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ROBUST DATA TRANSFER PARADIGM BASED ON VLC TECHNOLOGIES

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ABSTRACT

The article considers methods for improving the system quality of VLC systems design and operation. VLC technologies represent a system that consists of functions and software The main function of the VLC system is data transmission based on LED technologies. According to ISO / IEC 17025-2000, ISO 5725-2002-the main importance is given to metrological support. VLC systems are particularly critical to the stability of operating modes, they are demanding to control modes and operating conditions, to choose the technical parameters of the component base during design. Robustness can be considered an integral indicator of the overall quality of the VLC system. Taking this into account, as a robust paradigm, we study its functional part, in the scope of structural modeling, using the example of an optoelectronic channel for VLC information transmission, including some technical solutions, and the quality of control and measuring processes as a metrological component of robust system support. As a quantitative assessment of functional robustness, it is proposed to use control risks and the correlation function of the connection between “input” and “output”, which evaluates the quality of the data transmission channel. Mathematical and simulation models, as well as application software, were developed to assess and predict control risks. A method of qualitative integrated assessment of the robustness of the VLC system according to the Harrington and Chaddock criteria is proposed, which showed the values of: "Good" and "High".

Keywords: *System, LED, Photodiode, Robustness, VLC Technologies, Reliability, Errors, Metrology, Software, Simulation Models.*

1. INTRODUCTION

One of the most acute global problems of the modern world is terrorism, which is called one of the main threats to humanity. The problems of terrorism, ways to combat it are discussed at all levels, but to date, no effective ways have been found to resist this evil. The problem of ensuring the safety of closed facilities (“critical facilities”) with a large crowd of people, such as sports palaces, stadiums, etc., is especially urgent. Modern methods of destructive effects, implemented through wired and wireless channels, as well as through power networks, are currently a serious weapon against the protection systems of critical facilities, in particular, integrated security systems. These weapons are more effective than software destructive weapons for computer networks.

The development of methods for ensuring information security of critical facilities that are resistant to internal system interference and external deliberate electromagnetic influences becomes extremely necessary. Resistance to internal system interference and external intentional electromagnetic influences is commonly called robustness [1-3].

VLC (visible light communication) technology refers to wireless communication that uses the visible optical range (380 nm to 780 nm). As a data transmission source, light-emitting diodes (LEDs) are used, which simultaneously serve to illuminate the premises. One of the main advantages of this technology is its speed, which provides operation in the nanosecond time range, which allows using VLC technology for data transmission, both in analog and digital modes [4-6].

These indicators provide the advantages of this technology over Wi-Fi, both in data transfer rate and the protection of the information channel from passive interference and active external interference by constructively restricting access from potential attackers to the data transmission channel. In addition, the lack of communication over the radio channel allows you to protect yourself from industrial interference, which is saturated with the modern environment.

Improving information security and security of socio-economic objects opens great prospects, and the possibility of building integrated systems based on the constructive combination of visible and invisible infrared light, which has advantages over the visible part of the spectrum.

Following from the technical documentation and a review of literature sources, it is possible to achieve the highest quality infrared radiation from LEDs that operate in a pulsed mode only with "Strict control of voltage parameters. A deviation from the norm will lead to changes in the radiation power several times! For example, if on devices operating in continuous mode, 5 W/av is indicated, then when they switch to a pulsed mode - about 125 W/av. Therefore, for the stability of such systems, it is recommended to periodically pay increased attention to their maintenance [7].

This results in very high metrological, and even special, requirements for control and measurement equipment and service support at all stages of the VLC system lifecycle [8-10] Management at all stages of the system life cycle necessarily provides for a control process. The control contains three operations - measurement, comparison of the measured value with the standard and making a decision. Decision-making under conditions of uncertainty is usually accompanied by risks, which in the context of this study can also be attributed to the robustness indicators of the VLC system. An objective quantitative assessment and forecasting of risks, the experience of studying this problem, as it shows, is possible only with the involvement of formal approaches based on mathematical and simulation modeling, which makes the development of mathematical models for this purpose as paramount. Based on the foregoing, a conclusion follows about the relevance of this problem and the purpose of the research.

2. LITERATURE REVIEW

The aim of the research is to improve the systemic quality of the design and operation of VLC systems. In this context, the VLC system, like any other, is considered to be composed of functions and support. The main function of the VLC system is data transmission based on LED technology. In the environment of tools and mechanisms of system VLC support, according to the standards, the key importance is attached to metrological support [8, 11]. In the above standards and work [11, 12], it is noted that LED equipment, especially infrared, is extremely critical to the stability of operating modes and requires systematic monitoring of mode parameters under operating conditions, as well as the choice of technical and technological parameters of the component base during design. With that in mind, the paper proposes to study the functional part as a robust paradigm using the example of an optoelectronic channel for transmitting VLC information, including the technical implementation of the channel [13, 14].

As a quantitative estimate of the functional robustness of the channel, the transmission coefficient cannot be used, because the signals at the input and output of the channel have different physical nature. Therefore, the idea of using the correlation function is proposed [15]. The second component of a robust systemic assessment is proposed to consider the quality of control and measurement processes in the form of an integral indicator of control results - risks [16].

Since 2011, a new technology VLC (Visible Light Communication) has been rapidly developing, a technology that allows a light source not only to illuminate a room, but also to transmit information using the same light signal [17]. VLC technology uses visible light in the optical spectrum (about 400-800 THz). This technology can use fluorescent lamps for alarms at around 10 Kbps or LEDs for alarms at around 500 Mbps. The article mentions a prototype of a new generation of wireless data transmission network Li-Fi (Light Fidelity or Light-based Wi-Fi) based on an LED system used for room lighting [18-20]. Traditionally, wireless communication was understood as radio waves and Wi-Fi or cellular communication. But in 2011, it became possible to use light, not only for lighting, but also for transmitting information. This technology is called Li-Fi. A router was created that showed amazing capabilities [21]. Prof Haas noted that light wave technology is more reliable in terms of security than Wi-Fi. It is known that it is easy to hack a Wi-Fi network outside and intercept files as radio waves travel through walls outside the premises [22].

But this technology has certain limitations and disadvantages, such as: short data transmission distance, which at the moment is a maximum of 10 meters; the technology is not applicable outdoors and in open areas, because the generated light is scattered in the atmosphere and seriously reduces the signal reception area; reception of light waves can be carried out only within the line of sight, which is a big disadvantage compared to the radio frequency of Wi Fi technology. that is, Li-Fi can in theory only be used if you are in the same room as the transmitter and receiver, since light cannot pass through walls. Nevertheless, the developers have high hopes for VLC - for data transmission using visible light [23].

Most articles devoted to data transmission using visible light mainly give only a general diagram of the operation of VLC and Li-Fi technologies. One of the most difficult technical tasks in designing VLC and Li-Fi systems is dimming. Dimming is the process of controlling the intensity of lighting [24]. Adjusting the brightness for household purposes allows you to operate lighting devices in a gentle mode, which extends their service life, reduces energy consumption and heat generation. To transmit information, such as speech, there is a need to modulate the light flux. The most effective method of modulation is the method of applying pulse-modulated current to the led using pulse-width modulation (PWM). Physically, the method consists of the time spent by the led in the on and off States.

Designing robust systems is one of the urgent problems in the world practice of creating information-safe data transmission channels [25]. The term "robust" became popular in the 1970s, and initially it was understood as "the robustness of the results of statistical analysis of data", while measuring procedures were not considered. Subsequently, the scope of application of the concept of "robustness" has expanded significantly, and many works have appeared, for example, in control theory, as "robust control" [26]. As applied to statistical data processing systems, "robust statistical procedures must “withstand errors that in one way or another may fall into the initial data or distort the premises of the used probabilistic-statistical models". In the canonical sense, the main task in the design of a control system is to find a model for the synthesis of such a project, which would preserve the design conditions, indicators, and criteria of the system within acceptable limits, despite the presence of uncertainties in the design environment and be insensitive to small changes in the parameters of external and internal agents. Thus, the formulation of the robust design problem is associated with robust stability, that is, with the requirement that the system remains operational in the presence of uncertainties in its model implementation.

Unlike technical objects, in socio-economic systems the range of robustness criteria is very extensive and often depends on the researcher - his point of view.

In the design of complex multi-parameter systems, which include VLC systems, robustness can mean the quality or optimality of design risks [27-29]. In a broad sense, design robustness is a derivative of the uncertainty of design agents. The ultimate goal of designing VLC systems is to increase and maintain operational properties throughout its life cycle according to the criteria of total cost, information security and durability.

In the design of VLC systems, measurement information is widely used, for example, the physical properties of semiconductor materials, the accuracy parameters of radioelements, temperature instability of the functional parameters of electrical radio components, etc., which are studied both in laboratory conditions and in operational conditions with the involvement of technical means of measurement and control. Any measurement result contains errors, which are divided into random and systematic. However, a number of works prove that in the process of work quality management, where the results of measuring the values of some parameters are constantly being compared with the standards, there are control errors that acquire a systemic character in the form of complex compositions of agent-based uncertainties [6]. As it turned out from the studies, variations (uncertainties) of the standards have a greater effect on the control error than the measurement error (uncertainty). From this it follows that the quality of control is determined by the systemic connection and the ratio of uncertainties, which is very important in the design of complex multi-parameter systems [30].

The concept of "uncertainty" ("Uncertainty") appeared more than 30 years ago. According to [31, 32], it is "A parameter associated with the measurement result and characterizing the spread of values that can reasonably be attributed to the measured value. This parameter can be, for example, the standard deviation (or a multiple thereof) or the width of the confidence interval". In [32, 33], it is noted “there is no difference in the calculations whether the standard uncertainty is considered as a measure of the variance of the probability

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distribution of an input quantity or as a measure of the variance of the probability distribution of the error of this quantity."

Uncertainty gives rise to risks. At all stages of management, there is a process of control and decision-making, and as a result, the phenomenon of risk. Risk by its nature and role in technological progress can be called a phenomenon [34-36]. Risk theory began to develop intensively in the middle of the last century. The largest number of studies devoted to risk analysis belongs to American scientists, although this problem has been actively studied in Western European countries. A serious development of the mathematical apparatus of risk analysis is applicable in technical and natural fields of knowledge in [6, 21]. Risk is a statistical concept defined as the expected probability of undesirable consequences. Risk is generated by the factors of uncertainty in the nature of the agents of the control system. Risk management is one of the main challenges of the 21st century. A major difference between the new edition of ISO 9001:2008 from its earlier version is that changes have already been introduced in the general provision of the standard, where it is interpreted "the development and implementation of an organization's quality management system is influenced by its external environment, changes or risks". It follows that risk assessment and forecasting is a mandatory requirement of any important socio-economic or technical project. Therefore, in the development of conceptual provisions of the theory of risk and methodological approaches to assessing and optimizing risk in human life, an unprecedented amount of attention is currently being paid on the pages of publications and publications. Scientists in many countries are working on various aspects of the risk problem. Intensive research is carried out in all developed countries: the USA, Germany, Japan, the Netherlands, England, France, as well as within and under the auspices of international organizations - WHO, IAEA, UNIDO, and the international scientific center - International Institute for Applied Systems Analysis (IIASA).

Quantitative analysis of systemic risk involves a numerical definition of individual risks to the project size in absolute or relative form [37]. Since the risk is a probabilistic phenomenon, and it is necessary to measure it, as the probability of occurrence of certain events and related losses. All random variables when they are repeated obey a certain distribution law. Revealing the distribution law of a given random variable is a priority procedure for quantitative risk assessment.

As such a probable event, one can consider the case of discrepancy between the design results and the results of the project implementation in real conditions. This becomes possible because the design is carried out in conditions of statistical uncertainty of all agents of the life cycle system, for the reasons already indicated above. In such cases, in design, statistical reliability and the reliability of the result are taken as the equivalent of reliability in some areas of technology. In works [6], reliability is used as a quantitative measure of statistical reliability. In the process of making control decisions about the acceptability of risk, it is important for him to represent not so much the probability of a certain level of losses, as the probability that the losses will not exceed a certain level. Logically, this is the main indicator of risk. The probability that losses will not exceed a certain level can be taken as an indicator of robustness.

A quantitative assessment of the robustness of radio-electronic systems seems to be a probabilistic problem, and for its solution the mathematical theory of probability and mathematical statistics is used. The use of the probabilistic approach is justified by the fact that the physical and mechanical characteristics of the used technological materials and component base at different points of the object's life cycle have significant variation. The application of the theory of probability and mathematical statistics makes it possible to establish a quantitative relationship between the characteristics of the variability of the properties of materials, external and internal influences, and the calculated level of robustness.

The use of economic and probabilistic methods for design in practice encounters difficulties, since it is necessary to know the function of losses on the level of functional and operational reliability and design quality of radio-electronic systems, which is not always possible in practice and is associated with a large amount of research work to identify this functions in each case. Therefore, technical standards are used in the form of levels of probability of occurrence or non-occurrence of a certain event. Most often this level is taken as 95%.

The final part of the risk management process is the regulation of administrative decisions or physical impact on the object. This stage completes the risk management process and systematically links all its stages into a single concept. However, it should be noted that regulatory influence is also a random process. Standard values are also random, which should be taken into account when modeling and quantifying risks in the design, development and operation of VLC systems.

3. STATEMENT OF THE PROBLEM

At this stage, a theoretical study of the influence of statistical properties of tools on the quality of control in the VLC system is proposed. The quality of control is assessed by the amount of risk control errors. For these purposes, a formal apparatus based on mathematical and simulation modeling is used.

One of the system integrated metrological indicators of quality control is reliability and its components: the probable error of the P_{fm} - "false marriage" and the probable error of the P_{um} - "undetected marriage". In this case, "marriage" has a broad interpretation, for example, "producer risk "and" consumer risk", or in reliability theory, "false failure "and" undetected failure", the concept of "marriage" in this context is the correctness of the decision [37].

The control process contains: measurement of a certain conditional parameter $Si_{meas.}$, comparison of the measured value Siизм (measured value) with the lower or upper standard. If the measured value goes beyond the accepted standards, then measures are taken in the decision-making system to restore the functional performance of the object. In practice, it is generally accepted that control errors depend only on measurement errors. To quantitatively estimate probable errors and predict their level, depending on the statistical developments of process agents, there is a need for statistical tests or simulation models. Thus, the general task of developing mathematical models is used to quantitatively estimate all component functions of the statistical characteristics of the characteristics of a multi-agent model: errors, standards and decision-making procedures [38].

At the first stage of modeling, it is assumed that the standard values are deterministic. The first version of the model will consider the case of a single-limit restriction of the controlled parameter "from below" by the standard Sн (figure 1). Two erroneous events will be considered from a probabilistic point of view:

1) Actual parameter value is above the standard $(Si > S_н)$, that is, the monitored parameter is within the "fit" and the measured value Si_{meas}. randomly because the error was below the standard $(S_{meas\ i} < S_н)$ in the area "unfit," which is about marriage.

2) True value of the parameter below the standard $(S_i < S_н)$, the controlled parameter is in the "unfit" and the measured value by a random error was higher than standard $(S_{meas\ i} > S_н)$ in the area of "fit" that is undetected by marriage.

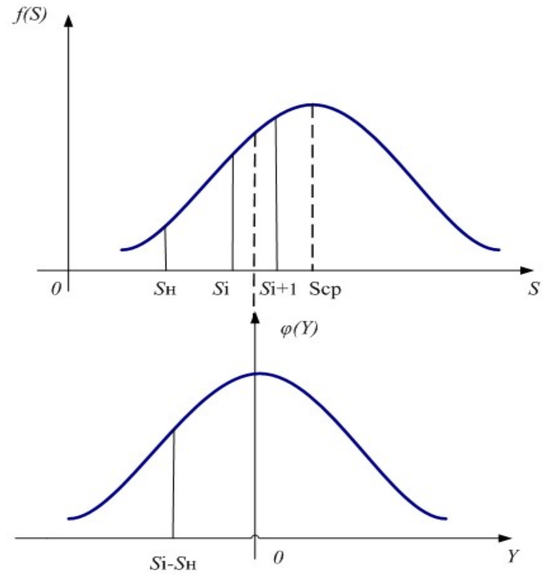

Figure 1. Control errors formation scheme for the lower limit of the controlled parameter

$f(S)$ - distribution density of the controlled parameter;
$\varphi(y)$ - distribution density of the random error of the measuring instrument;
S_i - the current value of the monitored parameter;
$S_н$ - the lower value of the standard of the controlled parameter.

It is necessary to develop mathematical models to assess the probability P_{fm} and P_{um} as a function of the statistical characteristics of model agents.

4. INTELLECTUAL ENVIRONMENT ARCHITECTURE

4.1 Probabilistic modeling of control results under conditions of uncertainty

Further, the hypothesis is considered that the statistical distributions of the controlled parameter $f(S)$ and the random error $\varphi(y)$ obey Gauss's laws. The distribution density functions of the controlled parameter and the error (uncertainty) are as follows:

$$f(S) = \frac{1}{\sigma_S\sqrt{2\pi}} \cdot e^{-\frac{(S_i - S_{cp})^2}{2\sigma_S^2}}$$

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$$\varphi(Y) = \frac{1}{\sigma_\varphi\sqrt{2\pi}} \cdot e^{-\frac{Y^2}{2\sigma_\varphi^2}}$$

where S_{cp} - average value of the controlled parameter; $\sigma_{S,}$ σ_φ - standard deviations of the distribution density functions of the controlled parameter and the measurement error. In accordance with the recommendations that have the weight of the standard, uncertainties (type A) are measured by the value of standard deviations [39].

If we call event A - the case when the value of the parameter S is in the range $S_i \div S_{i+1}$, and event B is the case when the Siism (device reading) is below the limit value of the parameter S_{imeas}, then an event is called a false marriage occurs. Mathematically, these probabilistic events are expressed as follows:

$$P_i(A) = \int_{S_i}^{S_{i+1}} f(S)dS$$

$$P_i(B) = \int_{-\infty}^{S_i - S_H} \varphi(Y)dY$$

Then, the final formula for calculating P_{fm} will be as follows:

$$P_{fm} = \sum_{t=1}^{n} \frac{1}{\sqrt{2\pi}} \int_{t_i}^{t_{i+1}} e^{-\frac{t^2}{2}}dt \cdot \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z_i} e^{-\frac{z^2}{2}}dz \quad (1)$$

Then, the final formula for calculating P_{um} will be as follows:

$$P_{um} = \sum_{t=1}^{n} \frac{1}{\sqrt{2\pi}} \int_{t_i}^{t_{i+1}} e^{-\frac{t^2}{2}}dt \cdot \frac{1}{\sqrt{2\pi}} \int_{z_i}^{+\infty} e^{-\frac{z^2}{2}}dz \quad (2)$$

The parameter t is obtained by replacing the integration variable S with $t = (S_i - S_{av})/\sigma_S$. For variable Y, a similar variable change is made.

Thus, the analytical models (1) and (2) allow one to quantitatively evaluate and study the influence of all statistical characteristics of the control system on the level of risks R_{fm} and R_{um}. The problem is solved in a similar way for the case of the parameter's tolerance limit from below and from above simultaneously. In the mathematical models of the tolerance limitation, the condition was set that the lower $S_н$ and upper S_v were in symmetry with respect to the average of the controlled parameter. However, in practice, this condition is not always met. Therefore, it will be advisable to consider the hypothesis of arbitrary positioning of standards in relation to the average of the controlled parameter and when the distribution function of the controlled parameter obeys the Weibull law, which will significantly expand the scope of practical application of the developed model in the field of universality. The universality is provided by the properties of Weibull's law. In studies on the theory of reliability, it has been established that the Weibull law accounts for about 60% of all statistics [40]. And also, many laws can be considered in some approximation, as special cases of Weibull's law. This property is provided by the shape parameter b, which at $b = 0{,}5$ is approximated by the exponential law, at $b = 2{,}5$ the Rayleigh law is approximated, and at $b = 3{,}25$ the Weibull distribution is close to the normal law. The distribution density of Weibull's law is as follows:

$$f(S,\alpha,\beta,\gamma) = \frac{\beta}{\alpha}(S-\gamma)^{\beta-1} \cdot e^{-\frac{(S-\gamma)\beta}{\alpha}}, \ \ S \geq \gamma$$

where α – is the scale parameter; β – shape parameter; γ – position parameter.

Figure 2 shows a graphical diagram that explains the development of the desired models.

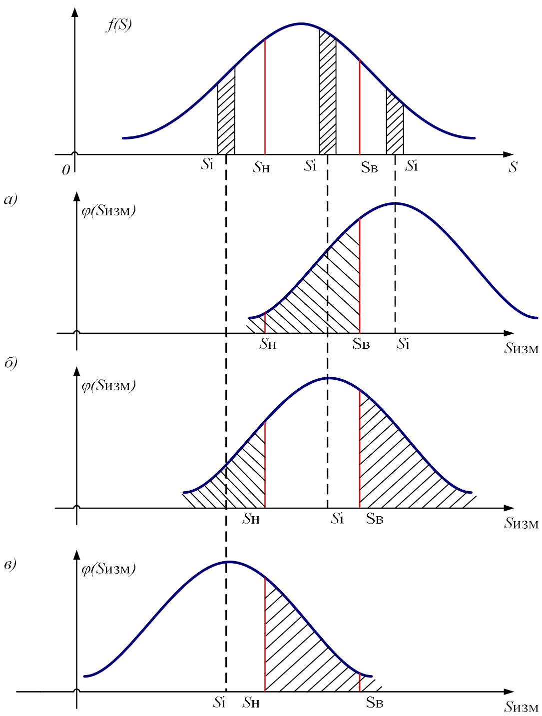

Figure 2. Formation of control errors at arbitrary positioning of standards in the field of the controlled parameter

Let's study the case when the true value of the parameter S is greater than $S_н$, but less than S_v. Limiting values of $S_н$ and S_v can be assigned arbitrarily at the discretion of the researcher. Unlike the normal law, Weibull's law has the analytical form of the integral function.

$$F(S) = 1 - e^{-\frac{(S-\gamma)\beta}{\alpha}}$$

Using the integral function of the Weibull law $F(S)$, we obtain the final expression for calculating the probability P_{fm}.

$$P_{fm} = \sum_{i=1}^{k}\left(e^{-\frac{S_i^{\beta}}{\alpha}} - e^{-\frac{S_{i+1}^{\beta}}{\alpha}}\right)\times$$

$$\times\left[\frac{1}{\sigma_y\sqrt{2\pi}}\int_{S_H}^{S_i-3\sigma_y} e^{\frac{y^2}{2}}dy + \frac{1}{\sigma_y\sqrt{2\pi}}\int_{S_b}^{S_i+3\sigma_y} e^{\frac{y^2}{2}}dy\right] \quad (3)$$

The expression for R_{nb} will be represented by the following two components:

$$P_{um} = \sum_{i=1}^{k}\left(e^{-\frac{S_i^{\beta}}{\alpha}} - e^{-\frac{S_{i+1}^{\beta}}{\alpha}}\right)\times$$

$$\times\frac{1}{\sigma_y\sqrt{2\pi}}\int_{S_H}^{S_i-3\sigma_y} e^{-\frac{y^2}{2\sigma_y^2}}dy +$$

$$+\sum_{i=1}^{k}\left(e^{-\frac{S_i^{\beta}}{\alpha}} - e^{-\frac{S_{i+1}^{\beta}}{\alpha}}\right)$$

$$\cdot\frac{1}{\sigma_y\sqrt{2\pi}}\int_{S_b}^{S_i+3\sigma_y} e^{-\frac{y^2}{2\sigma_y^2}}dy \quad (4)$$

In the examples above, it was assumed that the values of the tolerances for the controlled parameter were considered as deterministic values. However, for many reasons, the standards have a significant amount of uncertainty. This fact is systematically confirmed by various examples in all spheres of human life [36]. The development of optimal standards in each individual industry was included among the most important scientific and technical problems, which at present has not lost its importance, but has become even more relevant, since completely new and poorly studied principles and technologies are being introduced into the design practice. Therefore, a quantitative assessment of control errors in conditions of statistical uncertainty of standards becomes extremely important. It will be correct to hypothesize that the limiting values of the controlled parameter are random quantities that obey in each specific case certain statistical distribution laws.

The case of a tolerance limit is considered. The laws of distribution of random error, controlled parameter, and standards are normal. Let us assume that the distribution density functions of the upper and lower standard values have the form:

$$\Theta_1(S_l) = \frac{1}{\sqrt{2\pi}\cdot\sigma_l}e^{-\frac{(S_l-S_{lm-s})^2}{2\sigma_{lH}^2}}$$

$$\Theta_2(S_t) = \frac{1}{\sqrt{2\pi}\cdot\sigma_t}e^{-\frac{(S_t-S_{lm-s})^2}{2\sigma_t^2}}$$

where σ_l, σ_t – standard deviations of the lower and upper standard values; S_{lm-s}, S_{tm-s} average values of the lower and upper standards.

In this problem statement, to model the dynamics of errors in the RnB and RGB in the function of all statistical agents, we should choose a simulation method of modeling [6].

It is assumed that at the time of monitoring the state of the object by the conditional parameter S, this parameter has the true current value S_i, which in the simulation model will be generated ("played") by a special generator program according to a certain distribution law. It is assumed that all the distribution laws in this example are normal. In a real practical situation, the distribution laws for each parameter of the model are found experimentally, and for each law it is necessary to develop a random number generator program. The measurement is accompanied by a random error, and the result of the measurement S_{imeas} will randomly have a deviation from the true value S_i.

The simulation algorithm is shown in figure 3. the Algorithm works as follows. At the beginning of the algorithm program, all model arguments, and the value *N,* which determines the number of simulation cycles, are entered in block 1.

In the simulation model, *f(s)*, as mentioned before, is a function of the distribution density of the controlled parameter. $\Theta_2(S_N)$ is the distribution density of the lower standard.

The average value of the $S_{lm\text{-}s}$ is the center of the area of the lower standard uncertainty (scattering). Similarly, the average $S_{tm\text{-}s}$ value is the center of the range of variations of the upper standard. During each simulation cycle, the first step is to "play" the values of the current standards of S_{il} and $S_{it.}$

Block 2 opens a loop from *1* to *N*. During each simulation cycle, the first step is to "play" the values of the current standards of $S_{iн}$ and $S_{iв}$. These values are generated in blocks 3, 4. In blocks 5, 6, random values of the parameter S_i and the "measured" value S_{imeas} are generated ("played").

Block 7 contains the logical condition if (separation) $S_{il} < S_i > S_{it}$. If, under the condition that $S_{il} < S_i > S_{it}$ is within the tolerance (the condition is true – *YES*), then the condition for analyzing the measurement result of $S_{il} < S_{imeas} > S_{it}$ (block 8) now follows, and in the case of *YES* – the correct outcome, control is transferred to the organization of a new cycle to block 2.

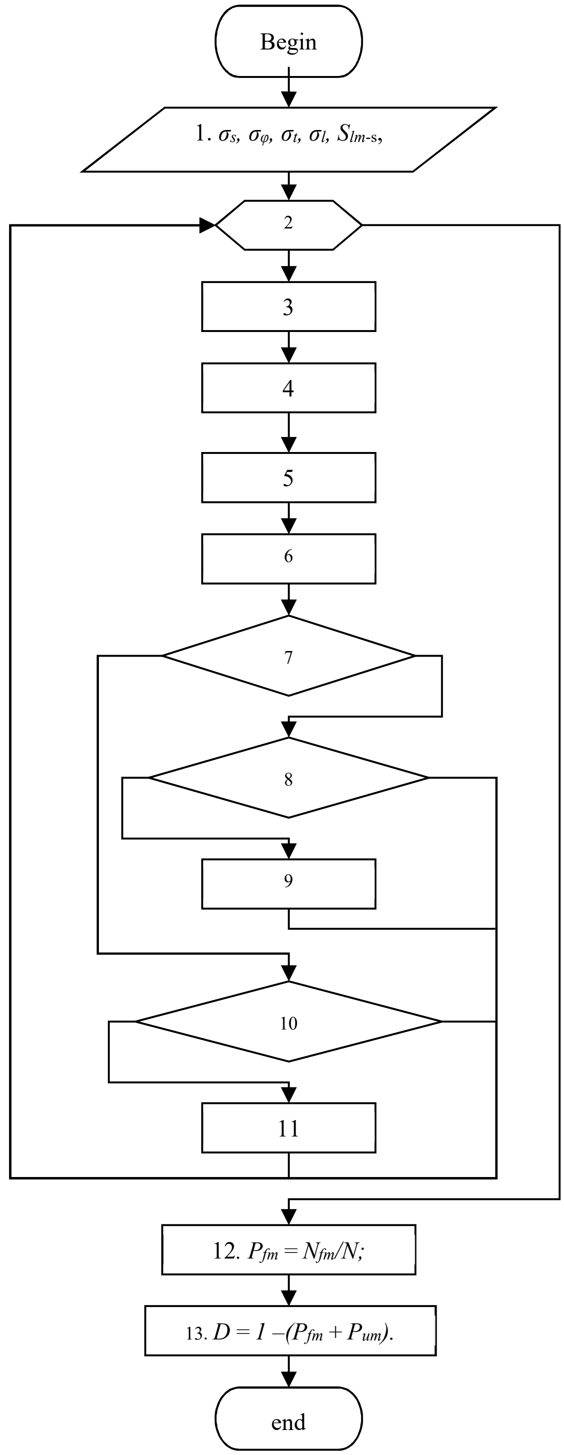

Figure 3. Simulation algorithm for assessing control risks in conditions of the regulatory values uncertainty

If the condition is false in block 8 – *NO*, then an error occurred a false marriage. In block 9, the

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counter of these cases is triggered, and a return occurs to the beginning of the next cycle in block 2.

If the condition is false in block 7 – *NO*, then the condition is analyzed in block 10 $S_{il} < S_{imeas} > S_{tl}$ and if the result is correct, control is transferred to the beginning of a new cycle (block 2), otherwise *(NO)* an error of undetected marriage appears and the N_{nb} counter is triggered in block 11 and a new cycle begins in block 2.

At the end of the given number of simulations equal to *N*, in block 12, the probabilities of false and undetected marriage are calculated using the formulas (probable control errors).

$$P_{fm} = \frac{N_{fm}}{N}; \qquad P_{um} = \frac{N_{um}}{N}$$

where N_{fm} - is the content of the false marriage counter; N_{um} - is the content of the undetected marriage counter; *N* - is the total number of simulated repetitions.

In block 13, the integral control confidence indicator D is calculated using the formula

$$D = 1 - (P_{fm} + P_{um})$$

Similar calculations can be made for different combinations of distribution laws and compare the degree of influence on the risks of controlling the distribution laws of modeling agents.

The results of the computer experiment are shown in graphic form in figures 4 and 5.

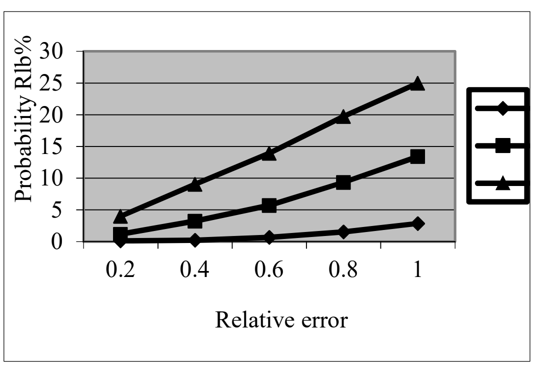

Figure 4. Result of machine modeling for deterministic standards (RLB probability)

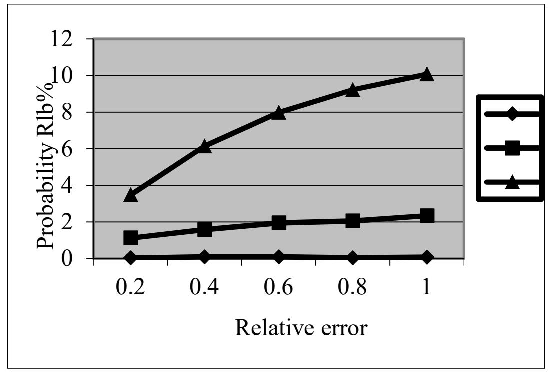

Figure. 5. Result of machine modeling for deterministic standards (probability of P_{um})

The task of the computer experiment was to study the influence of the uncertainty of the measuring instrument and the controlled parameter on the control result in the function of the ratio σ_φ/σ_s (σ_φ – the mean square of the device, σ_s - the mean square of the parameter). The ratio $\sigma\varphi/\sigma s$ varied in the range from *0.1* to *1.0* for different values of the standards of the conditional parameter *S*. The figures show that the quantitative values of control errors in both cases have a pronounced non-linearity and a considerable dependence on the system composition of the control error and limit values. As a result of modeling, it was found that when the value of measurement uncertainty σφ is comparable to the value σ_s, the risk of P_{fm} reaches *25%*. At the same time, as can be seen from the graphs, the influence of standard variation in the composition σ_φ/σ_s is higher than the influence of the error. The presented results make it possible to use modeling materials to predict the desired risks in an automated design system. studies have shown that control risks can be used as quantitative estimates of the robustness of the systems under study. Traditional metrological assessments of instrumental support for control and measurement processes cannot be used in practice due to the high degree of uncertainty of system control agents.

4.2 Software for instrumental quality control of VLC systems

Models for quantifying and predicting the quality of the control system will be technologically effective and economically justified in real practice if there is a software implementation of them.

The following are some screen copies of the working dialog with the application software package.

After starting the software environment, the user opens its main window, in which all work will be

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performed. The program allows for a comprehensive or selective study of models (figure 6).

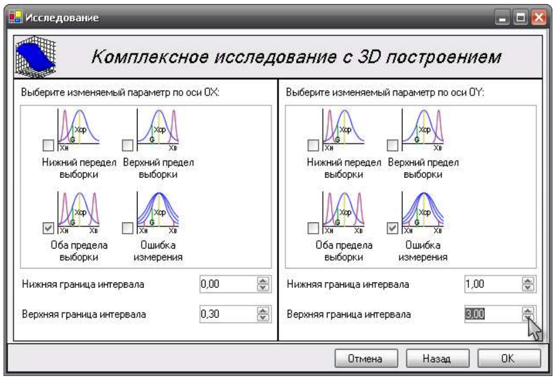

Figure 6. Setting parameters for a comprehensive study

The following variants of model research are possible: a comprehensive study of all model parameters with the output of graphical interpretation in the flat and 3D construction of calculation results; study of the influence of regulatory uncertainty; study of the influence of measurement uncertainty; study of the influence of regulatory uncertainty. The algorithms for studying variations in standards, measurement errors, and regulation are largely identical. As you can see in figure 7, to study the impact of regulations, you should specify which of them should be studied or both at the same time.

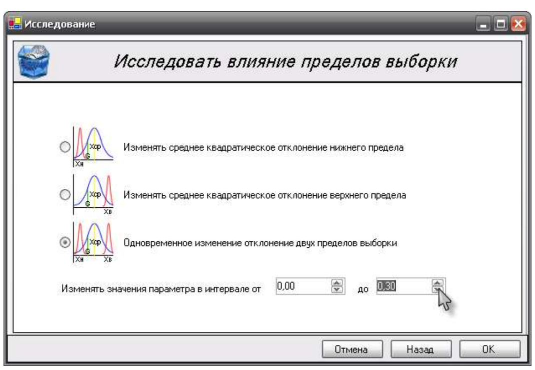

Figure 7. Study of standard deviation

The window for conducting research on the influence of measurement uncertainties is shown in figure 8.

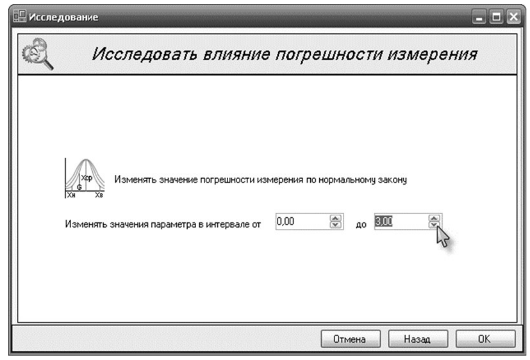

Figure 8. Study of the influence of measurement error

The software package is part of the computer-aided design system VLC systems. This complex provides dialog communication with other research tools, for example, with the complex of statistical information processing STATISTICA.

4.3 Experimental and statistical studies of VLC systems

Experimental studies were conducted to evaluate the effectiveness of mathematical and software for practical purposes. In experimental and statistical studies, the following tasks were set: justification of technical solutions and selection of industrial samples of drivers with PWM (pulse-width modulation) dimming, selection and technical and economic evaluation of control and measuring equipment for research and maintenance of VLC systems, collection and processing of statistical information; approximation of empirical data by theoretical distribution laws, conducting a computer experiment to quantify the reliability of control, and developing practical recommendations for the construction and operation of VLC systems. The normal law and Weibull's law were studied as theoretical statistical laws for smoothing empirical distributions. The STATISTICA environment was used for statistical processing of the experiment results, and the expert evaluation method was also used quite effectively [35].

Currently, there is a fairly large selection of drivers for controlling led lighting. An expert evaluation was carried out for optimal driver selection in terms of power, dimming quality, power supply, frequency and non-linear distortion, and price. The expert analysis was implemented according to the method modified by the authors, in which 5 known and applied in practice weighted average estimates were considered. Due to the fact that each of these assessment methods has its own advantages and disadvantages, the authors

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developed an approach consisting in aggregating these assessments into a certain composition that reduces the subjective component of the examination. Individual known and applied estimates were named local and are listed below:

arithmetic mean:

$$L_1 = \sum_{i=1}^{n} x_i k_i \quad (5)$$

geometric mean:

$$L_2 = \prod_{i=1}^{n} (x_i)^{k_i} \quad (6)$$

medium harmonic:

$$L_3 = \frac{\sum_{i=1}^{n} k_i}{\sum_{i=1}^{n} \frac{k_i}{x_i}} \quad (7)$$

root mean square (RMS):

$$L_4 = \sum_{i=1}^{n} k_i x_i^2 \quad (8)$$

root mean square (RMS):

$$L_5 = 1 - \sqrt{\sum_{i=1}^{n} k_i (1 - x_i)^2} \quad (9)$$

The first stage was carried out by an expert point assessment of local methods, designated as L_i, where $i = 1,5$. Calculations of local estimates are given above in formulas (5) - (9). Based on the results of local estimation L_i, the integrated indicator Q is calculated in the form of a convolution of local methods by the following expression:

$$Q = \frac{\sum_{i=1}^{5} L_i G_i}{\sum G_I \sum_{i=1}^{5} L_I} \quad (10)$$

Using this method, an integrated expert evaluation of the generated list of drivers was performed, with the exception OF the zxld1350 chip due to the low operating load current and power *(0,35 A, 10W)*. As a result of expert analysis, preference was given to the al9910 chip with a dimming function and the required power characteristics. LEDs or led structures serve as a load for the driver, depending on the specific purpose and place of use. To control the brightness for data transmission, a pulse-width modulated (PWM) signal is sent to the PWM_D input. The frequency of the analog information signal ranges from 25 Hz to 300 kHz .

In this paper, we study the VLC communication system of the "Center" for ensuring information security in closed premises in conditions of sports and cultural events. Communication in these rooms is carried out in a one-way direction from the source-the "Center" of security management to the receiver-special personnel equipped with small-sized portable photodetector devices, secretly attached to work clothes. The final link in the channel for transmitting useful information is used powerful led lighting designs.

The process of step-by-step transformation of information in an optoelectronic VLC system can be represented by the following information flow model:

$$X(t) \to Y_1(t) \to Y_2(t) \to Y_3(t) \to Y_{ex} \quad (11)$$

The signal $X(t)$ is the input acoustic information from the microphone, which is input to low frequency amplifier and, after amplification by power at its output a signal $Y_1(t)$. Amplifier output signal $Y_1(t)$ to the input dimming circuits where a signal is generated with pulse width modulation $Y_2(t)$. This signal, after power amplification $Y_3(t)$, is transmitted to the LEDs and converted into a light modulated information stream Y out.

The characteristics of the data transmission system can be studied both for individual links of the VLC system and for the entire optoelectronic channel. Study channel are differentiated according to the links recommended at the design stage of the system in the laboratory. Final studies must be performed under the operating conditions of the entire system.

At the final stage, the system implemented on the described VLC principle was studied to assess frequency distortion, temperature stability, and stability of its parameters under variations of external factors, such as climate, industrial electromagnetic, and artificial optical interference.

VLC is a system, and here the main system property is shown in practice, which consists in the fact that "the quality of the system as a whole is not a simple sum of the qualities of its constituent elements". Quality in this case is an integral concept and an indicator of the robustness of the system. The process of project synthesis of object functionality is a trajectory of robustness formation in statistical

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understanding and measurement. In the end (at the output of the system), a statistical law of distribution of the output integral indicator is formed. Along the entire trajectory of this process, input information is transformed into the final phase in the form of transformations of physical phenomena, preserving the statistical nature. The process of functional composition from system components into a whole is also accompanied by a dynamic composition of uncertainties that evaluate the parameters of individual elements or nodes during operation.

Any technical or technological decision under conditions of statistical uncertainty is accompanied by risk at every stage of VLC system synthesis. These risks are quantified using formulas (1) - (4). In that work, it is proposed to use these risks as design robust estimates of VLC systems, since this mathematical basis can be used for optimal design of radio-electronic and optoelectronic systems with a given level of robustness.

For operational assessment of robustness, criteria in the form of local risks do not give an overall picture, since they do not take into account the entire complex of factors of destructive impact on the system of natural and artificial origin. In that work, we propose to use as an integrated indicator of robustness the correlation coefficient of the *Rav* between the input electrical signal from the microphone and the output signal, which is a modulated light flux. The correlation coefficient of the *Rav* is in operational conditions according to the correlation function *R(t)* for a long period of time, as a result of monitoring (in this work for a monthly period) [5].

There are two ways to solve this problem: the first way is to evaluate the components of the final risks separately for all technical functional links of the information transmission channel. This method is extremely time-consuming and involves evaluating correlations between links at each stage. The second way is based on the ISO standard, which provides for ensuring the final quality of information at the top level of the system management process. In this case, the information security of the entire system is evaluated based on the level of correlation between the "input" and "output" and the calculated risks during design. Thus, the quality level of an optoelectronic system according to the degree of information security is proposed to be evaluated by two indicators: project risks, quantified by the probabilities of P_{fm} and P_{um}, and the correlation coefficient detected by long-term monitoring in real conditions.

In accordance with the methodology of laboratory research, the experimental assessment of control quality was aimed at identifying statistical characteristics and distribution laws of parameters of measuring equipment and optoelectronic channel links in the VLC system and processing them for further use in the process of machine experiment when assessing the risks of decision-making in design.

According to existing standards, the development of VLC systems requires high-precision instrumentation [1-3]. The following devices are used as instrumental metrological support for these purposes: an oscilloscope, a generator-calibrator CK6-122 ZEKB, a digital luxometer LX1010BS with a remote sensor.

This stage of the study was aimed at evaluating the frequency response of the dimming control channel of the MLX10803 chip, which is fed a signal from a low-frequency amplifier. A speech information amplifier (low-frequency amplifier) can use any circuit standard in industrial or private execution. As a microphone, a standard sample was used, according to Standard 53566-2009 of the second group of complexity.

At the input of the amplifier, signals were fed with a frequency of first 300 Hz 25 mV, then a second experiment of 15,000 Hz 25 mV. The frequency response was controlled at two extreme frequencies of 300 Hz and 15,000 Hz. The output signal was controlled by an oscilloscope. The minimum value of the output signal must not be lower than 250 mV.

Figure 9 shows a histogram of the empirical distribution of the output voltage of a low-frequency amplifier (300 Hz).

In visual analysis, you can see that the histogram has a form that allows you to put forward a hypothesis about the normal distribution law.

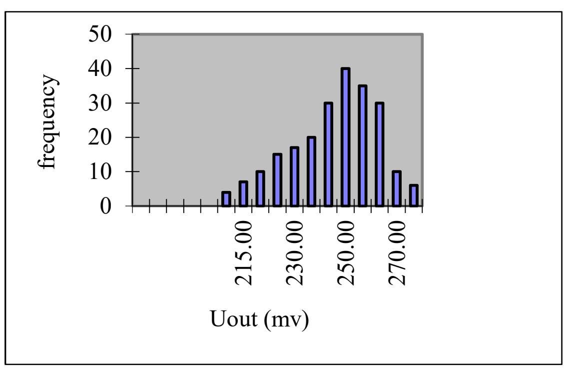

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Figure 9. Histogram of the empirical distribution of the amplifier output voltage at a frequency of 300 Hz.

As a result of data processing, it was found that the arithmetic mean value of the signal at the output of the amplifier is 255 mV, and the average square deviation is 18 mV.

Then, the analytical form of the U_{out} distribution density function will have the following form:

$$f_1(u, \sigma_u, u_{CP}) = \frac{1}{18\sqrt{2\pi}} e^{-\frac{(u-255)^2}{648}} \qquad (12)$$

The second step was a similar study conducted at a frequency of 15,000 Hz. Figure 10 shows a histogram of the empirical distribution of the output voltage of a low-frequency amplifier also from the output of a transistor at a frequency of 15,000 Hz.

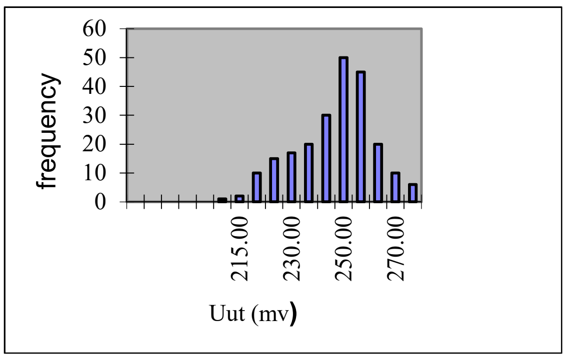

Figure 10. Histogram of the empirical distribution of the output voltage of the low frequency amplifier (15000 Hz)

As a result of data processing, it was found that the arithmetic mean value of the signal at the output of the amplifier is 258 mV, and the average square deviation is 16. mV. The approximation of the analytical function of the distribution density u by the normal law has the following form:

$$f_1(u, \sigma_u, u_{CP}) = \frac{1}{16\sqrt{2\pi}} e^{-\frac{(u-258)^2}{564}} \qquad (13)$$

The next step was to study the relationship between the light flow of a high-power led and the input harmonic signal at the input frequency range of 300-15000 Hz. The research was conducted under laboratory conditions. The tightness of the connection of the output signal of the optoelectronic channel was correlated with the input signal.

To study trends in the correlation between the "input" and "output" of an optoelectronic channel switched on for a constant daily load for a month under changing environmental temperature conditions and the optical quality of the atmosphere, the average daily correlation coefficient was determined. The results of this experiment are shown in figure 11.

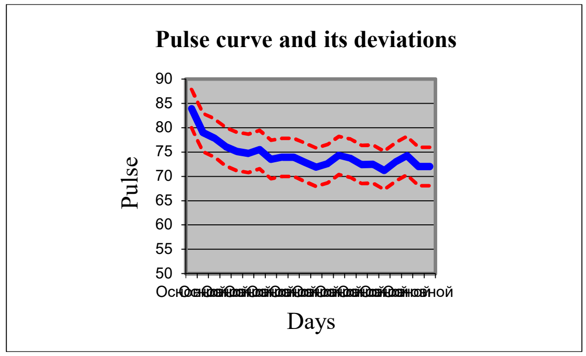

Figure 11. Trends in the average daily correlation between the optoelectronic channel "input" and "output"

The values of the correlation coefficient *R* as a percentage are shown vertically. Analysis of the experimental results showed that the temperature mode has the greatest influence on the quality of the optoelectronic channel.

Using the Harrington desirability scale [21], with the calculated average daily correlation coefficient equal to $R=0,74$, we obtain a qualitative assessment of robustness - "GOOD".

To increase the reliability of the qualitative assessment of the optoelectronic information channel, we used another indicator of the tightness of the connection between the "input" and "output" of the channel on the Cheddock scale, which is shown in table 1.

Table 1: Scale Of Chedoke

A quantitative measure of the closeness of the connection	Qualitative characteristics of the connection strength
0,1 - 0,3	Weak
0,3 - 0,5	Moderate
0,5 - 0,7	Noticeable
0,7 - 0,9	**High**
0,9 - 0,99	Very high

As follows from table 1, at the level of the correlation coefficient 0.74, the qualitative characteristic of the bond strength is estimated as "High".

5. RESULT AND DISCUSSIONS

As the analysis of literature sources has shown, VLC system design tasks should be considered poorly formalized, because the design is carried out in conditions of statistical uncertainty of design agents, and the system operation can be carried out in an environment of aggressive external electromagnetic interference. The key operational indicator of an object's information system is robustness, interpreted as functional and social reliability of the system. These characteristics include noise immunity and stability in conditions of external natural climatic and artificial, including unauthorized exposure, as well as from internal factors of industrial origin. Robustness is laid down at the design stage, implemented in the production process and maintained in operation.

In management processes, both at the system-wide level and in private design, production, technological and operational tasks of the object's life cycle, the most important function is control. The quality management system of the control process is multi-factor and multi-parametric, generating and determining the level of errors and risks at the decision-making stage.

It was found that the statistical reliability of the results of instrumental control in the design and operation of VLC systems is a composition of the laws of distribution of controlled parameters, the law of distribution of measurement uncertainty and the law of distribution of normative values.

In these system agents, the quantifiable "uncertainty" is of type "A" [23. As an integral conditional robust assessment, reliability can be accepted, which quantifies the level of risks, which is a function of: the accuracy parameters of the control and measurement equipment and the regulatory framework of the control and measurement process. The standard values of the controlled parameters are probabilistic values, and their optimal values can be estimated only in specific conditions, taking into account the statistical properties of external and internal factors that can be taken into account at the design stage and implemented at the production and operation stage.

In the scope of development plan software verification process in the design of VLC system were obtained the following results: the integrated methodology and the model of expert assessment in the system is of robust design for VLC systems management and information security socio-economic objects; also, was developed a universal probabilistic model for predicting control errors in the design of VLC systems; developed probabilistic and simulation models of risk assessment of control in the conditions of the statistical nature of standards. Algorithms and programs have been developed for quantitative calculation and forecasting of control risks for various statistical laws for designing complex systems. The developed software product implements an algorithm for constructing a probabilistic model for evaluating options for deciding (false and undetected) and the resulting confidence in the conditions of nondeterministic standards of the controlled parameter. Software applications allow you to study the degree of influence of individual characteristics of the control process on the type and magnitude of errors and risks.

A laboratory experiment was performed to study the statistical characteristics of system agents of the optoelectronic channel for generating and transmitting analog information under real operating conditions.

Implemented machine experiment to measure the statistical reliability of control processes according to the criteria of reliability and risks for design and operation, prediction of the parameters of robustness in terms of statistical uncertainty of system agents VLC technology, numerical computer experiments for the estimation of the impact probability-statistical variability of the basic arguments of the model and a given level of statistical reliability for the estimated value, practical recommendations for improvement are developed on the basis of theoretical and experimental studies.

Assessment of the quality of VLC project operation in monitoring mode for a long period in open atmospheric and industrial conditions, according to the criterion of the level of the "input" and "output" correlation function, showed that the system robustness on average over a long-time interval in quantitative measurement is 0.74 (74%). The integrated VLC system quality score based on the criteria of the Harrington desirability function is "good".

6. CONCLUSION

The overall result of the work is the further development of the theory of robustness

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management in the form of metrological reliability of control processes in technical policy, design system methodology, as well as metrological reliability (robustness) of data transmission systems based on optoelectronic technologies using VLC principles.

Statistical reliability of the results of instrumental control in the design and operation of VLC systems is a composition of the laws of distribution of controlled parameters, the law of distribution of measurement error and the law of distribution of normative values, where the "uncertainty" type "A" becomes major. Control risks and the correlation coefficient of "input" and "output" can serve as an integral conditional robust assessment. Differentiated assessment quality control at various stages of the transformation of information in the optoelectronic communication channel can be received the accuracy of quantitatively determining the level of risk which is a function of accuracy parameters of measurement-control equipment and the normative base of the control-measurement process.

Normative values of controlled parameters and indicators are probabilistic values, and their values can be estimated only in specific conditions, considering the statistical properties of external and internal factors that can be considered at the design stage and implemented at the production and operation stage.

The VLC system characteristics should be studied both for individual links and for the entire optoelectronic channel. The study of the channel is differentiated by links it seems necessary to carry out at the stage of system design in the laboratory. Final studies must be performed under operating conditions. As an integrated indicator of robustness, we should use the correlation coefficient *Rav* between the input electrical signal from the microphone and the output signal – modulated light flux. The correlation coefficient of the *Rav* is in operational conditions for the correlation function *R(t)* over a long period of time, as a result of monitoring. The overall qualitative rating of the VLC system robustness on the Harrington desirability scale was "Good", and on the Cheddock scale"High".

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