CAPACITORS, THERMAL RATING/DERATING (AC-DC OPERATION)

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SUMMARY

In order to optimize equipment designs within the constraints of current Hi-Rel systems, designers need to know component performance and ratings as a function of thermal environment. For capacitors, historically this need has been satisfied by assuming a worst-case condition usually based on life tests performed in still air with no heat sink. This approach is not adequate for the requirements being experienced today.

Reductions of weight and volume are realized when a simplified thermal model of the capacitor is used in place of worst-case data. This paper describes application techniques for determining performance and ratings of cased capacitors under combined AC-DC operation as a function of the actual operating conditions. Thermal impedances between the case and external environment and between the internal "Hot Spot" and case are taken into account.

INTRODUCTION

When components such as capacitors are operated in service conditions, stresses experienced do not relate directly to the life test conditions upon which ratings are customarily based. Typically, capacitors are life tested with a fixed DC voltage applied, suspended by the leads in still or forced air at a controlled temperature. Voltage and temperature ratings based on this type of test lose significance when there is an AC voltage applied which causes some degree of self heating.

The AC life test has been used in some cases to address this problem. The most conservative method readily available for mounting, suspension in free air by the leads, has been used for CLR79[1] capacitors. This method is quite acceptable from a conservative point of view because all applications employ some heat sinking or forced air cooling.

The problem addressed in this paper appears when the attempt is made to maintain or improve performance of standard circuits with increasing constraints on size and weight of packaged systems. For example, filter capacitors across the output of DC power supplies are usually limited to rated AC ripple currents determined by free air life tests. Actual useage heat sinking provides for removal of heat at a faster rate permitting a higher ripple current for the same internal hot spot temperature. If a more realistic rating scheme, based on the heat flow characteristics of the device, were to be applied, designers could take advantage of their estimates of the thermal environment to optimize capacitor selection. An increase in ripple current per capacitor implies a reduction in the number of capacitors or an increase in performance at the same volume.

This paper presents an approach to thermal rating which takes into account the use environment.

THERMAL MODEL

The model to be employed is designed to take into account the hot spot concept in which temperature is directly related to reliability. A distributed internal heat source of magnitude equal to the power input is assumed. The hot spot temperature is assumed to increase linearly with power dissipation for any fixed mounting/cooling configuration.

There are two regions of thermal gradient which must be considered:

I. Internal, $\Delta T_I = T_{HS} - T_c$ where the internal temperature rise, ΔT_I, is defined as the difference between the hot spot temperature, T_{HS}, and the case temperature, T_C.

II. External (mounting), $\Delta T_C = T_C - T_A$ where the case temperature rise, ΔT_C, is defined as the difference between the case temperature, T_C, and the mounting surface temperature, T_A.

Specifically we assume that the temperature rise across both of these regions is proportional to the heat (power) flow through them:

Region I $\Delta T_I = \theta_I P$ (1)

Region II $\Delta T_C = \theta_M P$ (2)

where θ_I and θ_M are the respective net thermal impedances for the two regions and P is the total dissipated power.

The hot spot temperature is then written as:

$$T_{HS} = T_A + \Delta T_C + \Delta T_I \quad (3)$$

$$= T_A + P(\theta_M + \theta_I) \quad (4)$$

Equation (4) is a relationship which can be used to calculate (predict) T_{HS} for a specific application given a mounting surface *temperature* T_A *and the dissipated power*, P. This can be compared to a "rated" maximum T_{HS} to be developed through testing. θ_M and θ_I can be estimated by calculation and can be verified by infrared scan temperature measurements.

It should be noted that the case temperature and the mounting surface temperature are implicitly assumed to be uniform over their respective regions. This is reasonable since these regions normally have high thermal conductivity and do not contribute appreciably to the temperature rise as do the intermediate regions.

APPLICAITON OF THE MODEL

In the applicaiton of equation (4) there are two parameters related to the capacitor design and consequently involved in the rating of the capacitor; these are T_{HS}(max) and θ_I. Two other parameters are related to the application and must be determined by the system designer; they are T_A and θ_M. The fifth parameter P determines the actual hot spot temperature in a given operating situation.

T_{HS}(max) may be estimated from knowledge of materials and internal construction; it would be the maximum T_{HS} consistant with a minimum reliability standard. As a starting point T_{HS}(max) should be limited to values below any melting points or other temperatures where physical changes such as crystal structure modifications take place. It should be assumed that any such critical temperatures related to structural or functional materials *of the capacitor must not be exceeded.* Equation (4) may be used to calculate the nominal T_{HS} for a given operating condition to determine acceptability. The absolute accuracy of this calculation will depend on the accuracy of the determination of the remaining parameters.

θ_I, the other parameter related to the capacitor, *must be calculated from a detailed* thermal model of the capacitor. where uncertainties arise, assumptions should bias the value of θ_I toward the high side in order to keep the estimate conservative for worst case T_{HS}. Uncertainties in θ_I can come from variations in internal geometry which are to some extent predictable based on differences in nominal capacitances and voltage ratings within the general family. More than one θ_I could be required to represent all the capacitors available in a given case size for a family. Another important consideration is the contribution of the leads to θ_I. The leads will remove heat and will lower the effective θ_I depending upon the efficienicy of the heat sinking of the leads. A *conservative approach would be to ignore the* leads in the model and consider only heat removal through the case.

θ_M and T_A represent the outside thermal world to the capacitor and are determined by the system design. θ_M may be calculated through considerations of material properties and geometry for the mounting interface. T_A may be calculated from known system parameters or measured on working models as part of a general thermal mapping. θ_M may be verified easily by measurements of T_C and T_A at specific operating conditions.

P must then be limited in actual service to a value which will give a conservative *prediction from equation (4) of* T_{HS} below (less than) the established T_{HS}(max).

Ultimately, established reliability (ER) specificaitons should relate failure rates to T_{HS} with a specified tolerance on θ_I. With heat sinking controlled for AC tests results would be much more meaningful independant of considerations for θ_I.

EXAMPLE: CLR79 TANTALUM CASED TANTALUM

The example chosen is of interest because these capacitors are being used to replace silver cased wet slug and solid tantalum capacitors where ripple currents are significant. The CLR79 type has an inherrant ripple current capability far exceeding either of the previous designs. The question immediately arises as to how much ripple *current a given CLR79 can take in a given* thermal environment, i.e. given (θ_M, T_A). This question can be approached by using equation (4) to establish a maximum power from which a maximum ripple current can be calculated. Since internal designs vary among suppliers the user must be concerned with determining θ_I and T_{HS} for all styles from all manufacturers.[1]

Internal Thermal Impedance - θ_I

Manufacturers data[2] includes standard power ratings for each case size based on a 50°C internal temperature rise (ΔT_I). The ratings relate to operation in 85°C still air. An estimate of θ_I can be obtained directly from these ratings for each case size.

CASE SIZE	SPRAGUE RATED POWER (WATTS)	CALCULATED θ_I (C°/W)
T1 (C)	1.0	50.0
T2 (F)	1.50	33.3
T3 (T)	1.75	28.6
T4 (F)	1.95	25.6

Maximum Hot Spot Temperature - T_{HS}(max)

An estimate of T_{HS}(max) can be made by considering equation (3) as it applies to standard ripple current life test conditions for which characteristics are known. The free air temperature (T_A = 85°C) takes the place of a mounting surface temperature and the case temperature rise, ΔT_C is determined by the power dissipated across the interface between the case and ambient air. Internal temperature rise, ΔT_I, is assumed to be 50°C, the maximum permitted. Curves are given in the references[3] which yield the following values of ΔT_C at rated maximum ripple currents for two capacitor types in each of the four case sizes:

CAPACITOR TYPE	CASE SIZE	ΔT_C AT STD 40 kHz CURRENT (C°)	
3.6uF,125V	T1(C)	120	
10uF, 50V	T1(C)	125	
47uF, 50V	T2(F)	60	Mean = 67.2°C
100uF, 25V	T2(F)	66	Standard
25uF, 125V	T3(T)	65	Deviation =
56uF, 75V	T3(T)	70	6.7°C
300uF, 30V	T4(K)	63	
1200uF, 6V	T4(K)	69	

Since our estimate of T_{HS}(max) is intended to be conservative we select 60°C (the lower one sigma limit) for ΔT_C(max). More extensive data would result in a better estimate. Applying equation (3) to the worst case we have:

$$T_{HS}(max) = T_A + \Delta T_C(max) + \Delta T_I(max) \quad (5)$$

$$= 85°C + 60°C + 50°C = 195°C \quad (6)$$

We have established a new rating parameter which can be derated in accordance with a rule determined by system reliability requirements. A typical rule states T_{HS}(max) must be derated 30°C for nominal operating conditions and 15°C for worst case conditions. Thus:

OPERATING CONDITION	T_{HS}(max)
Rated	195°C
Nominal	165°C
Worst case	180°C

Typical case

Let us consider a specific capacitor say M39006/22-0216. This capacitor's characteristics[1] are 25uF, 125Vdc, T3 case, 1200 mA (rms). Manufacturer's data[2] indicates a maximum equivalent series resistance (ESR) of approximately .6 Ω at 40 kHz in the internal temperature range of 160 to 200°C (obtained by extrapolation of ESR vs temperature for the case where no power is dissipated). We assume:

T_A = 70°C, mounting surface temperature

θ_M = 20°C/watt, mounting thermal impedance. Using our estimate above for the T3 case we then apply equation (4) and

$$I = \sqrt{\frac{P}{ESR}} \quad (7)$$

where P is dissipated power, I is current, and ESR is the equivalent series resistance.

The results for the various operating conditions are:

OPERATING CONDITION	T_{HS}(max) (C°)	P (WATTS)	I (Arms)
Rated	195	2.57	2.07
Derated worst case	180	2.26	1.94
Derated nominal	165	1.95	1.80

The results given compare to the standard rating of 1200 mA (rms) as follows: the new current rating based on T_{HS}(max) is nominally equivalent to but slightly more conservative than the standard rating with respect to stress at the worst case operating condition. Derated currents based on derated T_{HS}(max) which correspond to conservative estimates of power dissipation still exceed the free air rated current.

The results of the example are given for illustrative purposes to show the relative merits of this approach in providing the circuit designer with greater freedom of selection. This technique will permit identification and elimination of situations where over design has been necessary to provide required circuit performance and reliability.

CONCLUSIONS

There is a distinct need to specify more closely the power dissipating capabilities of capacitors for AC applications. Life test conditions should be modified so as to relate better to use conditions. The typical life test condition where capacitors are suspended in free air is difficult to relate to any use condition except to the extent that it may be considered "worst case". Known heat sinks should be used so that the internal characteristics of the capacitors could be verified more accurately. The correlation of, T_{HS}(max), maximum hot spot temperature with failure rate and, θ_I, internal thermal impedance will enable system designers to make very significant improvements in space efficiency ands system performance.

REFERENCES

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2. Engineering Bulletin 3760A, Sprague Electric Company 1978.
3. England, Walter F., Tantalum - Cased Wet-Slug Tantalum Capacitors, Proc. 27th Electronic Components Conference, 1977.