Application of Stress Redundancy and its Influence upon the Reliability of Electronic Elements and Systems

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Abstract – **In this article is discussed the application of stress redundancy to achieve more reliable electronic systems. Here are researched some variations of the failure rate of several typical electronic elements in different stress conditions and ambient temperature. Diagrams of received dependencies are shown. In the paper is analyzed this form of redundancy that causes improving of reliability parameters.**

Keywords – **reliability, failure rate, stress redundancy**

I. Introduction

The modern way of life is unthinkable without the use of various in type and complexity electronic devices. Their quantity and variety is growing sharply, and their areas of application cover the whole spectrum of human activities. People in ever greater extent rely on electronic systems in ensuring the safety of complex and hazardous industrial processes.

An essential tool to enhance the reliability of electronic components and devices is introduction of so-called "redundancy". According to Gindev [1] redundancy is a measure of exceeding of a value or quantity. Hristov [2] defines redundancy as a generalised notion that covers capable to work devices, more than the necessary to fulfill the functional requirements according to the specifications of the system.

Gindev [1] formulates five types of redundancy: time redundancy, stress redundancy, structure redundancy, function redundancy and information redundancy. Structure and function redundancy is most commonly used as non-operating reserve, while the others are mostly used as an operating reserve.

The stress redundancy is applied mostly to the elements so they are not fully loaded when operate - by mechanical efforts, working power, flowing current, reverse voltage, etc. [2].

The presence of this type of redundancy carries out benefits in terms of reliability in two ways: first, slows up the development of aging processes and postpones entering in the period of parametric failures; and second, allows the elements to withstand higher transitory load, and thus reducing the probability of sudden failures during normal operation. The implementation of stress redundancy can be performed without complication of the scheme solutions or adding additional elements and blocks. Thus it becomes possible to increase reliability without increasing the price of the products.

Stress redundancy causes a better reliability of components and devices. Its application improves a probability of flawless work, a Mean Time To Failure (MTTF) and a failure rate. However, it is not appropriate to talk about fault tolerance – its improvement is achieved by applying other types of redundancy.

This article examines variations of reliability of electronic components and circuits when applying stress redundancy. These results are represented graphically.

II. Theory

To examine the reliability of electronic devices first have to determine their structure in terms of reliability. There are described different types of structural schemes in the literature [1], [2], [3]. We will focus on the two main structures. If the failure of any component causes the failure of the entire system, it has a serial structure on reliability [3] – Fig. 1.

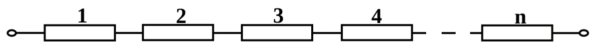

Fig. 1. System of *n* independent elements, connected in series

In contrast, the system which has parallel structure continues to function until fails and its last component [3], [4] – Fig. 2.

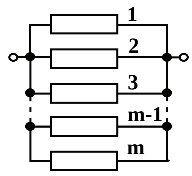

Fig. 2. System of m components, connected in parallel

Systems with serial structure in terms of reliability are the most widespread in practice [5]. To improve their reliability it is used stress redundancy. Therefore, an object of our further research and analysis is the stress redundancy in elements of electronic devices with serial structure.

The mathematical model that describes the reliability of the system with connected in series elements is based on Bernoulli's theorem [3]. According to this theorem, if failures are independent and the flow of failures is fixed in time, ordinary and without subsequent effects (this applies to the majority of electronic devices), the probability of flawless operation $P(t)$ of the system is evaluated by the product of probabilities of flawless operation $P_i(t)$ of its components [3]

$$P(t) = P_1(t) \cdot P_2(t) \cdot P_3(t) \cdot ... \cdot P_n(t) = \prod_{i=1}^{n} P_i(t) . \qquad (1)$$

The life of an electronic component can be divided into three periods during which the intensity of failures is changed in a different manner [1]. These are period of early failures, period of normal operation and aging period. During the first and third periods the failure rate alters significantly and acquires high values. During normal operation, the failure rate remains constant and acquires its smallest values determined only by the occurrence of sudden failures.

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The probability of flawless work of electronic components in cases of sudden failures is described by an exponential law

$$P(t) = \exp\left(\int_{t=0}^{\infty} \lambda(t)dt \right) , \quad (2)$$

where the parameter $\lambda(t)$ represents the failure rate of electronic components. The failure rate is the number of failures per hour.

When the failure rate is constant $\lambda(t)=\lambda$, the expression (2) acquires the type

$$P(t) = \exp(-\lambda \cdot t) \quad (3)$$

and the MTTF is

$$MTTF = \frac{1}{\lambda} . \quad (4)$$

The MTTF represents the average time of operation before failure.

Replacing (3) in (1) gives a new expression for the probability of flawless work of the system

$$P_{SYS}(t) = \exp(-(\lambda_1 + \lambda_2 + \lambda_3 + ... + \lambda_n) \cdot t) = \exp(-\lambda_{SYS} \cdot t) \quad (5)$$

and then the Mean Time Between Failures (MTBF) of the system is

$$MTBF = \frac{1}{\lambda_{SYS}} , \quad (6)$$

where λ_{SYS} is the sum of the failure rates of the system components

$$\lambda_{SYS} = \sum_{i=1}^{n} \lambda_i . \quad (7)$$

In other words, if we determine the failure rate of components in the system we can find the failure rate of the entire system. Then we can make an assessment of the other reliable indexes of the system - probability of flawless work and MTBF.

The purpose of reliability prediction is to be estimated reliability indexes of the elements and devices in order to identify existing weaknesses and to perform adequate actions to achieve the desired level of reliability.

Based on the exponential distribution law in “Military Handbook MIL-HDBK-217F” [6] has proposed the method “Part Stress Analysis” for predicting reliability of electronic components and systems. It takes into account the impact of various influences on the failure rate of electronic components to estimate the part failure rate

$$\lambda_p = \lambda_b \cdot \prod_{i=1}^{n} \pi_i , \quad (8)$$

where λ_p is the part failure rate; λ_b is base failure rate usually expressed by a model relating the influence of electrical and temperature stresses on the part; π_i is the factor of impact of the *i*-th influence.

They are taken into account all important influences of each element. For example, for capacitors they are operating temperature, the value of capacity, the voltage stress, its quality and environment, and for resistors they are working temperature, dissipation rate parameter, the power stress, its quality and environment.

We will consider an element with base failure rate λ_b and m numbers influencing factors. By X_i we denote the vector of values of the *i*-th influence, and with Π_i - vector of values of the factor of *i*-th influence. $\varphi_i (x_i)$ is the function describing the impact of the *i*-th influence. We can write

$$X_i = \{x_{i1}, x_{i1},..., x_{in(i)}\}, \quad i = \overline{1, m} \quad (9)$$

$$\Pi_i = \{\pi_{i1}, \pi_{i2},..., \pi_{in(i)}\}, \quad i = \overline{1, m} \quad (10)$$

$$\pi_{ij} = \varphi_i(x_{ij}) , \quad i = \overline{1, m} , \quad j = \overline{1, n(i)} \quad (11)$$

where $n(i)$ is броя на стойностите на *i*-th influence; m is a number of influences.

It must be noted that the values x_{ij} of the influence X_i may be of numeric or linguistic type, while their factors of impact π_{ij} accept only numeric type.

Let the first two of influences are modified in their entire range, and the others accept their first values. Then we can write a matrix $\Lambda_1^{(1,2)}$ of the values of the failure rate with dimension $n^{(1)}$ X $n^{(2)}$ as follows

$$\Lambda_1^{(12)} = \left\| (\lambda_b \cdot \pi_{31} \cdot \pi_{41} \cdot ... \cdot \pi_{m1}) \cdot \Pi_1^{'} \times \Pi_2 \right\| . \quad (12)$$

Performing consecutively multiplying all values of the coefficients of influence, we get p numbers two-dimensional matrices describing the values of the failure rate in m-dimensional area defined by the factors of influences, where

$$p = \prod_{i=3}^{m} n(i) . \quad (13)$$

These results can be used to determine the limits of variation of influences for a given maximum failure rate

$$\lambda(x_{1j(1)}, x_{2j(2)}, x_{3j(3)},..., x_{mj(m)}) < \lambda_t , \quad (14)$$

where $\lambda(x_{1j(1)}, x_{2j(2)}, x_{3j(3)},..., x_{mj(m)})$ - failure rate in certain combinations of values of the influences X_1, X_2, X_3, …, X_m.

Examining the information received, we can choose the most optimal option for which we have an acceptable value of the failure rate and optimal parameters for practical implementation of the influential factors.

III. Experimental Results

Usually some of the influences are predetermined and can be adopted with specific values. Then the failure rate is considered when changing just one or two impacts.

We apply the proposed by MIL-HDBK-217F [6] methodology in the study of the impact of stress redundancy on the failure rate of several capacitors as shown in Table I.

The resulting failure rate is shown in failures per hour if not mentioned specially. The MTTF and MTBF are expressed in hours or years.

In practice there is previously known the quality of the elements, the environment in which they work, and the values of their capacity. This allows us to fix the value of the coefficients of these factors as listed in Table I.

TABLE I
EXAMINED ELEMENTS

	Type and capacity	λ_B, failures in million hours	π_Q	π_E	π_C	***k***, variant of Π_t	***l***, variant of Π_V
λ_{Al}	**Electrolytic Al_2O_3, 220 µF**	0.00012	3	10	3.46	2	1
λ_C	**Ceramic, 100 nF**	0.00099	3	10	0.81	2	3
λ_T	**Electrolytic Tantalum, 10 µF**	0.00040	3	10	1.7	1	4
λ_{CC}	**Ceramic multilayer, Chip, 100 nF**	0.0020	3	10	0.81	2	3
λ_{TC}	**Electrolytic Tantalum, Chip, 4.7 µF**	0.00005	3	10	1.43	1	4

The level of stress in capacitors is determined by the ratio between the maximum values of the applied operating voltage to the electrodes and the nominal voltage of capacitors. Range of variation of the stress is from 0.1 to 1.0 and the reporting values are set with the vector $X_V=\{x_{V1},x_{V2},\ldots,x_{Vi},\ldots x_{Vn}\}$ and

$$x_{Vi}=0.1+(i-1)\cdot\frac{1-0.1}{n-1},\ \ i=\overline{1,n} \qquad (15)$$

where n - number of reported values of the stress.

The influence of the working temperature on the reliability parameters is investigated in the range -20°C ÷ 150°C divided into equal intervals. We set the values of the temperature with vector $X_t=\{x_{t1},x_{t2},\ldots,x_{tj}\ldots,x_{tn}\}$ and

$$x_{tj}=20+(j-1)\cdot\frac{150-20}{m-1},\ \ i=\overline{1,m} \qquad (16)$$

where m - number of reported values of the temperature.

For further analysis we assume $n = 10$ and $m = 15$.

The factor of impact of temperature denotes with vector $\Pi_t^{(k)}=\{\pi_{t1}^{(k)},\pi_{t2}^{(k)},\ldots,\pi_{tj}^{(k)},\ldots,\pi_{tm}^{(k)}\}$, where k is the version of the factor depending on the capacitor's type [6]

$$\pi_{tj}^{(k)}=\exp\left[\frac{-E_a^{(k)}}{C}\cdot\left(\frac{1}{x_{tj}+273}-\frac{1}{298}\right)\right],\ \ j=\overline{1,m},\ \ k=1,2 \qquad (17)$$

where: $E_a^{(k)}=\{0.15;0.35\}$ and $C=8.617\cdot10^{-5}$.

The factor of impact of voltage stress denotes with vector $\Pi_V^{(l)}=\{\pi_{V1}^{(l)},\pi_{V2}^{(l)},\ldots,\pi_{Vj}^{(l)},\ldots,\pi_{Vm}^{(l)}\}$, and l is the version of the factor depending on the capacitor's type [6]

$$\pi_{Vi}^{(l)}=\left\{\left(\frac{x_{Vi}}{0.6}\right)^{R_l}+1\right\},\ \ i=\overline{1,n},\ \ l=\overline{1,4},\ \ R_l=\{5;10;3;17\} \qquad (18)$$

$$\pi_{Vi}^{(l)}=\left\{\left(\frac{x_{Vi}}{0.5}\right)^{3}+1\right\},\ \ j=\overline{1,m},\ \ l=5\ . \qquad (19)$$

On Fig. 3 are shown the two variants of temperature factors. There is clearly seen that capacitors, for which is valid variant 2 are much more sensitive to increased operating temperature.

Fig. 4 presents the options of modifying the stress factor. There is a big difference between minimum and maximum values - from 0.1 to 6000. We apply logarithmic scale to get better informative graphic displaying. It clearly differentiates the limit value of the voltage stress by 0.6, to which the impact of stress on reliability is relatively low and approximately the same for all types of capacitors. Above 0.6 there are significant differences in values of the various stress factors. For example, under stress $x^{(V)} = 1$ we calculate values $\pi^{(V)3}=5.6$ for ceramic capacitors and $\pi^{(V)4}$=5900 for tantalum capacitors.

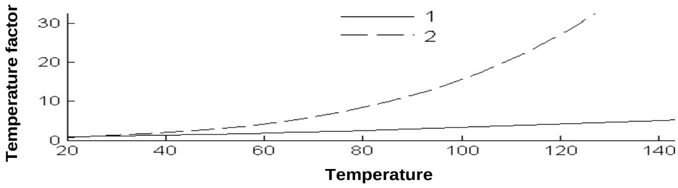

Fig. 3. Variants of temperature factor

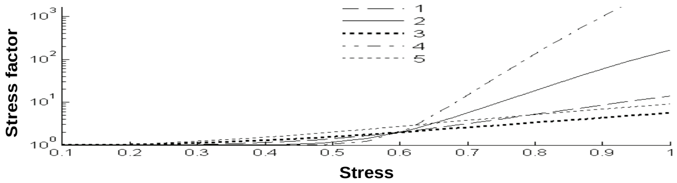

Fig. 4. View of the fifth variants of stress factor

Let us consider in detail the results for the electrolytic capacitor with aluminum oxide.

We calculate the matrix of the failure rate as a function of temperature and voltage stress factors

$$\Lambda_{Al}=\left\|(\lambda_b^{Al}\cdot\pi_Q^{Al}\cdot\pi_E^{Al}\cdot\pi_C^{Al})\cdot\left(\Pi_t^{(2)}\right)'\cdot\Pi_V^{(1)}\right\|. \qquad (20)$$

If we use resulting data we can show the failure rate in various combinations of stress and operating temperature - Fig. 5.

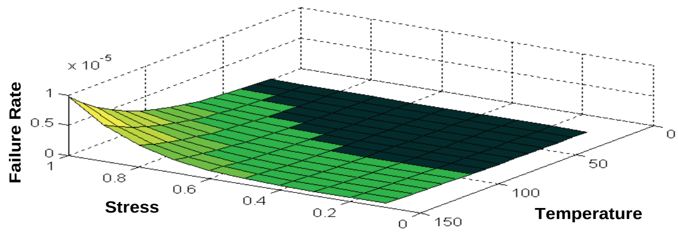

Fig. 5. Failure rate vs. stress and temperature

We can see the range of values of temperature and stress in which the failure rate changes in small range, followed by a significant and steep rise. Special attention should be paid at the level of stress when we expect high operating temperatures - over 60°C.

It is easy to identify eligible areas of change in operating temperature and stress on the placed requirements for the failure rate - Fig. 6.

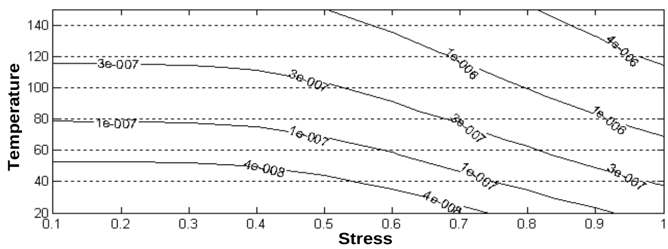

Fig. 6. Nomogram of failure rates

It is seen that when the working temperature is 60°C for example, the change of stress from 0.8 to 0.5 leads to three times decreasing of the failure rate.

By the same way we obtain data on other types of capacitors from Table I. On Fig. 7 there is shown the failure rate of examined elements as a function of voltage stress at operating temperature 50°C.

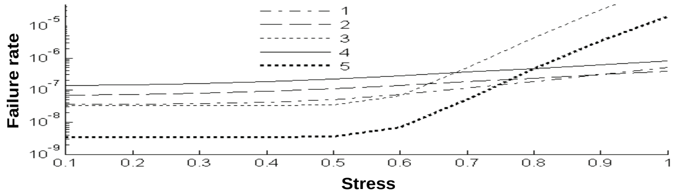

Fig. 7. An influence of stress levels on failure rate of capacitors
1 - Aluminum electrolytic capacitor; 2 - Ceramic multilayer capacitor; 3 - Tantalum electrolytic capacitor; 4 - Ceramic chip capacitor; 5 - Tantalum electrolytic chip capacitor

For example, let us have a system with 25 capacitors in it, equally distributed among the types counted in Table 2. Assumed operating temperature is 50°C. We calculate the failure rate of the system using Eq. (7)

$$\lambda_{SYS} = \lambda_R + 5\cdot\lambda_{Al} + 5\cdot\lambda_C + 5\cdot\lambda_T + 5\cdot\lambda_{CC} + 5\cdot\lambda_{TC}\,, \qquad (21)$$

where λ_R is the aggregated failure rate of the other elements of the system. Assuming $\lambda_R=10.10^{-6}$ failures in hour. The results are shown in Fig. 8.

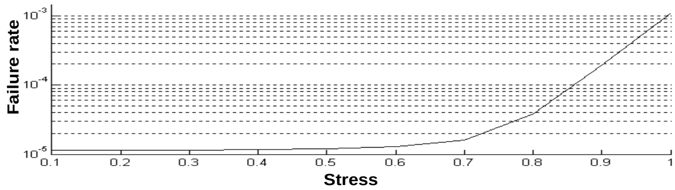

Fig. 8. An influence of different stress levels on the system failure rate

If we use Eq. 4 we could calculate MTBF depending on voltage stress. The results are shown in Fig. 9.

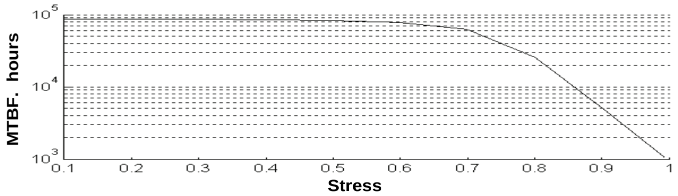

Fig. 9. An influence of stress levels on the system MTBF

Using Equation 5 we calculate the probability of flawless work of the device from the beginning of its operation up to a year - 8760 hours. The results are shown in Fig. 10.

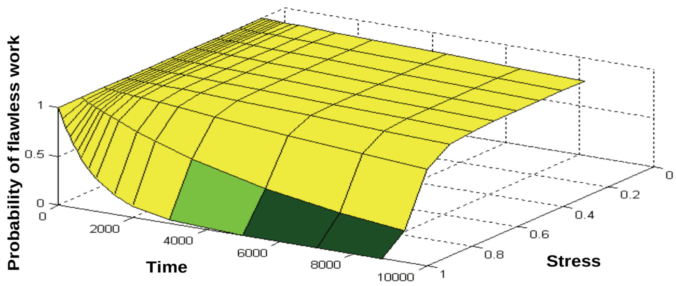

Fig. 10. Variation of system probability of flawless work

Table II shows several values of the probability of flawless work $P_{SYS}(t)$ at the end of the first year of operation under different stress conditions.

There is a relatively smooth reduction in the probability of flawless work in time when the stress is up to 0.7 and a sharp drop for higher values.

TABLE II
VALUES OF $P_{SYS}(t)$ AT THE END OF THE FIRST YEAR

STRESS	0.6	0.7	0.8	0.9
$P_{SYS}(t)$	0.89	0.87	0.71	0.18

In Table III we express the values of the MTBF according to several stress levels.

TABLE III
VALUES OF *MTBF* ACCORDING TO STRESS

STRESS	0.6	0.7	0.8	0.9
MTBF, years	8.89	7.15	2.95	0.59

It is clearly seen that when the voltage stress on the capacitors is low – 0.6 or less, we may expect the first failure of the device after nearly 9 years. Otherwise, if the voltage stress is 0.9 the expected time for the first failure is just 7 months.

IV. CONCLUSION

In this paper the application of stress redundancy to achieve more reliable electronic elements and systems is considered. Research is done and results are shown in improving reliability of electronic elements and systems by implementing a stress redundancy.

Stress redundancy leads to a better reliability of components and devices. Its implementation increases the probability of flawless work, the MTBF and reduces the failure rate. It is important to be applied in case where a relatively high working teperature is expected.

The proposed approach is applicable to different electronic components and devices and allows quick view of the possibility of improving the reliability by increasing the stress redundancy.

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