

The lack of recommendations in the normative and technical documentation related to fiber-optic communication lines (FOCL) for assessing their technical condition necessitated devising a method to control the lines' quality and reliability of operation.

The method creates the basis for calculating the quality and reliability indicators of FOCL operation and suggests measures to improve them. It determines the methods of control, as well as the acquisition, accounting, and analysis of damage statistics with and without interruption of communication.

The graphic sequence of implementation of the stages of the method demonstrates that resolving the task to control these indicators should involve:

– managing the acquisition and actual acquisition of operational data on damages (the causes, nature, quantity, the duration of communication breakdown and complete elimination of damage);

– determining the quality and reliability indicators of FOCL operation annually;

– analysis of the obtained results and the development (correction) of measures to comply with the norms of these indicators;

– the implementation of measures to comply with the norms of quality and reliability of FOCL operation (if necessary).

Based on the operational data from a line operator acquired over three years in the specified climatic zone (a cable of the type OKLBg-3 DA12-3××4E-0.4F3.5/0.22N18-12/0), the methodical component of the method was examined.

The obtained results on the operational quality (damage density, average damage duration, break (downtime) of communication) and reliability indicators (FOCL readiness factor) of a subscriber access network without reservation showed that the line had low efficiency. The communication breakdown over three years amounted to $K=12,569.8$ stream-hours. The downtime at this volume of digital stream-hours has led to significant economic losses.

Line operators have been given recommendations for the proper FOCL operation and ensuring a normalized value of the line readiness coefficient. To this end, it is necessary to reduce the time to re-link and prolong the line's failure-free operation

Keywords: method of indicators control, quality and reliability of fiber optic communication lines

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DEVISING A METHOD TO CONTROL THE OPERATIONAL QUALITY AND RELIABILITY OF FIBER-OPTICAL COMMUNICATION LINES

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1. Introduction

The problem of the quality and reliability of fiber optic communication lines includes a very wide range of issues. They are associated with the use of high-quality elements (optical cable, detachable and non-detachable connections, terminal devices, earthing devices, etc.), as well as the design, construction, and operation of lines.

Of particular importance in the operation of fiber-optic communication lines (FOCL) is the level of their maintenance. At the same time, studying the quality and reliability of FOCL requires investigating the phenomena that occur over time and lead to a violation of the normal functioning of certain elements.

Based on the FOCL reliability theory, ways to improve their quality and reliability in design, construction, and operation are being looked for. A special role in the operation of FOCL belongs to the techniques of annual control of the parameters of the line. That requires collecting, accounting, and analyzing statistical data on damage to line elements, determining and evaluating the values of performance quality and reliability indicators of the line. Statistics include the causes, nature, number, and duration of damage with a breakdown and without interruption of communication.

Ensuring the quality and reliability of the fiber-optic transmission system (FOTS) is undeniably relevant and requires control over the parameters (indicators) of the quality and reliability of its components. It is known that one of these components is FOCL, which contributes up to 95 % of all damage to FOTS. In turn, FOCLs are in operation under various climatic conditions. This predetermines the use of various cable structures, couplings, connections of optical fibers, earthing devices, measuring columns, control and measuring sites (CMS), and other elements of linear structures in its individual sections. In other words, the reliability of FOCLs depends not only on the quality of their elements, the methods of design and construction but also proper operation.

It is known that the assessment of the quality of FOCL operation is determined by such indicators as the density of damage, the average duration of damage, and the interruption (downtime) of communication.

In turn, the reliability of FOCL is estimated by such indicators as the failure intensity, average time between failures, the probability of trouble-free operation, and a readiness coefficient.

The quality and reliability of the mainline based on an optical cable (OC) should be evaluated taking into con-

sideration all damages with and without interruption of communication. Taking all damages into account is necessary as it makes it possible to more accurately identify the disadvantages and advantages of a given mainline. They are based on the quality of FOCL components (OC and cable equipment), design, construction, and operation. Assessing the FOCL performance indicators makes it possible to take measures to reduce the number of damages and the time of communication recovery.

To constantly monitor FOCL, the assessment and analysis of its quality and reliability of work based on the above indicators are absolutely necessary and relevant. It is important both for telecom operators with an extensive network of large capacity and length and for those operating only one line. On fiber-optic networks of some telecom operators, no current operational measurements of parameters of linear structures are carried out at all. The exception is measurements when the line is damaged. Moreover, such network operators do not have an organizational system for acquiring, analyzing, and final processing data on the quality and reliability of the line operation.

At present, there is no systematized set of tasks for the maintenance of FOCL to comply with the norms of indicators of its quality and reliability. Therefore, devising a method to control the quality and reliability indicators is a relevant and necessary task to ensure the service life of the line for at least 30 years.

2. Literature review and problem statement

Work [1] shows the structural systemic reliability of research objects. An overview of theories and optimization plugins is given. However, there remain unresolved issues related to the assessment of the operational quality and reliability indicators of FOCL and its components, such as OC, couplings, grounding of metal cable shells, control and measuring sites, measurement columns.

Study [2] investigated only the operational indicators of the quality of FOCL work for the flat, mountainous, and near-Black Sea climatic areas; the issues related to the assessment of the reliability of line operation remained unresolved.

The results of reliability studies and their analysis for underground optical cables with different laying technologies are given in paper [3]. However, other FOCL elements were not investigated by the authors. That makes it impossible to manage the quality and reliability of the existing line in general.

Work [4] provides an international guide to the reliability of optical fiber and cable in systems and means of transmission, digital systems, and networks. However, no attention is paid to determining and systematization of steps and their sequence in addressing current tasks of quality control and reliability of FOCL operation. Therefore, in order to control the quality and reliability of FOCL operation, it is necessary to tackle a number of issues related to the proper organization of its maintenance. These tasks include the organization of acquisition, the actual acquisition of statistical data on the annual quantity, nature, and duration of damage, the assessment of FOCL quality and reliability indicators. The experience of line operation has shown that the service life of FOCL depends not only on the factors noted earlier. It depends on a series of factors that determine the condition of

the protective hose of the cable, the resistance of grounding devices of metal cable shells, measuring columns, control and measuring sites, the means of OC protection from external electromagnetic influence (storm electricity, power lines, etc.), etc.

Work [5] pays attention to the reliability control over one of the FOCL components – the reliability of OC with the help of Brillouin reflectometry. It reproduces the physics of the influence of multi-zone cracks in the material of quartz (OV) on their reliability and service life, depending on the stress in the material and its location. That is, the Brillouin reflectometry (BR) establishes the nature of the dependence of the service life of the fiber on its tension, namely the action of mechanical stresses. Stresses in OC arise as a result of the landslide affecting underground lines and the effects of wind and ice on air FOCL.

Analysis of the data obtained using BR allows line operators to determine with great accuracy the location of the OC section with loaded fibers. As well as assess the level of its tension and predict reliability (cable service life). The reported values of BR tension manifest themselves in the elongation of the fiber. In work [5], it is noted that the Brillouin reflectometry can distinguish three tension ranges: safe, up to 0.3 %; unacceptable, exceeding 0.6 %; and intermediate, requiring additional analysis.

The latter indicates the need for replacing, during the line operation, OC sections with fiber lengthening greater than 0.6 %. The above raises the need to consider replacing the cable.

Work [6] also addresses optical reflectometry. It reports the results of studying the strength and accuracy of OC operation based on monitoring the deformation of the cable located in wells during mining. However, the use of its results to control the quality and reliability of underground and air FOCL is not covered.

In [7], attention is paid to the role of nonlinear analysis in the organization of cable cars; a procedure for determining the optimal initial OC tension is presented. The practical significance of the cited work is the proposed concept of limiting the displacement of the cable. However, these results do not give grounds for their use in underground and suspended OC when assessing the quality and reliability of FOCL operation. Therefore, devising a method to control the indicators of quality and reliability is a relevant task, necessary to comply with the service life of the line for at least 30–40 years.

Work [8] provides international recommendations on the features of laying optical cables to take into consideration the impact of physical and climatic factors of the zone of operation. Particular attention is paid to laying and protecting the cable in the soil. However, there are also no methods for quality control and reliability of FOCL operation.

Paper [9] is an international recommendation from the Telecommunication Union L.68 series L Construction, installation, and protection of cables and other elements of external objects [9]. It provides recommendations on the laying of optical cables, taking into consideration the physical and climatic factors of the zone of operation, that is, recommendations for the technical operation of optical communication lines are provided. However, it lacks data on the organizational system of collecting and analyzing the final processing of data on the quality and reliability of the line taking into consideration all its elements.

NTT Access Network Service Systems Laboratories devise various technologies for the efficient operation of optical

network access systems. Paper [10] gives an overview of new technologies of optical network access systems to resolve the task of servicing a multimillion group of subscribers. The issues of using means and equipment that support the network in the process of efficient operation and maintenance are considered. However, no method to control the quality and reliability of FOCL operation is given.

Thus, several works have widely covered the analysis of the reliability of systems with time management, the modeling of reliability and operation of networks, the concept of OC reliability, as well as cables and connections. At the same time, there is no systematized set of tasks for the maintenance of FOCL to comply with the norms of indicators of its quality and reliability. In addition, there are no recommended methods for controlling the quality and reliability of FOCL operation in the recommendations from the international telecommunication union.

At the same time, literary sources do not give complete information about what tasks need to be solved to assess the quality and reliability of FOCL operation, which could make it possible to constantly adhere to the norms by executing various maintenance activities within a separate method.

The latter gives rise to an issue resolving which requires many years of labor-intensive research to determine the intensity of damage per 1 km of the track and the average time of communication recovery for armored and non-armored OCs under operating conditions in different climatic zones. Therefore, one should consider promising the study aimed at devising a perfect method for controlling the quality and reliability indicators of FOCL operation.

Addressing this task can be based on theoretical advancements on the reliability of electric cable communication lines, as well as the MCE-T Maintenance: introduction and general principles of maintenance and maintenance organization recommendations, and statistical values for the quantitative indicators of reliability of FOCL operation under different climatic conditions [2].

3. The aim and objectives of the study

The purpose of this work is to devise a method to control the quality and reliability indicators of FOCL operation, taking into consideration all components of linear structures. It could create conditions for calculating these indicators, recommends means of the line quality and reliability management during operation.

To accomplish the aim, the following tasks have been set:

- to develop the content of accounting the statistical data on FOCL damage over *n* years of operation from the beginning of its normal functioning;
- to build estimation ratios for assessing the quality and reliability indicators of FOCL operation;
- to determine the norms of quality and reliability indicators for fiber-optic communication lines;
- to develop the content of accounting the results from the calculation of the quality and reliability indicators of FOCL operation;

- to assess a FOCL technical condition and devise maintenance measures to correct the quality and reliability indicators of FOCL;
- to validate, based on experimental studies, the method to control the quality and reliability indicators for the operation of fiber optic communication lines.

4. The study materials and methods

The object of this research is the process of managing the quality and reliability indicators of FOCL operation.

The subject of the study is the quality and reliability indicators of FOCL operation.

To solve the tasks set in this work, I used methods of mathematical statistics and probability theory. Recommendations included in the method to control the quality and reliability indicators of FOCL operation are formed on many years of experience in the technical operation of lines under different conditions of laying OC and climatic zones.

The sequence of implementation of the stages of the method to control the quality and reliability indicators for the operation of fiber-optic communication lines is shown in Fig. 1.

The following assumptions were accepted in this work:

- the quality and reliability indicators of FOCL operation are determined for the period of normal functioning when the failure intensity $\lambda = \text{const}$, that is, it does not depend on time;
- the probability of trouble-free operation of the line follows the exponential law of reliability.

Based on this graphic sequence of implementation of the stages of the method, the methodological components in determining the quality and reliability indicators of FOCL operation have been considered in detail and the main estimation ratios for determining these indicators have been determined.

As an example, in the process of experimental verification, the density of damage, the average duration of one damage, the number of communication breaks, and the readiness factor at the FOCL with a length of 52.431 km were determined. The line is operated in the Southeastern climatic region of Ukraine.

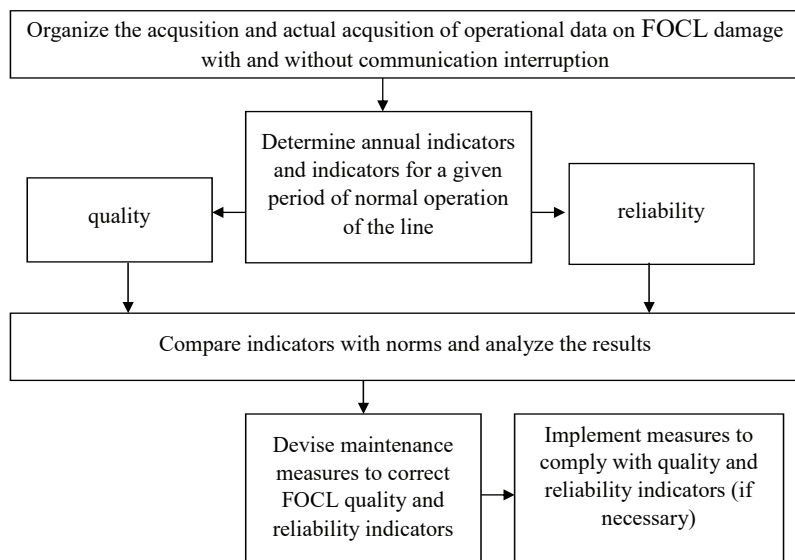


Fig. 1. Graphical sequence of implementation of the stages of the method to control the quality and reliability indicators for the operation of fiber-optic communication lines

5. Results of developing a method to control the quality and reliability indicators for the operation of optic communication lines

5.1. The content of accounting the statistical data on damage to fiber-optic communication lines

Table 1 gives the content and form of accounting the operational data. The operational data on FOCL damage include the dates, causes, nature, number, and duration of communication interruption and complete elimination of damage.

Table 1

Example of the table showing data on FOCL damage over n years of operation

Operation year	Damage cause	Damage nature	Damage quantity	Communication breakdown duration, h	Duration of damage complete elimination, h
1	-	Communication breakdown	-	-	-
		No communication breakdown	-	-	-
...	-	Communication breakdown	-	-	-
		No communication breakdown	-	-	-
N	-	Communication breakdown	-	-	-
		No communication breakdown	-	-	-
Total over n years	-	Communication breakdown	-	-	-
		No communication breakdown	-	-	-

The reliability of determining the quality and reliability indicators of FOCL operation depends on the organization of the process of acquiring and actual acquisition of operational data on damage by the operator.

5.2. Devising an estimation of the operational quality and reliability indicators of fiber optic communication lines

5.2.1. Quality indicators for the operation of fiber optic communication lines

The quality indicators of FOCL operation are represented by the density of damage, the average duration of damage, and the interruption (downtime) of communication.

The density of damage is the number of FOCL damage incidents per 100 km per year, that is:

$$m = \frac{n}{g \cdot L} 100, \quad (1)$$

where m is the number of FOCL damage incidents along a length of 100 km per year; n – the number of damage incidents along the entire line during a given period; L – line length, km;

g – the number of years over which n damage incidents occurred, year.

The average duration of damage or the average time to resolve it is determined from the following expression:

$$t_{ave} = \frac{\sum_{k=1}^n t_k}{n}, \quad (2)$$

where t_{ave} is the average duration of damage to FOCL, h; t_k – the time of the k -th damage, hour; n – the number of damage incidents during one year.

The break (downtime) of communication is taken in the channel-hours or stream-hours and is determined from the following expression:

$$K = \sum_{i=1}^{n'} \tau_i \cdot \alpha_i, \quad (3)$$

where K is the communication break, channel-hour (stream-hour); τ_i – the duration of the i -th break of communication, hour; α_i – the number of communication channels (streams) that failed during the i -th break; n' – the number of communication breaks during the year.

In real time, the break of communication (downtime) in modern FOCLs occurs on the lines without reservation with the topology of the “tire” or “star” network. These communication network topologies are used on the access network.

In transport telecommunication networks with the FOCL reservation, determining K according to the results of statistical data on damage is not required.

Communication downtime is the time for switching FOTS to a backup line, so such a connection breakdown does not lead to material losses.

These indicators make it possible to evaluate the quality of FOCL operation and its service personnel. Quality assessment is carried out for topology without reservation, that is, the communication break (downtime) in the channel-hours should be minimized.

5.2.2. The operational reliability indicators of fiber-optic communication lines

The FOCL reliability indicators are determined for lines with and without reservation.

The most important feature in the operation of FOCL and networks of synchronous digital hierarchy (SDI) is that the optimization of the communication organization scheme is ensured by the required value of the readiness coefficient K_r (or idling coefficient K_d). That is, by the necessary quality of network performance during operation.

The above is predetermined by the following:

– first, stricter current regulations on the parameters of digital channels and tracts of FOTS compared to channels that are organized on modern telecommunication means;

– second, a potentially greater design capacity of the transport network, organized on the basis of FOTS SDI.

According to the existing FOCL recovery strategy, which begins from the moment of detection of failures (accident), K_d is determined from the following formula

$$K_d = \frac{\Lambda \cdot t_{ave11}}{1 + \Lambda \cdot t_{ave11}}, \quad (4)$$

where K_d is the downtime factor; Λ – the parameter of failure flow per 1 hour for the period of normal FOCL operation; t_{ave11} – the average FOCL idling time.

In this expression, Λ is defined as:

$$\Lambda = \frac{N}{\Delta t}, \tag{5}$$

where Λ is the failure flow parameter, 1/h; N – the number of failures with a break of communication along the entire length of the line over a certain period; Δt – period, hour per year.

In turn, the readiness factor is found from the following expression:

$$K_r = 1 - K_d. \tag{6}$$

Thus, the value of K_d derived from expression (4) makes it possible to obtain the value of the FOCL readiness coefficient.

5. 3. Determining the norms of quality and reliability of fiber-optic communication lines

According to MCE-T M.60 Maintenance: introduction and general principles of maintenance and maintenance organization, the readiness of the tonal frequency (TF) channel of the main digital channel (MDC) is normalized on the reference hypothetical circle of a transmission system of length L . For a transport telecommunication network (TTCN), $L=2,500$ km; for a communication access network (CAN), $L=200$ km in one direction. In this case, the value of the readiness coefficient must be at least 0.996.

The readiness factor required on a cable line of length L_m can be calculated from the following expression:

$$K_{r\ need} = (K_{rLnorm})^{\frac{L_m}{L}}, \tag{7}$$

where K_{rLnorm} is the norm of the readiness coefficient on the reference hypothetical circle of length L ; L_m – the maximum length of a cable communication line.

According to this recommendation, taking into consideration the high reliability of modern equipment for digital transmission systems (DTS), it is advisable to accept the value for a cable line readiness coefficient of 0.985; for the equipment – 0.995. Then the following indicators should be provided along an underground cable line:

- readiness factor – not less than 0.985;
- average time between failures – not less than 340.5 hours;
- average recovery time – no more than 5.2 hours;
- the density of damage – not more than 0.1823.

Note: for the equipment of the line tracts on transport telecom networks and the subscriber access networks, the following is required:

- recovery time of maintenance-free regeneration points (MRP) – T_{recMRP} is less than 2.5 hours (including a time to reach it of 2 hours);
- recovery time of serviced regeneration points (SRP), endpoints – T_{recSRP} is less than 0.5 hours;
- OC recovery time T_{recOC} is less than 10 hours (including the time to reach it – 3.5 hours).

When reserving FOCL according to the scheme $n+m$ on SDH networks with a point-to-point topology, the downtime factor K_d^r of the transmission system is equal to:

$$K_d^r = \frac{n+m}{n!(m+1)!} K_d^{m+1} + \frac{n}{n+m} \cdot \frac{\lambda_{res}}{(n+m) \cdot \lambda_0 + \lambda_{res}}, \tag{8}$$

where n is the number of working items; m – the number of backup elements; λ_0 – the failure rate of one element of the transmission system; λ_{res} – the intensity of equipment failure switching to reserve; K_d – downtime factor.

This expression holds when parallelly connected by the reliability of FPTS elements with the same downtime coefficients.

For the circular communication structure, that is at $\lambda_{res}=0$ and $n=m=1$, a FOCL downtime coefficient is equal to:

$$K_d^{res} = K_d^2. \tag{9}$$

For a serial connection on the reliability of FOCL elements (for example, sections of a cable telecommunication line or certain types of equipment), the total downtime coefficient ($K_{d\Sigma}$) is determined from the following formula:

$$K_{d\Sigma} = \sum_{i=1}^p K_{di}, \tag{10}$$

where K_{di} is the downtime coefficient of individual elements of the operation object (cable, coupling, terminal devices); p is the number of items.

In the case of FOCL operation based on an optimal recovery strategy, which begins by determining the pre-failure state of technical operation object, it is necessary to use the following expression instead of expression (4) in the engineering calculations of K_d :

$$K_d \approx \frac{\Lambda \cdot (t_{rec} - 0.7 \cdot t_1)}{1 + \Lambda \cdot t_{rec}}, \tag{11}$$

where Λ is the failure flow parameter; t_{rec} – the average time of communication recovery, hour; t_1 – the time of travel to the site of FOCL damage.

The average duration of complete damage elimination is:

$$t_{avedced} = \frac{1}{N} \sum_{i=1}^K t_{reciN} + \frac{1}{H} \sum_{i=1}^K t_{reciH}, \tag{12}$$

where $t_{avedced}$ is the average duration of the complete elimination of damage, hour; N – the number of damage incidents with a communication interruption along FOCL over k years; H – the number of failures without a break of communication along FOCL over k years; k – the number of years during which the damage occurred.

5. 4. The content of accounting the results from calculating the operational quality and reliability indicators of fiber-optic communication lines

Indicators of the FOCL operation quality and reliability (m, t_{ave}, K, K_r) should be determined from expressions (1) to (6).

The results of the calculation of these indicators are summarized in a table (Table 2), built for their annual accounting and accounting for a given period of operation.

Thus, the values to be obtained regarding the quality and reliability indicators of FOCL operation, given in an example of the form for the results of calculating the line indicators in Table 2, could make it possible to assess the technical condition of the elements and the line in general.

Table 2

Example of a form showing the results of the calculation of FOCL operation quality and reliability indicators

Operation year	Damage nature	(<i>m</i>) Damage density (<i>m</i>)	The average duration of communication damage (<i>t_{ave11}</i>), hour	Communication breakdown (<i>k</i>), stream-hour	The average duration of damage without communication interruption, h	The average duration of damage complete elimination, h	Down-time coefficient	Readiness factor
1	communication breakdown	–	–	–	–	–	–	–
	no communication breakdown	–	–	–	–	–		
...	communication breakdown	–	–	–	–	–	–	–
	no communication breakdown	–	–	–	–	–		
N	communication breakdown	–	–	–	–	–	–	–
	no communication breakdown	–	–	–	–	–		
Total over <i>n</i> years	communication breakdown	–	–	–	–	–	–	–
	no communication breakdown	–	–	–	–	–		

5. 5. Assessing the technical condition of fiber-optic communication lines and devising maintenance measures to correct the quality and reliability indicators of line operation

Analyzing the obtained results regarding the technical condition of the line based on the indicators determined for certain years of operation of the mainline makes it possible to judge the improvement or decrease in the quality and reliability of its performance compared to the previous periods.

The comparison of the obtained values of the quality and reliability of FOCL operation (Table 2) with the norms makes it possible to evaluate the technical condition of the lines.

Based on the assessment of the causes and nature of the damage, measures are taken to prevent them. In addition, according to the values of these indicators, it becomes possible to compare the performance of individual FOCL main lines with each other, both in a transport telecommunication network and in subscriber access networks.

The indicators considered are quite simple and convenient for use in practice.

The main practical recommendations on the maintenance regarding the correction of quality and reliability indicators of FOCL operation can be reduced to the following:

- proper organization of the service of operation by highly qualified personnel, equipping it with measuring equipment and vehicles, equipping spare parts, tools, accessories and their arrangement along the line track;
- preventive maintenance of line’s elements and monitoring of OC parameters;

- reliable acquisition of operational data on damage to line’s elements;
- control and analysis of quality and reliability parameters of the line;
- maintaining the line readiness factor within the norms by reducing the number of failures and the time of re-communication;
- reduction of the number of damage incidents in FOCL due to malicious actions and economic activity.

5. 6. Results of studying experimentally the method to control the quality and reliability indicators for the operation of fiber optic communication lines

5. 6. 1. Statistics on damage incidents on fiber-optic communication lines over three years of operation

During the three years of normal operation, the damage incidents occurred whose data are given in Table 3, according to the operational data of the line operator.

Data given in Table 3 make it possible to calculate the indicators of quality and reliability of line operation.

Table 3

Statistics on FOCL damage incidents over three years of operation

Operation year	Damage cause	Damage nature	Damage incidents quantity	Communication breakdown duration, h	Duration of damage complete elimination, h
1	Action of malefactors	Communication breakdown	2	10.09; 7.00	11.03; 9.00
		No communication breakdown	1	–	10.00
2	The effect of landslides	Communication breakdown	3	9.80; 4.00; 6.00	16.40; 7.00; 6.70
		No communication breakdown	2	–	9.00; 5.00
3	Uncoordinated work of third parties	Communication breakdown	2	8.08; 4.10	11.10; 8.50
		No communication breakdown	3	–	6.00; 4.70; 4.50
Total over 3 years	Actions of malefactors, landslides, uncoordinated works of third-party organizations	Communication breakdown	7	49.88	69.73
		No communication breakdown	6	–	25.00

5. 6. 2. Results of the experimental study into the operational quality and reliability indicators of fiber optic communication lines

Calculations were performed for the annual quality and reliability indicators of FOCL operation and for the three-year period of its functioning.

The route of the cable line of the subscriber access network without reservation was implemented on a cable the type of OKLBg-3DA12-3×4E-0,4F3,5/0,22N18-12/0, and the equipment STM-1.

Based on the data from Table 1, the m , t_{ave} , K , and K_r indicators over the first year of operation were determined. The results are given in Table 4.

Table 4

Results of calculating the annual quality and reliability indicators of FOCL operation

Indicator	Designation	Calculation formula	Result
The density of damage with interruption of communication (density of failures) per 100 km of FOCL route	m_{11}	(1)	3.81
The density of damage without interruption of communication per 100 km of FOCL route	m_{12}	(1)	1.91
The total density of FOCL damage per 100 km of route	m	$m=m_{11}+m_{12}$	5.72
The average duration of damage time N with a break in communication, h	t_{ave11}	(2)	8.95
The average duration of damage time N without a break in communication, h	t_{ave21}	(2)	6.6
The average duration of complete repair of damage, h	$t_{avedced}$	(12)	20.02
Communication interruption in the first year of operation, stream-hour	K	(3)	4,510.8

The quality indicators of FOCL without reservation for the 2nd and 3rd years of operation were determined similarly. The calculation results are summarized in Table 5.

Data on the quality and reliability indicators of FOCL operation, listed in Table 5, create an opportunity to provide an assessment of the technical condition of the line. Thus, the experimental study into the quality indicators of FOCL operation has shown that the density of damage over three years of operation was 2.54, the average duration of damage with a communication interruption – 7.13 hours, and the break (downtime) – 12,569.8 stream-hour.

The downtime coefficient was determined according to (4). At the length of the track of 52.431 km, $\Lambda=\lambda_{ave}L$ will be equal to $4.71\cdot 10^{-5}$ 1/h. In the K_d calculations, the values of the average duration t_{ave11} were taken according to the data from Table 1.

According to [8], when calculating the value of the parameter of the flow of failures adopted for the FOCL for the Black Sea coast – the territory of the Southeastern climatic region of Ukraine, the average failure rate $\lambda_{ave}=9.22\cdot 10^{-7}$ 1/h.

Then the values of the K_d , K_r , K_{rreq} indicators would correspond to those in Table 6.

Table 6

Estimation values for the K_d , K_r , K_{rreq} indicators

Indicator	Designation	Formula	Result
Downtime coefficient	K_d	(4)	$4.213\cdot 10^{-4}$
FOCL readiness factor	K_r	(6)	0.9996
Required FOCL readiness factor	K_{rreq}	(7)	0.996

The indicators of FOCL reliability based on the data on damage during operation for the 2nd and 3rd years were determined similarly. The calculation results are summarized in Table 5.

Thus, according to the experiment, the task of devising maintenance measures to correct the quality and reliability indicators of a given FOCL is reduced to the following.

The experimental study into the FOCL operation reliability indicators over three years of operation showed that despite unsatisfactory values of damage density, the average duration of damage with a communication interruption, the line readiness factor corresponds to the norm.

The latter raises doubts about the correctness of the acquisition of operational data on FOCL damage incidents.

Therefore, in order to improve the maintenance of the line, the network operator needs to consider the maintenance measures given in chapter 5. 5.

Table 5

Results of calculating the indicators of FOCL operational performance and reliability

Operation year	Damage nature	Damage density (m)	The average duration of damage with a break in communication (t_{ave11}), h	Communication breakdown (k), stream-hour	The average duration of damage without a break in communication, h	The average duration of the complete elimination of damage, h	Downtime coefficient	Readiness factor
1	communication breakdown	3.81	8.95	4510.8	–	10.02	$4.213\cdot 10^{-4}$	0.9996
	no communication breakdown	1.91	–	–	10.00	10.00		
2	communication breakdown	5.72	6.60	4989.6	–	10.03	$3.1\cdot 10^{-4}$	0.9997
	no communication breakdown	3.82	–	–	7.00	7.00		
3	communication breakdown	3.81	6.09	3069.4	–	9.80	$2.87\cdot 10^{-4}$	0.9997
	no communication breakdown	1.91	–	–	5.07	5.07		
Total over 3 years	communication breakdown	4.45	7.13	12569.8	6.53	17.31	$3.36\cdot 10^{-4}$	0.9997
	no communication breakdown	2,54	–	–	–	–		

6. Discussion of results of studying the method to control the quality and reliability indicators of fiber-optic communication lines

The features of the proposed method include the possibility of ensuring full control over the quality and reliability indicators of FOCL operation due to the possibility of considering the technical condition of all components of the line's structures. Existing FOCL methods, including reflectometry, do not allow for such a possibility. In addition, the high cost of BR (USD 240–250 thousand) does not make it possible to use it for all FOCLs.

Unlike the technological advancements reported in [2–6, 9], my method makes it possible to take into consideration and analyze the impact exerted on all components of FOCL line's structures by the time (aging), the physical and climatic factors of the line operation environment, economic activity, unauthorized activities.

Thus, the proposed method creates the possibility of line control taking into consideration the technical condition of all its components. It is easy to use and requires little material cost.

The method makes it possible to resolve the issue related to controlling FOCL operation quality and reliability indicators due to the following:

- assessment of the technical condition of FOCL by the proposed content and accounting of statistical data on line damage with and without interruption of communication over n years of operation, which are summarized in Table 1;
- estimated ratio for assessing the quality and reliability of FOCL operation (1) to (11) taking into consideration long-term studies by the author of [2] on determining the intensity of damage per 1 km of the track and the average time of communication recovery for armored and non-armored OCs under operating conditions in different climatic zones;
- assessment of the technical condition of FOCL by the devised content for accounting the calculation results (Table 2) regarding the indicators of quality and reliability of line operation and analysis of the obtained results of these indicators;
- recommendations for the choice of line maintenance measures to correct the quality and reliability indicators of its operation to increase the service life.

With the practical use of the results from the devised method, the estimation ratios of the quality and reliability indicators of FOCL operation can be changed in accordance with the change in the law of reliability over time. The latter is the development of this study within the framework of additional work (paper) in order to improve and simplify FOCL maintenance measures.

The use of the devised method is limited by the presence of incomplete and unreliable operational data on line damage with and without interruption of communication. The implementation of a given method in practice would ensure the possibility of maintaining the line readiness factor within the norms by reducing the number of failures and the time of communication recovery.

Some limitations of the current study are worth noting:

- the lack of results from the experimental studies on controlling the quality and reliability indicators of FOCL

operation in other climatic zones in order to determine and develop measures for the proper maintenance of the line;

- the lack of recommendations to determine m , t_{ave} , K , and K_r in accordance with the probability of trouble-free operation by another reliability law.

7. Conclusions

1. The devised content of accounting for the acquisition of statistical operational data on FOCL damage is recommended for line operators to organize the collection of information on the quality of its maintenance.

2. The estimation ratios for determining the indicators of quality and reliability of FOCL operation have been built. These ratios create the possibility to obtain the values for these indicators. These include the damage density, the average duration of damage with communication interruption, communication break, the average duration of damage without a communication interruption, and complete elimination of damage, the downtime and readiness coefficients.

3. The norms for the quality and reliability indicators of FOCL on the reference hypothetical circles of transmission systems have been adopted. The lengths of reference hypothetical circles are as follows:

- 2,500 km for a transport telecommunication network;
- 200 km for a subscriber access network in one direction (including reservation).

In this case, the value of the readiness factor must be at least 0.996. This norm makes it possible to determine the value of K_r required by the FOCL in the carrier's coverage area.

4. The content of accounting the results of calculation of the quality and reliability indicators of FOCL operation has been devised. The results of the calculation of these indicators make it possible to give their assessment over the established period of operation.

5. To assess the technical condition of FOCL, the terms for determining annual indicators and indicators for a given period of operation of the line under a normal mode have been accepted. The latter creates conditions for constant clarification of the results of control of the technical condition of the line due to the increased control time and changes in its indicators. The conditions to analyze the technical condition of the line were defined on the basis of the results of the obtained indicators of the quality and reliability of FOCL operation, which are summarized in the compiled table. Based on the results from this analysis, communication network operators are recommended to apply maintenance measures to correct the quality and reliability indicators of FOCL operation and their implementation to prolong the service life of the line.

6. The results of the experimental verification of the devised method to control the quality and reliability indicators of FOCL operation have shown that the calculation of the value of its readiness coefficient differs from the norm K_{req} by 1%. The latter indicates the feasibility of using the method to control and manage the quality and reliability of FOCL operation and correct, if necessary, the line's maintenance means.

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