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MODEL OF VOLTAGE CONVERTER WITH REDUNDANCY OF POWER CHANNELS FOR CALCULATION OF ITS OPERATING TIME IN STATISTICAL MODELING

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Abstract – The problems of forming the operating time to failure of multi-channel voltage converter for statistical modeling are considered. A formal model of the converter with “N out of M active redundancy” is proposed, which allows for the calculation of the converter's operating time taking into account changes in the electrical load of the channels in case of failures. The developed model is created within the limits of assumptions and the restrictions accepted in operating standard documents. The possibility of reducing the computational costs when applying this model in statistical modeling is shown.

Keywords: voltage converter, power channel, dependability, redundancy, operating time, statistical modeling.

INTRODUCTION

When designing power electronic equipment, one of the tasks is to ensure the required level of dependability. Along with various methods, designing power electronics equipment, one of the most frequently used methods in practice to ensure of reliability level is redundancy. Thus, in [1] it is shown that in order to achieve high values of reliability indicators, multi-channel voltage converters must be made on the basis of a backbone-modular architecture. This architecture allows for the implementation of sliding "N out of M active redundancy" for power channels.

At the early stages of designing multi-channel voltage converters, calculation methods and software are used to evaluate their reliability indicators [2. 3]. It is obvious that the more accurate the estimate of these indicators is, the more likely it is that the created converter will meet the requirements. However, in practice, the calculation is limited to obtaining "lower" estimates of reliability indicators, which is due to limitations inherent in analytical methods [4].

At the same time, the method of statistical modeling is a universal method for calculating the reliability of electronic equipment [5]. This method is used mainly for calculating indicators of the "operating time" type (numerical integration method). For the practical implementation of this method, software tools for simulation have been created that have universal languages for describing the formal model. This makes it much easier to create a software model, since it is generated automatically [6-8]. However, these languages have a number of limitations, for example, in terms of the ability to describe changes in the parameters of the reliability block diagram (RBD) when component parts fail, and this applies not only to universal, but also specialized languages [9].

Therefore, when simulating operating time, even with "typical" redundancy methods (in this case, with "N out of M"), but having specific features, the software model must be created "manually" based on the formal model.

PROBLEM STATEMENT

Backbone-modular architecture of the power part (PP) of a multi-channel voltage converter with "N out of M" redundancy present in [1] and is shown in fig. 1.

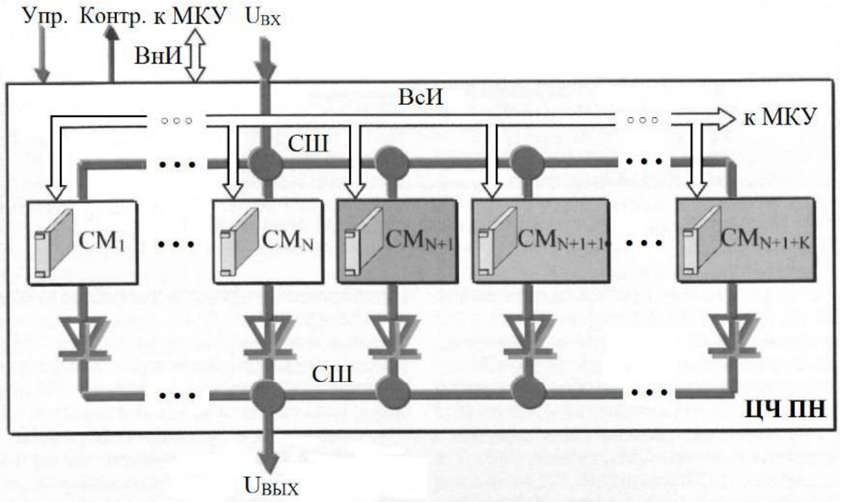

Fig. 1 Power part of the voltage converter with "N out of M active redundancy"

As seen in fig. 1 the power part of the voltage converter (PP VC) contains of N main power modules (PM_1-PM_N) and redundancy modules (PM_{N+1}, PM_{N+1+1},..., PM_{N+1+K}) that are in the operation mode. The reliability block diagram (RBD) for this redundancy method of power modules (channels) is shown in fig. 2.

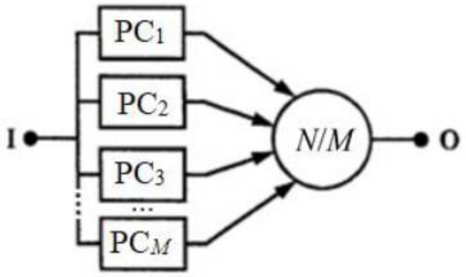

Fig. 2 Reliability block diagram of power part of a multi-channel voltage converter

Reliability function of such a group is determined by the formula from standard [10]:

$$P(t) = \sum_{i=0}^{M-N}\left[C_M^i \cdot \left(e^{-\Lambda \cdot t_{бр}}\right)^{M-i} \cdot \left(1-e^{-\Lambda \cdot t_{бр}}\right)^i\right], \quad (1)$$

where C_M^i is number of combinations; Λ is the failure rate of the element; t is time; N is number of elements; M is the total number of elements.

As can be seen from (1) in the method for calculating the RBD of the group “N out of M active redundancy”, given in the standard [10], the dependability characteristics (Λ) for each element of the RBD are assumed to be constant (do not depend on the number of failed elements). However, this condition is not met for the voltage converter in question.

SOLUTION OF THE PROBLEM

This is due to the fact that the power channel (P_{PC}) depends on the number of operable channels (m) that work on the load [1]:

$$P_{PC}(m) = \frac{P_{VC}}{m}, \quad (2)$$

where P_{VC} is the rated power of the converter.

It follows from (2) that the electrical stress factor of the channel (K_L) also depends on m:

$$K_L(m) = \frac{P_{PC}(m)}{P_{PC_{nom}}}, \quad (3)$$

where P_{PCnom} is the nominal capacity of the channel.

Note that for m = N, the value of $P_{PC}(m)$ will be equal to P_{PCnom}.

Since the channels are electronic modules of the first level (EM1), the values of their failure rate (Λ_{PC}) are calculated using the method given in the standard [10]:

$$\Lambda_{PC} = \overset{I}{\underset{i=1}{}} \lambda_{O_i}, \quad (4)$$

where λ_{Oi} is the operational failure rate of the i-th element of the channel; I is the total number of elements in the channel.

In turn, the value of λ_{Oi} is calculated using the models given in the handbook [11]:

$$\lambda_O = \lambda_b \cdot \prod_{j=1}^{J} K_j, \quad (5)$$

where λ_b is base failure rate of the element; K_j are factors; J is the total number of factors.

One of the factors that are included in the model (5) is the operating mode factor (K_{OM}). K_{OM} электрической нагрузки и температуры на величину λ_O [11]. Factor K_{OM} takes into account the influence of electrical and temperature stresses on the value of λ_O [11]. For example, for silicon semiconductor devices (except mixing and microwave detector diodes), the mathematical model of the K_{OM} has the form:

$$\mathrm{K}_{\mathrm{OM}} \quad A \cdot e^{\left[\frac{N_T}{273+t+175-t_{\mathrm{Jmax}}+\Delta t\cdot \mathrm{K}_{\mathrm{ES}}\cdot\left(\frac{t_{\mathrm{Jmax}}-t_{\mathrm{dec}}}{150}\right)}\right]+\left[\frac{273+t+175-t_{\mathrm{Jmax}}+\Delta t\cdot \mathrm{K}_{\mathrm{ES}}\cdot\left(\frac{t_{\mathrm{Jmax}}-t_{\mathrm{dec}}}{150}\right)}{T_M}\right]^L}, \tag{6}$$

where a A, N_T, T_M, L, Δt are model’s constant; t is ambient temperature (package); K_{ES} is the ratio of the working electrical stress to the maximum allowed temperature t_{dec}; t_{dec} is the maximum ambient temperature for which at 100% electrical stress junction temperature does not exceed maximum allowable t_{Jmax}.

For transistors and transistor assemblies, the K_{ES} value is defined as:

$$\mathrm{K}_{\mathrm{ES}} = \frac{P_{\mathrm{OM}}}{P_{\max}}, \tag{7}$$

where P_{OM} is scattering power in operating mode; $P_{\max}$ is the maximum allowable power of scattering at a temperature equal to t_{dec}.

The graph of the K_{OM} dependence on the K_{ES} is shown in fig. 3.

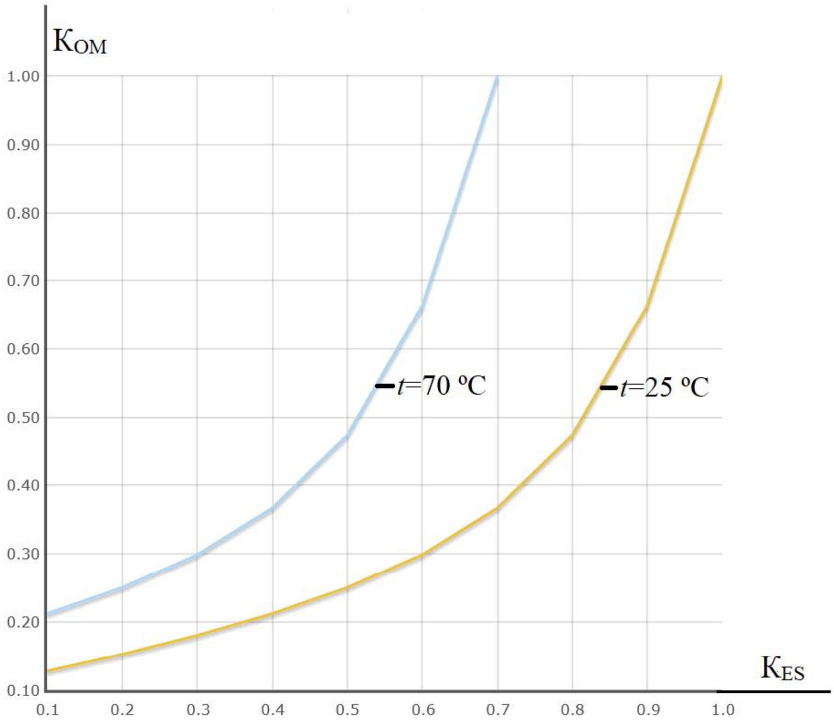

Fig. 3 Dependence operating mode factor on electrical stress factor

As seen in Fig. 3 the decrease in $_{\mathrm{ES}}$ leads to a significant decrease in the K_{OM}, and, consequently, to a decrease in the λ_{O}.

Since the Λ_{PC} is calculated for the nominal stress of the channel ($\mathrm{K}_{\mathrm{L}} = 1$), when using this value (Λ_{CKnom}) in the reliability prediction of the PP VC according to the method of the standard [10], only their lower estimate (“worst case”) can be obtained, and the calculation error will grow with the increase in the number of redundancy channels.

This is due to the fact that if the K_{ES} values of the control circuit elements are weakly dependent on the channel K_{L} value, the K_{ES} of the power circuit elements is already largely determined by the K_{L} value, and these elements significantly affect the final value of Λ_{PC}.

In contrast to analytical methods, the statistical modeling method allows you to take into account changes in the dependability characteristics of the converter channels in case of failures.

For an exponential failure model, the value of the operating time realization ($\hat{t}$) is calculated using the formula:

$$\hat{t} = -\frac{\ln(x)}{\Lambda_{\text{PC}}}, \tag{8}$$

where x is realization of the basic random variable (BRV).

As shown above, the P_{PC} value depends on m and can be calculated for m = (N+1), ..., (M+N):

$$P_{\text{PC}_m} = \frac{N}{m} \cdot P_{\text{PC}_{\text{nom}}}. \tag{9}$$

Then, for these $P_{\text{PC}m}$ values, it is necessary to determine the electrical (and, if necessary, thermal) modes of operation of the channel elements, i.e. find the values of K_{ES} and t_m for all elements. Then, using the formulas (4) and (5), can be calculated the channel failure rates when fails 0, 1, 2, ..., (M-N) channels in the converter and then can be forms an array $\Lambda_{\text{PC}0}$, $\Lambda_{\text{PC}1}$, $\Lambda_{\text{PC}2}$, …, $\Lambda_{\text{PC}(M\text{-}N)}$.

This array is used for calculating the realization of channel's operating time, namely:

- according to the formula (8), the realizations of channel's operating time ($\hat{t}_{\text{PC}_m}$) are calculated for failures and an array is formed (values of $\hat{t}_{\text{PC}_{M-N+1}} = \hat{t}_{\text{PC}_{M-N+2}} = \ldots = \hat{t}_{\text{PC}_M}$, because they are calculated for $\Lambda_{\text{PC}} = \Lambda_{\text{PCnom}}$);
- according to the formula (8) for the same values, the realizations of channel's operating time ($\hat{t}_{\text{NOM}_l}$) are calculated and an array ($\hat{t}_{\text{NOM}_1}, \hat{t}_{\text{NOM}_2}, \ldots, \hat{t}_{\text{NOM}_M}$) is formed;
- array elements $\hat{t}_{\text{NOM}_1}, \hat{t}_{\text{NOM}_2}, \ldots, \hat{t}_{\text{NOM}_M}$ are ordered in ascending order;
- calculated the realizations of converter's operating time ($\hat{t}_{\text{PC}_{l,(M-m)}}$) to failure of the 1-st, 2-nd, ..., M-th channels:

$$\hat{t}_{\text{PC}_{l,(M-m)}} = \sum_{s=0}^{M-m} \frac{\left(\hat{t}_{\text{NOM}_{l,(s+1)}} - \hat{t}_{\text{NOM}_{l,s}}\right) \cdot \hat{t}_{\text{PC}_s}}{\hat{t}_{\text{NOM}_{l,(s+1)}}}, \text{ при } \hat{t}_{\text{NOM}_{l,0}} = 0, \tag{10}$$

where the first index (l) is the number of channels in the converter, and the second (s) is the number of their operating times in ascending order.

After the calculation $\hat{t}_{\text{PC}_{l,(M-m)}}$ is determined by realization of operating time of PP VC ($\hat{t}_{\text{VC}}$) to failure, which is the realization of operating time (M-N+1)-th channel:

$$\hat{t}_{\text{VC}} = \hat{t}_{\text{PC}_{l,(M-N+1)}}. \tag{11}$$

Since the statistical modeling method requires multiple calculations $\hat{t}_{\text{VC}}$, in this case, the amount of computational costs can be reduced.

Indeed, it follows from (8) that:

$$\frac{\hat{t}_m}{\hat{t}_{\text{NOM}}} = \frac{\Lambda_{\text{PC}_{\text{NOM}}}}{\Lambda_{\text{PC}_m}} \Rightarrow \hat{t}_m = \frac{\Lambda_{\text{PC}_{\text{NOM}}}}{\Lambda_{\text{PC}_m}} \cdot \hat{t}_{\text{nom}} \Rightarrow K_m = \frac{\Lambda_{\text{PC}_{\text{NOM}}}}{\Lambda_{\text{PC}_m}}, \tag{12}$$

where $\hat{t}_{\text{NOM}}$ is realization of the channel's operating time at $\Lambda_{\text{PC}} = \Lambda_{\text{PC}_{\text{NOM}}}$; $\hat{t}_m$ is realization of the channel's operating time at $\Lambda_{\text{PC}} = \Lambda_{\text{PC}_m}$.

Then, using (12), you can pre-generate an array K_0, K_1, K_2, …, $K_{(M\text{-}N)}$, which will be used for calculating realizations of the converter's operating time, namely:

- using the formula (8), the realizations of the converter's operating time ($\hat{t}_{\text{ном}_l}$) are calculated and an array $\hat{t}_{\text{NOM}_1}, \hat{t}_{\text{NOM}_2}, ..., \hat{t}_{\text{NOM}_M}$ is formed;

- array elements $\hat{t}_{\text{NOM}_1}, \hat{t}_{\text{NOM}_2}, ..., \hat{t}_{\text{NOM}_M}$ are ordered in ascending order;

- calculated the realizations of channel's operating time:

- realization of channel's operating time that failed first:

$$\hat{t}_{\text{PC}_{m=M}} = \hat{t}_{\text{NOM}_{l,1}} \cdot \text{K}_0\,, \tag{13}$$

- realization of channel's operating time that failed second:

$$\hat{t}_{\text{PC}_{m=(M-1)}} = \hat{t}_{\text{PC}_{m=M}} + \left(\hat{t}_{\text{NOM}_{l,2}} - \hat{t}_{\text{NOM}_{l,1}}\right) \cdot \text{K}_1\,, \tag{14}$$

- realization of channel's operating time that failed (M-N) (the last of the redundancy channels):

$$\hat{t}_{\text{PC}_{m=(M-N)}} = \hat{t}_{\text{PC}_{m=M}} + \sum_{s=1}^{M-N} \left[\left(\hat{t}_{\text{NOM}_{l,(s+1)}} - \hat{t}_{\text{NOM}_{l,s}}\right) \cdot \text{K}_s\right], \tag{15}$$

- realization of channel's operating time that failed (M-N+1) (the first of the main ones):

$$\hat{t}_{\text{PC}_{m=(M-N+1)}} = \hat{t}_{\text{PC}_{m=(M-N)}} + \left(\hat{t}_{\text{NOM}_{l,(M-N+1)}} - \hat{t}_{\text{NOM}_{l,(M-N)}}\right), \tag{16}$$

- realization of channel's operating time that failed M (last):

$$\hat{t}_{\text{PC}_{m=M}} = \hat{t}_{\text{PCK}_{m=(M-N)}} + \sum_{s=M-N}^{M-1} \left(\hat{t}_{\text{NOM}_{l,(s+1)}} - \hat{t}_{\text{NOM}_{l,s}}\right), \tag{17}$$

Since the criterion for failure of the group "N out of M active redundancy" is the failure of its (M-N+1) elements, the realization of the converter's operating time before failure (M-N+2), (M-N+3), ..., M channels can be not calculated. The value of $\hat{t}_{\text{VC}}$ will be equal to the realization of the operating time of the channel that failed (M-N+1).

Then, taking into account (13)-(16), the formal model of the PP VC with "N out of M active redundancy" of power channels can be presented in the following form:

$$\hat{t}_{\text{VC}} = \hat{t}_{\text{NOM}_{l,1}} \cdot \text{K}_0 + \sum_{s=1}^{M-N} \left[\left(\hat{t}_{\text{NOM}_{l,(s+1)}} - \hat{t}_{\text{NOM}_{l,s}}\right) \cdot \text{K}_s\right] + \left(\hat{t}_{\text{NOM}_{l,(M-N+1)}} - \hat{t}_{\text{NOM}_{l,(M-N)}}\right), \tag{18}$$

where the values of the model parameters are determined by formulas (12), (8), (4) and (5).

To create a software model (program module), you can use the algorithm calculation $\hat{t}_{\text{ПН}}$ shown in fig. 4.

Block 1 (see fig. 4) runs the module on a command from the simulation program. In Block 2, enter the parameters of the formal model - N, M, Λ_{PCnom} and the array Λ_{PCK0}, Λ_{PC1}, Λ_{CK2}, …, $\Lambda_{\text{PC}(M\text{-}N)}$. In Blocks 3-5, elements of the array K_0, K_1, K_2, …, $\text{K}_{(M\text{-}N)}$ are calculated using the formula (12). In Blocks 6-9, elements of the array $\hat{t}_{\text{NOM}_1}, \hat{t}_{\text{NOM}_2}, ..., \hat{t}_{\text{NOM}_M}$ are calculated using the formula (8). In Block 10, elements of the array $\hat{t}_{\text{NOM}_1}, \hat{t}_{\text{NOM}_2}, ..., \hat{t}_{\text{NOM}_M}$ are ordered in ascending order. In Block 11, calculates on the formula (13) the realization of operating time of channel that failed first. In Blocks 12-14, the realization of operating time of channel that failed last from the number of redundancy channels is calculated using the formula (15). In Block 15, the formula (18) is used to calculate the realization of operating time of the PP VC. Block 16 outputs this value, and Block 17 terminates the module and passes control to the simulation program.

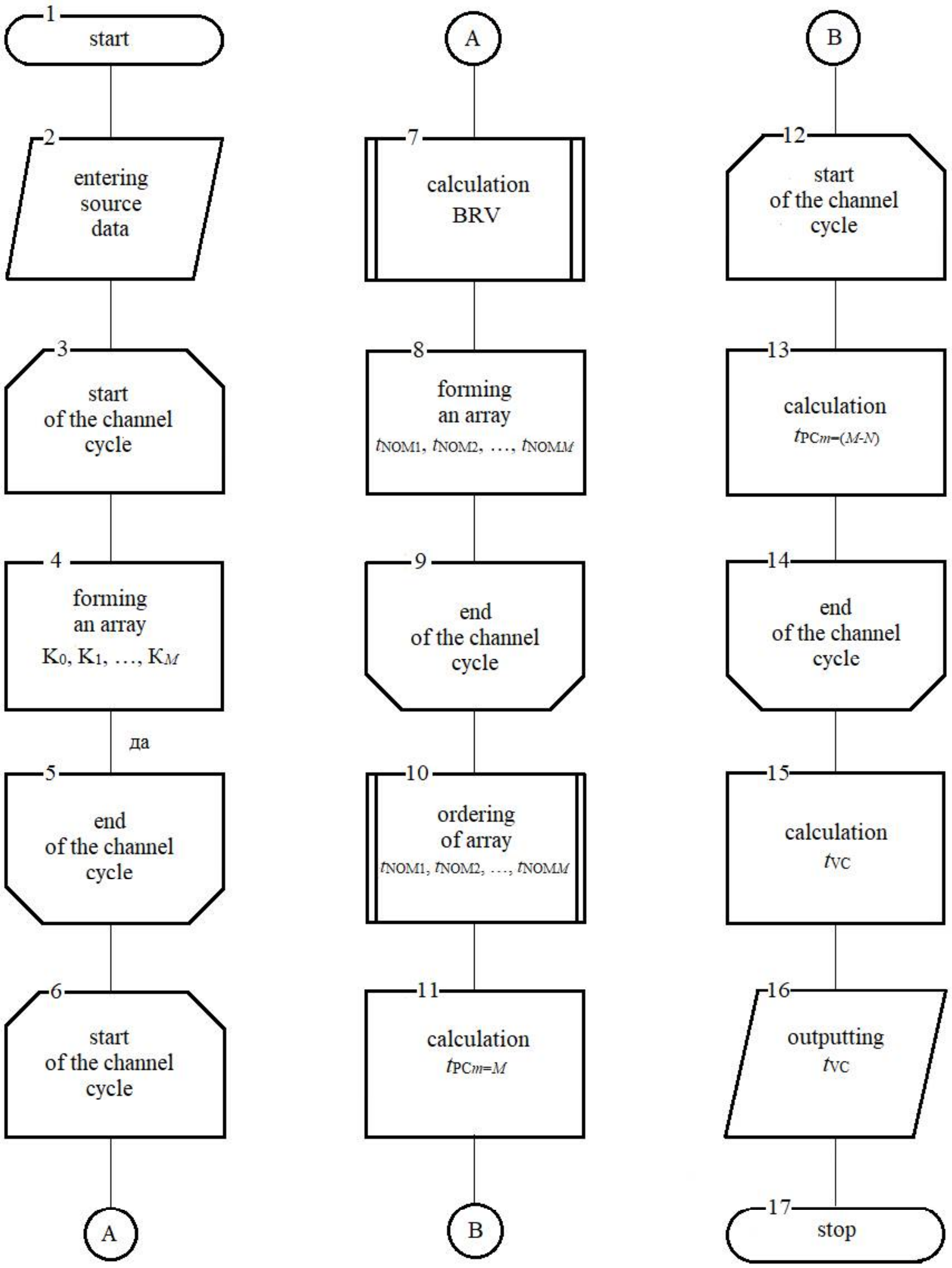

Fig. 4 Algorithm for calculating the operating time of the voltage converter

CONCLUSION

Thus, the model (18) makes it possible to the reliability prediction of multi-channel voltage converter (“N out of M active redundancy” method), taking into account changes in the reliability characteristics of their power channels in case of failures.

However, it should be noted that the effect of using this model can only be obtained if can be calculated Λ_{PC} for the power channels (i.e., there are initial data). In practice, such data is often not available, because often ready-made modules are used as PC, for which the reliability characteristics are given in the Data Sheet only for typical (nominal) modes.

In addition, the above model, like any other model, is valid within the limits of the above restrictions (exponential model of channel failures, accuracy of calculating their failure rates, etc.).

Therefore, the results of reliability prediction of multi-channel voltage converter obtained with this model help should be adjusted according to the results of tests and controlled operation.

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INFLUENCE OF NON-FLUCTUATION INTERFERENCE ON THE NOISE IMMUNITY OF INCOHERENT RECEIVING OF SIGNALS WITH DIFFERENTIAL PHASE-SHIFT KEYING

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Abstract— The paper studies the noise immunity of an autocorrelation demodulator of signals with differential phase-shift keying in the presence of Gaussian noise, Rayleigh fading, harmonic and retransmitted interference in the radio channel. Analytical formulas are obtained for the error probability at M=2 and 4 in two cases: with harmonic interference and Rayleigh fading and with harmonic interference without fading. The results of simulation are given, including in the presence of retransmitted interference, confirming the theoretical results.