $I_m(R)$, relationship between overvoltage and circuit resistance can be approximated by the power law. But in this case such approximation would be rougher.

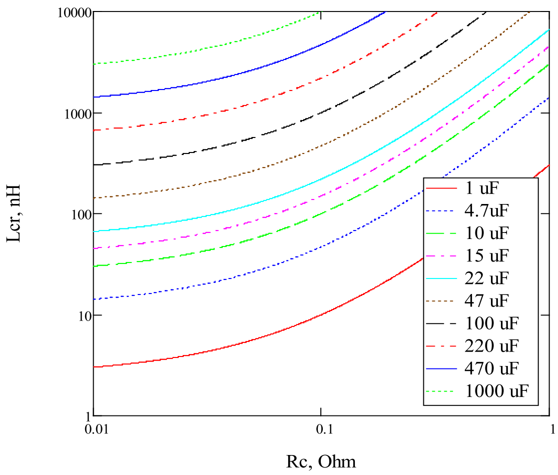
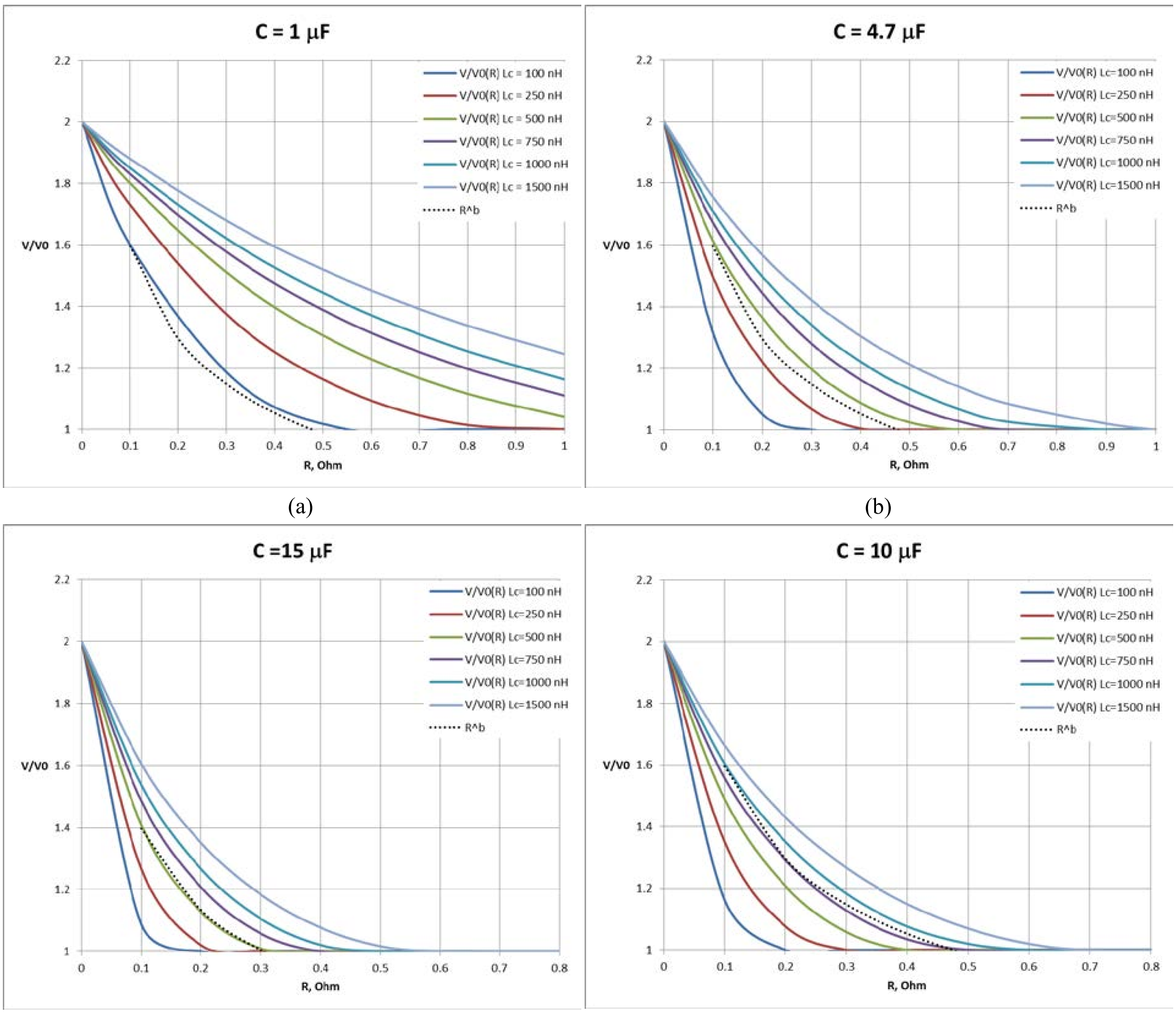


Figure 5. The relationship between critical inductance L_{cr} and circuit resistance R_c at different capacitance



(a) (b)

(c) (d)

Figure 6. The relationship between overvoltage across the capacitor and circuit resistance at different circuit inductance during surge current testing of 1 µF (a), 4.7 µF (b), 10 µF (c) and 15 µF (d) capacitors. The black dotted line shows approximations with the power law

Theoretical maximum overvoltage across the capacitor is equal to $2V_0$ at circuit resistance $R_c = 0$. In this case sustained electrical oscillations will occur. For the range of circuit inductance 100–1500 nH at R_c = 0.1 Ohm oscillations can be observed at capacitance up to ~ 100 μF, whereas at R_c = 1 Ohm transients become overdamped at the capacitance $C > 10$ μF. Thus, circuit resistance significant reduces the probability and value of overvoltage. Capacitors of smaller values more often suffer from overvoltage. In this case, failure mechanisms of capacitors with small and high values can be different. The duration of overvoltage also is of value and can significantly effect on the probability of breakdown. Capacitors can be exposed to several spikes of overvoltage at high enough inductance. Teverovsky in [3] suggested that it may be necessary to develop the special method of testing to establish the capability of tantalum capacitors to withstand impact of short spikes of overvoltage. It is may be a challenge because it is quite difficult to keep values of circuit inductance and resistance in the narrow range. From the other hand, during charging the capacitor is exposed to joint effects of current spike and voltage rise. To develop such testing method it is necessary to take into account all these factors. Obviously, this issue requires further investigations.

CONCLUSION

Circuit resistance R_c and inductance L_c have a significant influence on surge current conditions. Even slight variations of R_c and L_c can lead to significant changes of the amplitude of current spike, spike width, the rate of current rise di / dt and the rate of voltage rise dV / dt. All this changes influence on the probability of surge current failure. Moreover, such variations of surge current conditions can produce different failure mechanisms. In this case it is quite difficult to achieve reliable and reproducible evaluation of performance of tantalum capacitors under surge current conditions. Calculations show that at R_c above ~ 0.4 Ohm the effect of circuit resistance and inductance on amplitude of current spike is less significant. May be it is reasonable to determine the allowable resistance of surge current testing circuit in narrower range, for example, between 0.4 Ohm and 1 Ohm. But in this case surge current conditions would be less stressful. To guarantee the reliable operating of tantalum capacitors in surge current conditions, an appropriate derating must be applied [2].

Another problem that deserves attention is the possible oscillations during surge current testing. Overvoltages which develop at underdamped conditions of transients can reach values up to $2V_0$. It is reasonable to assume that failure mechanisms in the presence and absence of overvoltages across the capacitor would be different. Note that capacitors with small values would be more likely exposed to overvoltages. The probability of occurrence of overvoltage decreases as the circuit resistance increases and circuit inductance decreases. For achieving reproducible testing all possible measures to decrease circuit inductance must be taken. The length of wires must be as short as possible and all elements of testing circuit must be with a very low inductance.

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