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Endurance Test on Carbon Film Fixed Resistor under Escalated Voltage Stress

Yuan Fuqing*[1], Jinmei Lu[1]

[1]Department of Engineering and Safety, University of Tromsø, 9037, Norway

Yuan.fuqing@uit.no

Abstract. Film fixed resistor is a basic unit in the electronic devices. As it is less frequently failed than other units such as capacitor, the reliability and robustness of it are less concerned both in the academics and in the industries. This paper investigates the endurance of the carbon film fixed resistor. The resistance shift and life of it under the escalated voltage stress level are the aim. A PCB board is designed to test the performance under various voltage stress levels. It was observed at lower stress level, the resistance can maintain the resistance in certain level, and can function even they burned. However, at high stress level, the resistor will also burn but the resistance will be extremely high to reach unacceptable level. The individual difference is obvious due to material dissimilarities. Resultantly, the life of the resistor is far deterministic but uncertain. A life model is developed in this paper to capture the uncertainty.

1. Introduction

The ubiquitous use of fixed resistor in electronics highlights the importance of this basic electrical unit. The resistors are designated to work under certain electrical stress, typically at certain levels of voltage, power. The resistance will fluctuate with the ambient temperature and electrical stress. The fluctuation could destabilize or even damage the electronic. The endurance is of question since the voltage fluctuation is very common in practical operating environment. The endurance test is thus necessary before the resistors are integrated into the electronic board. Some endurance relevant information are provided in the specification of the resistor from the manufacturers. Practitioners from the electronic engineering can rely on the specification provided by the manufacturers to obtain the endurance information.

For example, manufacturer specification provides the temperature coefficient, maximal & minimal operating temperature, power rating, allowable voltage etc., according to certain standard, such as the ISOC/IEC QC 4000000 [1]. However, the over-stress situation is out of the specification scope. Unfortunately, the practitioner in electronic engineering ignore these over-stress situations as the device is supposed to be working under the normal stress. One has to be aware, when electrical stress is applied above the nominated level, the aging and the resistance shift will be accelerated. It is still necessary to investigate the behavior and performance at elevated stress level, since it substantially affect the durability, reliability of the resistor, therefor at the over specified electrical stress, the fixed resistor exhibits dynamic procedure. This paper conducts experiments to investigate the behavior under several elevated electrical stress. This paper conducts experiments to investigate the resistor behavior from electrical perspective. The section 2 will describe the designed experiment. Section 3 will present the results and the analysis on the data. Section 4 offers discussion. Section 5 presents conclusion.

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2. Experiment Design

The material used in the fixed film is ceramic as a base, and metal film is surrounding the base. A protective coating is applied outmost layer. The protective coating is less resistant to overheating, as the normal coat material is epoxy. Epoxy is with meting point around 120℃. The metal or carbon film that customizes the designated resistance is with high melting temperature. Metal such as aluminum alloy, iron alloy, copper alloy have melting temperature from 400℃ to 1500℃. Ceramic served as carrier or base of the resistor is well-known as the high temperature withstanding. It can stand a temperature over 1000℃. Although abnormal phenomenon cannot be observed until the temperature elevated to the melting temperature. However, the resistance shift will certainly occur, for all material, as the resistance will change with increasing temperature, due to the free electrons moving. The resistance shift of resistor can degrade the performance, or lead to dysfunction the whole electronic device.

If the resistor is connected to a direct power source and no other electric unit is in this circuit. Resistor loses power through joule effect [2]. The heat dissipates by conduction, convection and radiation. When the resistor operates at the nominated or lower the nominated electrical stress, failure is unexpected to occur. As under the allowable operating condition such as humidity, ambient temperature, the resistor will be heated up with escalated temperature, with no significantly increasing. The generated heat will be dissipated into the ambient air and the leading wire, i.e. the newly generated heat can be dissipated into the surrounding, the temperature will not increase and therefor the thermos-equivalence obtained. In a mathematical form, the thermo-equivalence is described as

$$Joule\ Effect\ Heat = J_{Conduction} + J_{Convection} + J_{Radiation} \tag{1}$$

When the thermos-equivalence obtained, the surface temperature of the resistor is stabilized. Practitioner in electronic design considers mainly the thermo-equivalence state, as it is the designated working condition. However, the temperature is suffering an escalated procedure after voltage has been applied. Heat started to accumulate inside the resistor body, although simultaneously heat dissipation started. Initially the dissipation is not significantly as the dissipation depends on the difference between resistor and the nearby objects such as air, wire lead. Since the resistor's temperature is close the ambient temperature initially, the heat dissipation is not effective. Heat will accumulates. The resistor's temperature will increase [3]. This experiment is designed to observe the temperature's increasing procedure. The resistor is laid horizontally in the board. Two thermal sensors are mounted with one designated to measure the resistor body temperatures. Another sensor is mounted a little far away from the resistor designated to be the ambient temperature. As the thermos-sensor can not be installed inside the resistor, it has to be mounted near the resistor body as near as possible to approximate the body temperature. The method will induce some error but it is practical. Figure 1 shows the temperature gradient around the resistors.

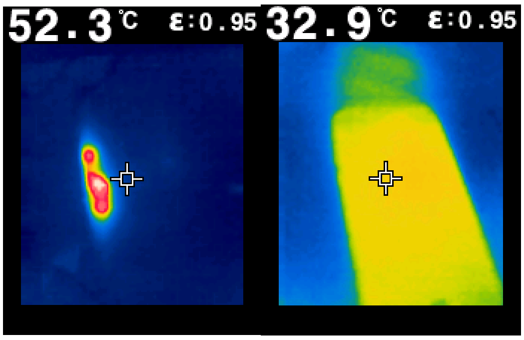

Figure 1. Temperature Gradient

Direct power source is applied to the resistor so that power source can be considered as constant voltage. As the dynamic output of the power source, the real source voltage is fluctuating, around the designated voltage. A extra voltage sensor is mounted to measure the source voltage in real time. Moreover, aiming to measure real time resistance of the resistor, an extra resistor with 1 Ω resistance

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is connected in series with the test resistor. The magnitude of the current is identical to the voltage of the 1 Ω auxiliary resistor.

Although each resistor for test is unique with same nominated specification, the difference among them is well known. The dissimilarity of material, erratic ambient environment will result to different resistance. This experiment measure 7 resistors at one time. The 7 resistors are with same specification but on one board. In general, it can be considered to be operating in same operating condition, event not realistic but acceptable. The resistance difference can thus considered due to the resistor inherently.

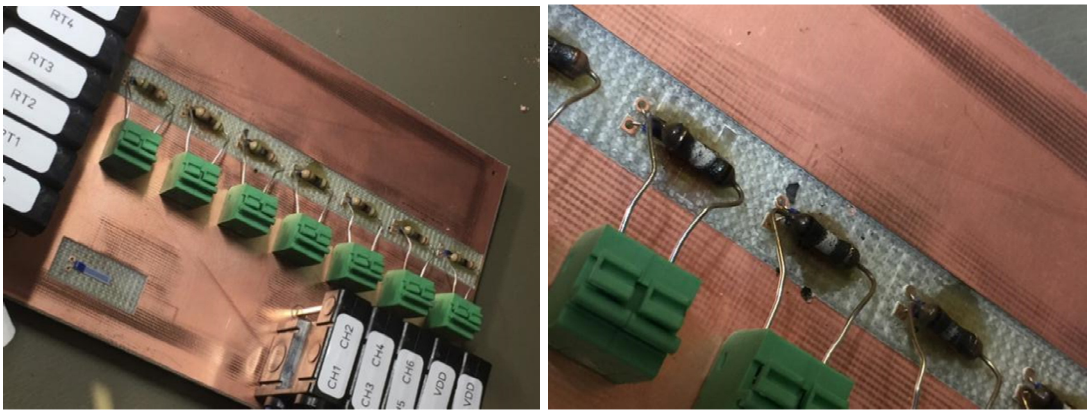

Figure 2. Manufactured PCB Board for test

Carbon file fixed resistor axial leaded are used in the experiment. The resistor is specified 56Ω with nominal 0.5W power. Four levels of constant direct voltage have been applied: 12V, 13V,15V,15.5V, 16.7V. Under these stress levels, supposing the nominal resistance is 56Ω, the applied powers are shown in Table 1.

Table 1. Applied Stress Levels

Stress Level	Applied Power (W)	Over Stress Level
12V	2.57	5.1
13V	3	6
15V	4	8
15.5V	4.3	8.5
16.7V	4.98	9.96

The last column of Table 1 shows the times of over stress than nominal power. At 12V, it is 5.1 times than the nominal power. The body temperature of each individual resistor, ambient temperature, real time voltage over all resistor, current of each individual resistor are measured at time interval 0.8 seconds. Data was collected in the excel files and processed in Matlab further.

3. Data Analysis

A preliminary test was carried, no failure and any abnormal phenomenon was observed under 12V stress. At 12V stress, some resistors burned, some not. At 12V, initially the outside body are observed colored to dark at the center of the resistor. Soon after, on some resistor, smoke was observed and odor was smelt; while on others, no further symptoms observed. The smoke results from the melting of the epoxy. We noticed the melting starting at temperature around 120°C-130°C. Table 2 shows part of the collected data.

Table 2. Raw Measurement Data

Nr.	**Time (S)**	**Ambient T (℃)**	**Temp for R1 (℃)**	**Temp for R2 (℃)**	**…**	**Current for R1 (A)**	**…**
1	0	25.7580	26.0790	26.8100	…	0.2082	…
…	…	…	…	…	…	…	…
25	20.0500	25.7780	39.9180	46.9500	…	0.2171	…
…	…	…	…	…	…	…	…
408	316.0580	29.7090	114.62	154.03	…	0.2175	…
…	…	…	…	…	…	…	…

At same stress for all levels, body temperatures exhibit different obviously from each other for temperature against time, as shown in Figure 3,

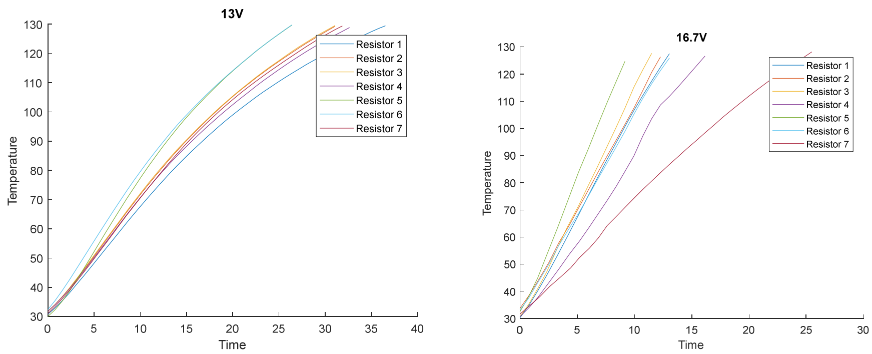

Figure 3. Temperature Vs Time

This difference of individual reveals the material dissimilarity, even they are from same batch of production. At higher stress level, the differences become greater from the individuals than the lower ones. Simultaneously, the resistance varies with the time when the temperature is ever changing, as shown in Figure 4. The right figure in Figure 4 shows the detailed curve of resistance against time. The resistor is with negative coefficient. When the temperature rises, the resistance decrease. But when the epoxy starts to burn, the resistance starts to increase. At 16.7 level, some resistor will have high resistance after it burned, the functions of the resistor is therefore destroyed. Electronics will probably dysfunction when resistance reaches this level.

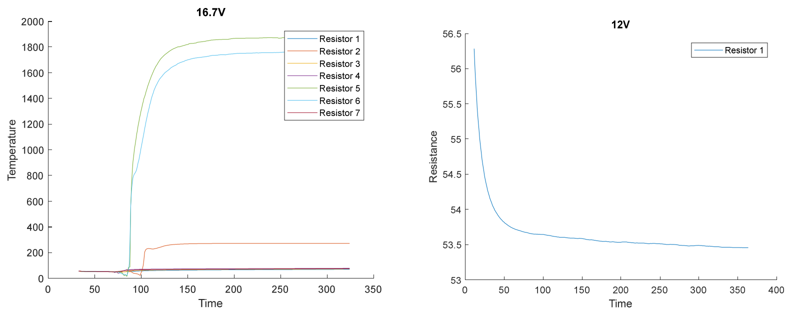

Figure 4. Resistance vs Time

3.1. Power Law Model

The left of Figure 4 shows the temperature increasing with time nonlinearly. In order to analyze it quantitatively, we fit the data into a power-law model in the form

$$T = T_0 + a * V^2 * (1 - e^{-bt}), \tag{2}$$

where $\mathbf{T_0}$ is ambient temptation, V is applied voltage, a and b is unknown coefficients. This power law model is not purely data-driven. It is derived from thermo-dynamics models with some simplifications. In this model, the ambient temperature $\boldsymbol{T_0}$ and stressed voltage are considered constant, although it is dynamic as shown in Table 2. Since the variation is not significantly, we can consider it as constant to simplify the model and can simplify the model parameters evaluation significantly.

As the model (2) is not able to rewritten into a linear function, we have to use numerical method to find the coefficient a and b. The non-linear algorithm used are from [4]. In the regression computation, the $\mathbf{T_0}$ used is 30°C. The initial values of a and b in the iterative procedure are chosen both as 1. No automatic initial values choosing methods are using, since the other initial values will lead to same results. At level 16.7V, for results shown in Table 3. The P-values is extremely small, i.e. the parameter values are reliable and it is supported by sufficient large data. The R-squared value is 0.839. The model is not fitting the data perfectly, but it is reasonable. As the original data, as shown in the right of Figure 5, the original is dispersing. Theoretically, it is impossible to fit all of them perfectly using a curve.

Table 3. Non-linear Model for 16.7V

Parameter	Value	SE	P-Value
a	0.37512	0.02276	2.53e-33
b	0.10093	0.02233	4.1e-15

If we only consider one resistor instead of all resistor data, we can obtain a much better fitting. The model values for Resistor 7 at 16.7V is shown in Table 4. The R-squared value is 0.999. it is perfect fitting.

Table 4. Non-linear Model for 16.7V for R7

Parameter	Value	SE	P-Value
a	0.986	0.0225	5.62e-38
b	0.018	0.0005	1.24e-33

The left of Figure 5 shown the power law model using one levels data, the right figure shows the plot for one resistor. The fitting performance can be visually for both power law models.

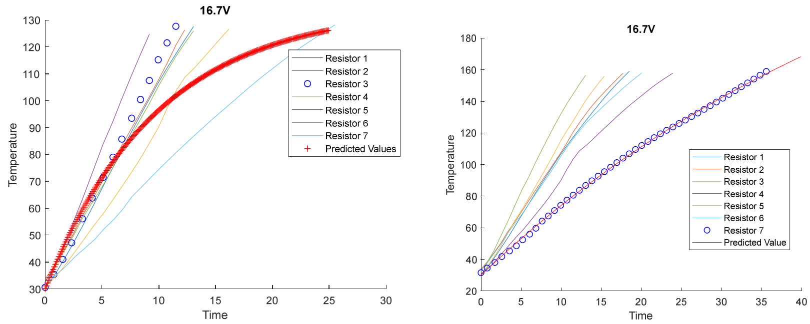

Figure 5. Power law model plot at 16.7V

3.2. *Uncertain Life Time*

Section 3.1 present the model of temperature against time. In practice, engineering could be interested in the life under certain stress level. The Equation (2) can be rewritten as

$$\boldsymbol{t} = -\frac{\ln(1-\frac{T-T_0}{aV^2})}{b} \tag{3}$$

If we suppose the failure occurs when the temperature reaches 130°C, as described in the experiment design, the life of the resistor can be evaluated. The life is the (3) when T=130°C. As we mentioned before, the temperature against time differs from each individual, as shown in Figure 5, the life could be uncertain as well. If we consider the coefficients a and b is random variables, a variance of the TTF can be derived. According to the delta method [5], the variance of TTF can be obtained from

$$\boldsymbol{Var(TTF)} = (\frac{\partial t}{\partial a})^2 . \boldsymbol{Var(a)} + (\frac{\partial t}{\partial b})^2 . \boldsymbol{Var(b)} \tag{4}$$

$$\frac{\partial t}{\partial a} = -\frac{T-T_0}{a^2bV^2-(T-T_0)a};\ \frac{\partial t}{\partial b} = \frac{\ln(1-\frac{T-T_0}{aV^2})}{b^2} \tag{5}$$

Using the values presented in Table 3, we obtain the $\frac{\partial t}{\partial a}$=2.9776, $\frac{\partial t}{\partial b}$=-311.4720. The mean life at 16.7 is 19.5 seconds according to (3). According to (4), the standard deviation of TTF is 6.9555. The uncertainty in the lives has thus been measured.

4. Discussion & Conclusion

The resistors exhibit a dynamic phenomenon. At higher stress level, the resistor decreases in its resistances against time initially for most of the tested resistors. When the epoxy melted and burned, the resistances start to increase. The non-constant resistance will fluctuate the electronics performance, as in the electronic design, some designer consider the resistor is with constant value. Another observed pheromone is for the stress level is lower, such as 12V, 13V, the epoxy will melt after a while. Smoke can be observed, however, surprisingly the resistance can still maintain around the nominal values. It can deviate maximum 5% around its nominated resistance. But at higher stress level, the resistance can surge to 40% even to open circuit. The surge from nominal resistance to open circuit is with few seconds.

The tested resistors at each stress level are from same manufacturer and with same specification. We observed obvious individual difference. For example, at 16.7 level, one resistor reaches 80℃ at around 12 seconds; while another takes only 5 seconds. The operating condition is almost identical, as they are mounted in the same PCB board. The differences result mainly from the resistor inherently. These inherent dissimilarities could be the epoxy cover material, thickness difference, or the carbon material dissimilarities. Microscopic level examination can be used to further find the root causes. But it is out of the scope of this paper.

Fixed film resistor is a common unit in the electronic unit. The reliability and robustness is less concerned as they are supposed to be stable. However, the dynamics and dissimilarities among the individuals suggests the electronic engineer should concern the resistance shift at the higher electrical stress level. Failure might occur rapidly when an unexpected insurgent voltage applied on the board.

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