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Experimental Verification of Mathematical Models for Failure Estimation of Electronic Systems

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Numerous techniques for analyzing electronic circuits play a key role in the design process of any product designed for harsh environments. This article compares the design and analysis approach with the experimental verification of a real circuit for a diode-based semiconductor circuit that is part of voltage balancing systems for lithium-polymer cells for industrial applications. The purpose of the design and analysis process is a reliable solution that performs all the required functions under real operating conditions, including critical parameters that may occur during normal system operation. Preliminary circuit design is done using ideal components. Using the truth table as a representation of the requirements, the correctness of the system's operation was checked. LTSpice was used as the main program for designing and testing analog and mixed integrated circuits. Based on the system requirements, real components are selected, followed by the worst case analysis that takes into account tolerances, noise, mains voltage disturbances, temperature and aging. Foster and Cauer thermal models were created for components exposed to thermal stress. After a successful WCA analysis, a security analysis is carried out that predicts possible defects and their impact on the entire project due to problems during system production and operation. The WCA results were compared with experimental measurement of a real system that was subjected to a high temperature in a thermal chamber that simulates the work of the system after 10 years.

topics: failure estimation, experimental test, electronic circuit, WCA test

1. Introduction

Designing electronic circuits is an extremely difficult and complicated process. It requires a lot of service and an appropriate sequence of analyzes to achieve the desired effect. Numerous techniques for analyzing electronic circuits play a key role in the design process of any product designed for harsh environments. The basic analyzes are: computer simulations using the LTSpice program, worst case analysis, design failure modes and effects analysis or safety analysis. Correctly carried out gives almost 100% on proper functioning of the designed system in the expected operating conditions.

2. Analyzed system

The electronic system analyzed in the article is the module responsible for providing information on the temperature of individual battery packs (Fig. 1). The system consists of an actuator being a semiconductor diode working in the system as a temperature sensor, a resistor limiting current consumption and a capacitor filtering the output voltage. Diodes are often used as temperature sensors in a wide range of temperatures with moderate precision. A linear temperature coefficient such as −2 mV/ °C for operating temperature makes diodes an excellent solution for flexible and cheap applications. A system based on a diode may be simple, but its implementation may require excitation, compensation and amplification [1, 2].

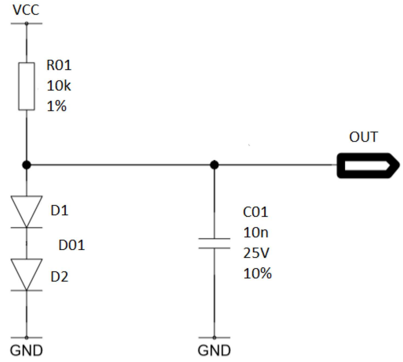

Fig. 1. Circuit diagram.

3. Working conditions

The system under analysis should perform all functions under real operating conditions that may occur during normal system operation. The requirements for the analyzed module are as follows:

- Operating voltage VCC (5 V ±0.25 V)
- Working temperature (−40 °C, 25 °C, 120 °C)
- Lifetime (10 years)

4. Selection of components

The initial simulation was carried out using the LTspice program for the design and testing of analog and mixed integrated circuits. In the application one will find a huge library of elements and schemes for creating individual layouts. After obtaining the confirmation of the correct operation of the system from computer simulations the components of the system were selected:

- Diode: Vishay 1N4148
- Resistor: Vishay CRCW060310K0FKTABC
- Capacitor: Kemet C0603C103F3GACTU

5. WCA analysis

Circuit analysis in the worst case is an analysis technique that determines circuit performance in the worst case scenario (in extreme environmental and operational conditions). Environmental and operational conditions are defined as input requirements, which are external stresses applied to each circuit element. Parameters for individual components and implemented functions will be adjusted for the tested system on the basis of [3].

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In the WCA one calculates:

- *Total tolerance resistance* (R_{tot}): The calculation contains the most important factors that change the resistance value. $R_{\text{tolerance}}$ being the initial value of the resistor tolerance, R_{temp} that is the effect of temperature on the change of resistance and R_{life} being the effect of aging on the value of the resistance. Finally one calculates the range of resistance for R01 (R_{tot}) to further calculations of power dissipation.

$$R_{\text{tot}} = R_{\text{tolerance}} + R_{\text{temp}} + R_{\text{life}}. \quad (1)$$

- *Power dissipation* ($P_{\text{R01 max}}$): This parameter is calculated to check if the element does not overheat. Performed calculation includes all conditions that component is designed to work under. It is also assumed that there is none minimum voltage drop on diodes, since manufacturer does not provide it.

$$P_{R01\ \text{max}} = \frac{(\text{VCC})^2}{R_{\text{tot}}} \quad (2)$$

The calculated maximum power should be compared with the power that can be dissipated by the resistor/housing selected. Moreover, it should be checked whether the maximum voltage that may appear on the resistor is within the allowable voltage described in the documentation.

- *C01 bias voltage*: The maximum voltage $V_{C\ \text{max}}$ that can appear on the capacitor corresponds to the voltage that is deposited on both diodes V_D.

$$V_{C\ \text{max}} = 2V_D \quad (3)$$

- *C01 capacitance total*: Calculation was done takin into account all conditions that component is designed to work under. $C_{\text{tolerance}}$ is the capacitor's initial tolerance, C_{temp} is the capacitance range that a capacitor can take in a given temperature range, C_{aging} is the capacitance range that a capacitor can have after a certain lifetime, C_{bias} is the capacitor capacity depends on the voltage applied to it.

$$C_{\text{tot}} = C_{\text{tolerance}} + C_{\text{temp}} + C_{\text{aging}} + C_{\text{bias}} \quad (4)$$

- *D01 forward voltage and current*: To calculate the voltage at the diode under analysis, the maximum current through it must be determined, taking into account the effect of temperature on the maximum value of current. Thus, equation for VCC is given as:

$$\text{VCC} = R_{\text{tot}} I_R + [U_D(I_D, T_{\text{min}})]_{\text{max}} \quad (5)$$

and it refers to particular operation of the system for which one can assume that $I_R = I_D$. When the voltage U_D and current I_D values on the diode are calculated, the maximum power value that will be generated on the diode should be determined.

- *D01 self-heating*: One will determine whether the maximum temperature at which the diode can work, denoted as T_D, will not be exceeded. A thermal model in the form of Foster and Cauer networks has been created for the semiconductor diode as the sum of the maximum ambient temperature T_{ambient} and the product of the power dissipated P_D on the diode and the thermal resistance R_D of the diode [5]:

$$T_D = T_{\text{ambient}} + P_D R_D. \quad (6)$$

6. Safety Analysis

Safety analysis predicts possible defects and their impact on the entire project due to problems during system production and operation. For individual components, the case of potential short circuit between element outputs, openings and changes of key parameters are analyzed. Table I presents the analysis for the tested system.

7. Experimental measurement

In this paper only the results of the experimental studies on one of the elements (resistor $R01$) of the system has been presented. A series of resistors (to the test has been prepared PCB with 532 resistors) were subjected to high temperature in a thermal chamber that simulates the work of an element after 10 years. A series of calculations were used to

TABLE I

Safety analysis for the tested system.

Part	Potential failure	Effect
Resistor R01	open	Voltage on OUT pin undefined.
	short	Biasing resistor shorted. VCC voltage breakdown. Damage of D01 due to overcurrent. Temperature measurement not possible.
	$R/2$	Voltage on OUT is higher. Indicated temperature is too low.
	$2R$	Voltage on OUT is lower. Indicated temperature is too high.
Diode D01	pin 1 open	Temperature measurement not possible.
	Pin 2 Open	Temperature measurement not possible.
	parameter change ×0.5 Diode 1 (Ub)	Voltage on OUT is lower. Indicated temperature is too high.
	parameter change ×0.5 Diode 2 (Ub)	Voltage on OUT is lower. Indicated temperature is too high.
	parameter change ×2 Diode 1 (Ub)	Voltage on OUT is higher. Indicated temperature is too low.
	parameter change ×2 Diode 2 (Ub)	Voltage on OUT is higher. Indicated temperature is too low.
	Diode 1 short	Voltage on OUT is lower. Indicated temperature is too high.
	Diode 2 short	Voltage on OUT is lower. Indicated temperature is too high.
Capacitor C01	open	No low pass filter at OUT.
	short	OUT shorted to ground. Indicated temperature is too high.
	$C/2$	Change of cutoff frequency at OUT.

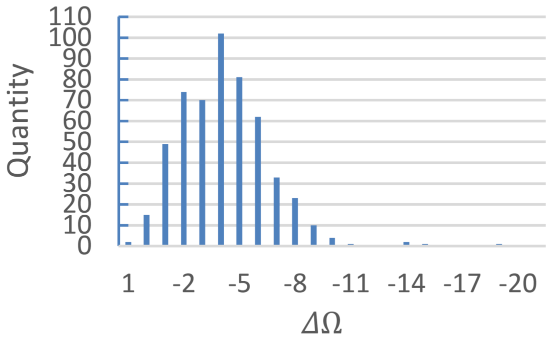

Fig. 2. Distribution of the number of resistors as a function of resistance change.

conclude the simulation conditions in the thermal chamber. This includes self-heating of parts and possible temperature increase of individual components — it is assumed that temperature of resistors is maintained within limits under worst conditions (working temp. (−40 °C, 140 °C) [6].

The one experiment cycle takes 35 min in −40 °C and 146 min in 140 °C [7]. Figure 2 shows the distribution of the number of resistors as a function of resistance change after the test.

Each resistor was measured before and after simulation. Analysis of the obtained results gives the following conclusion presented in Table II. It has been calculated that 96.8% of the tested components increase the resistance value. The obtained average and trend results suggest that the resistance of the resistors is noticeable, but very insignificant. Further calculations were carried out to better assess the phenomenon. The significance of linear one-dimensional regression function was tested. The previously calculated means and standard deviations were used for this, then the moment of correlation of the variables from the sample was calculated according to the formula [5]:

$$m_{xy} = \frac{1}{n} \sum_{i=1}^{n} (x_i - m_x)(y_i - m_y). \tag{7}$$

Calculation of the linear correlation coefficient was done as:

$$R_{xy} = \frac{\sum_{i=1}^{n} (x_i - m_x)(y_i - m_y)}{\sqrt{\left[\sum_{i=1}^{n} (x_i - m_x)^2\right]\left[\sum_{i=1}^{n} (y_i - m_y)^2\right]}} \tag{8}$$

The linear correlation coefficient characterizes the degree of linear relationship between random variables. When the coefficient is −1 or 1, there is a close linear relationship between the random variables. When the factor is 0, the variables are uncorrelated. The closer to 1, the stronger the correlation is. For the analyzed case, the correlation coefficient is 0.95, which means that the correlation of changes in resistance of the time function is very strong.

For further analysis, one calculates:

$$t = \frac{R_{xy}}{\sqrt{1 - R_{xy}^2}} \sqrt{n-2}. \tag{9}$$

Using the t-Student distribution for ∞ degrees of freedom and $\alpha = 0.01$ (it is assumed that for more than 120 elements number of degrees of freedom

TABLE II

Resistance (in Ω) of parts before and after the simulation.

	Before test	After test
average value	10008.92	10012.73
standard deviation	10.87	11.15

is ∞, the $\alpha = 0.01$ was calculated from the datasheet of the product) one can read from the student's t-tables that $t_\alpha = 2.576$. The t factor for the analyzed case is 67.94. If the obtained result is greater than or equal to t_α, it means that the hypothesis about the lack of correlation between the analyzed variables should be rejected.

8. Conclusions

The article describes the methodology for conducting electronic system analysis on the example of a module working as a temperature sensor. The worst case analysis and safety analysis showed critical places and situations in the system that could potentially be a source of failure in the future. In addition, laboratory simulations were carried out to verify the actual relationship between the change in resistance and the lifetime of the resistor. Based on the analysis of the data obtained from the test, it was found that an increase in resistance for more than 96% of elements is present.

Subsequent statistical calculations gave the possibility to state that there is a correlation between the change in resistance and lifetime, but it is so small (less than 1% change in the value of resistance) that it can be assumed for simplicity, without losing the correctness of the calculation, that there is no change in value of resistance. Thanks received results helps one can tell that lifetime of the system can be extender.

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