A Model of the Fiber-Optic Cable Reliability with the Restoration of Communication by Connecting at the Breakage Point Caused by a Sudden Failure

V.P. Shuvalov, B.P. Zelentsov, I.G. Kvitkova

***Abstract*— The article proposes a method for calculating the reliability measures of a fiber-optic cable, taking into account the effect of both gradual and sudden failures. The cause of gradual failures is the aging of the optical cable, and an increase in signal attenuation over time, resulting in a degradation failure (a decrease in the level of the received signal below the critical one), which leads to the replacement of the optical cable. The appearance of a sudden failure caused by an outside intervention is accompanied by repair work on connecting the cable at the breakage point. The appearance of each new connection leads to an additional attenuation of the signal and an increase in the unavailability factor. In the article is also considered the impact of control errors of the first kind on the unavailability factor.**

***Keywords*—Connection at the breakage point, degradation cycle, degradation failure, optical cable, optical fiber, periodic monitoring, reliability measures, semi-Markov process, signal attenuation, sudden failure, testing period, type I error probability.**

I. INTRODUCTION

During operation, various factors affect the fiber optic cable, which ultimately lead to failures. A failure is an event that consists in a malfunction of an optical cable when one or more operating parameters exceed acceptable limits. Depending on the rate of change of the operating parameter, sudden and gradual failures are distinguished. Gradual failures are characterized by a gradual change in one or more operating parameters, which leads to a deterioration in the quality of information transmission. Gradual failures include degradation failures, i.e. failures caused by the natural processes of aging, wear, corrosion and fatigue in compliance with all established rules and norms of design, manufacture, and operation of the facility [1]. As a result of the degradation processes occurring in the fiber, the depth of microcracks increases, which leads to a decrease in the strength of the fiber and, eventually, to its break. Degradation processes can also be expressed by a gradual decrease in the signal level at the receiver input and, consequently, a gradual increase in the error rate.

Publications [2-4] and others are devoted to the degradation of optical cables. In [2] the results of observing the attenuation coefficient of a signal in an optical cable for 16 years are presented. Theoretical aspects of the mechanical reliability of an optical cable are described in [3]. In [4], the physical processes that determine the strength and durability of an optical cable are considered.

Sudden failures are characterized by a sharp change in the operating parameters of the optical cable. The reasons for sudden failures are discussed in [5, 6] and others. In [5], an analysis of statistical estimates of the damage (breaks) of an optical communication cable during putting in the ground and in protective polymer pipes is presented. In [6], a FUJIKURA report on the reliability of optical cables laid in various conditions is given. Both publications emphasize the main cause of sudden failures is outside interference.

The warranty period of the fiber, which is set by the manufacturer, is 25 years. Currently, on many sections of the tracks where the optical cable is laid, its service life already exceeds the warranty period, and the question arises of replacing it with a new one. Obviously the warranty period from the beginning of operation and the period until the replacement of the optical cable are different terms. And, as a rule, the service life of the optical cable exceeds the warranty period. Thus, it is known that the optical cable laid in the late 60s of the last century in the United States was successfully operated 40 years later, of course, undergoing maintenance and repair [7]. During the maintenance process, cable sections can be repaired by connecting at breakage points, replacing individual cable sections, and replacing the entire optical cable [8, 9]. Deciding which maintenance and repair strategy will be most beneficial for any facility, including an optical cable, is a difficult technical and economic task [10-12]. Thus, replacing the entire optical cable is very expensive and is performed when the cost of replacing the entire cable will be less than the cost of

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replacing individual sections and making connections.

A lot of articles have been devoted to the evaluation of the service life of an optical cable [13-15] and others. In [13], the influence of the external environment on the lifetime of an optical cable is considered. In [14], traditional indicators and criteria of optical cable durability are considered, and theoretical models of optical fiber and cable aging are presented. The author of the article [14] pays special attention to the monitoring of the attenuation factor. In [15], an optical cable is considered, which is divided into sections that must be replaced because of failure. In this case, the site is replaced both in the event of a sudden failure and a degradation failure caused by the aging of the fiber. Also in [15], the concept of the degradation cycle of a cable section was introduced and it was shown that the degradation cycle increases with growing sudden failures rate, since these failures are accompanied by the replacement of an optical cable.

II. Problem Statement

The article considers the problem of determining the degradation cycle for the case when a connection is made at the point of an optical cable breakage because of sudden failure. At the same time, it is known that such connections lead to an increase in signal attenuation, the magnitude of which depends on the connection method (welding, mechanical connection). It is also known that the appearance of additional connections in the optical cable, as shown in [16, 17], simplifies the interception by an attacker of information transmitted in the upstream of the passive optical access network (TDM PON).

III. Theory

A planned degradation cycle is considered, for determining the duration of which it is proposed to use a gamma-percentile operating time to failure, defined as the duration of time from the start of an optical cable operation, during it will not reach the limit state with a given probability γ [18].The planned degradation cycle is divided into several states with the same duration.

Transitions between degradation states occur during the operation of an optical cable. The degradation state is estimated by the signal attenuation parameter, which is directly related to the depth of the crack on the fiber surface. The value of the signal attenuation parameter increases from state to state. This means that in some state, in sudden failures lack, the attenuation parameter reaches a value (limit value) at the so-called planned degradation failure occurs. After the occurrence of such a failure, the cable is restored by replacing it with a new one.

The initial state of the degradation cycle is the state corresponding to the minimum value of the attenuation parameter. In each state of degradation characterized by a given (planned) duration, a sudden failure or failure of the technical condition monitoring system may occur with the appearance of a control error of the 1st kind, after that the optical cable is restored. Then there is a transition to the next state of degradation.

In each state of degradation, a degradation process takes place and a sudden failure or error of control of the first kind may happen as a result of monitoring the technical condition of the fiber by periodic tests. The test duration is negligible compared to the testing period [15]. These factors enhance the degradation process, which leads to a reduction in the number of degradation states before failure. A sudden failure or control error of the first kind interrupts the degradation state, causing recovery and transition to the next degradation state. According to this view, in the last state of degradation, a degradation failure occurs, leading to a complete replacement of the optical cable. During the restoration, the optical cable is not used for its intended purpose, that is, it is inoperable.

When constructing a mathematical model for the conditions described above, diagrams of state transitions of the semi-Markov process are compiled, reflecting the degradation process at different levels: at one testing period, in one degradation state and on the degradation cycle.

To form a model, the number of degradation states and the number of testing periods is assumed to be five. However, the result obtained is further generalized to an arbitrary number of degradation states and testing periods.

IV. Description of the Optical Cable Degradation Model

A. *Designations Used in the Model*

The terms used in the article and their designations are given in Tables I, II, III.

Table I. Designations of states and events used in the model

Designation	Name
CD	Degradation cycle
D	Degradation state
DF	Degradation failure
E	Control error of the first kind
F	Sudden failure
TP	Testing period
US and DS	Up and down states of the optical cable
TUS and TDS	Checking the optical cable in up and down states at the end of the testing period
R	Restoration of optical cable after a sudden failure or control error of the first kind
RD	Restoration of optical cable after degradation failure

Table II. Initial parameters of the model

Designation	Name
T_{CD}	Planned duration of the degradation cycle
T_D	Planned duration of one degradation state
T_{TP}	Testing period
m	Planned number of testing periods on one degradation state
n	Planned number of degradation states on degradation cycle
λ	The sudden failures rate
α	The I type error probability
μ_1	The optical fiber recovery rate after a sudden failure or after an error of the first kind
μ_2	The optical fiber recovery rate after degradation failure
Δb	An increment of the attenuation parameter due to the degradation process in one degradation state
η	The influence coefficient of sudden failure or control error of the first kind on the degradation process

Table III. Calculated parameters of the model

Designation	Name
p_F	The probability that the sudden failure will not occur in a testing period
q_F	The probability of sudden failure in a testing period
p_E	The probability that the control error of the fist kind will not occur in a testing period
q_E	The I type error probability in a testing period
p_D	The probability of transition between two degradation states
q_D	The probability of recovery after a sudden failure or after error of the first kind on one degradation state
p_{TP}	The probability of transition to the next testing period on one degradation state
q_{TP}	The probability of transition to recovery after a sudden failure or after error of the first kind on one testing period
m_{TP}	An average number of testing periods on one degradation state
n_D	An average number of the degradation states in the degradation cycle
n_R	An average number of recoveries after a sudden failure or after type I error on one degradation cycle
θ_{UT}	The up state average time after a sudden failure during one testing period
θ_{DT}	The down state average time after a sudden failure during one testing period
t_{TP}^{UT}	The up state average time during one testing period, from which the transition to recovery occurs
t_{TP}^{DT}	The down state average time during one testing period, from which the transition to recovery occurs
t_D^{UT}	The up state average time in one degradation state
t_D^{DT}	The down state average time in one degradation state
t_D	An average time of one degradation state
t_{CD}^{UT}	The up state average time in the degradation cycle
t_{CD}^{DT}	The down state average time in the degradation cycle
t_{CD}	An average time of the degradation cycle
t_R	An average time of recoveries after a sudden failure or after type I error on one degradation cycle
F_D^{AV}	The availability factor for one degradation state
F_D^{UN}	The unavailability factor for one degradation state
F_{CD}^{AV}	The availability factor for the degradation cycle
F_{CD}^{UN}	The unavailability factor for the degradation cycle

The planned degradation cycle time of the optical cable T_{CD} is divided into n degradation states with a constant duration T_D:

$$T_{CD} = n \cdot T_D, \tag{1}$$

and the planned duration of one degradation state is divided into m testing periods T_{TP}:

$$T_D = m \cdot T_{TP}. \tag{2}$$

B. Diagrams of State-Transitions on One Testing Period and One Degradation State

The diagram of state-transitions on one testing period is shown on Figure 1.

On the diagram Figure 1: $1US_i$ − up state at the i-th testing period, i = 1, 2 ,..., $m-1$ where m is a number of testing periods; $7US_{i+1}$ − up state when switching to the (i+1)-th testing period [15].

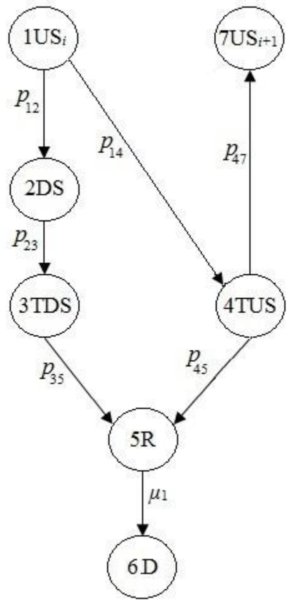

Figure 1. Diagram of state-transitions on one testing period

The transition probabilities between the diagram states on Figure1 [15]:

$$p_{12} = 1 - \exp(-\lambda \cdot T_{TP}); \;\; p_{14} = \exp(-\lambda \cdot T_{TP}); \\ p_{23} = p_{35} = p_{56} = 1; \;\; p_{45} = \alpha; \;\; p_{47} = 1 - \alpha. \tag{3}$$

The probability of transition to the next testing period is

$$p_{TP} = p_{14} \cdot p_{47} = (1-\alpha) \cdot \exp(-\lambda \cdot T_{TP}), \tag{4}$$

where p_{14} and p_{47} are defined in (3).

The probability of transition to recovery is

$$q_{TP} = p_{12} + p_{14} \cdot p_{45} = 1 - p_{TP}, \tag{5}$$

where p_{12}, p_{14} and p_{45} are defined in (3) [15].

The diagram of the state-transitions on one degradation state is shown on Figure 2 [15]. Parameter p_{TP} on Figure2 is defined in (4) and q_{TP} is defined in (5).

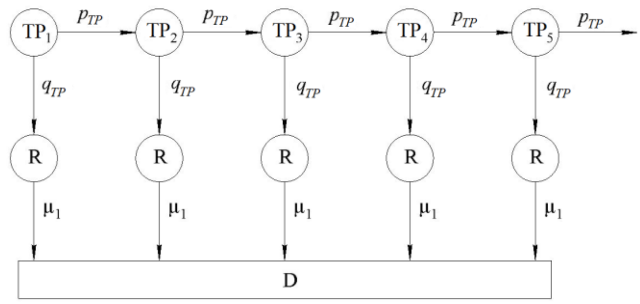

Figure 2. Diagram of state-transitions on one degradation state

The probability of transition to the next state of degradation is

$$p_D = p_{TP}^5. \tag{6}$$

The probability of recovery after a sudden failure or error of control of the first kind in one state of degradation is

$$q_D = 1 - p_{TP}^5. \quad (7)$$

The average number of testing periods in one state of degradation is [15]

$$m_{TP} = \frac{1 - p_{TP}^5}{1 - p_{TP}}. \quad (8)$$

C. Diagram of State-Transitions on Degradation Cycle

The degradation cycle includes being in states of degradation and in states of recovery after sudden failures and control errors of the first kind.

Figure 3 shows a transition-state diagram with five degradation states and transition probabilities p_D from (6) and q_D from (7).

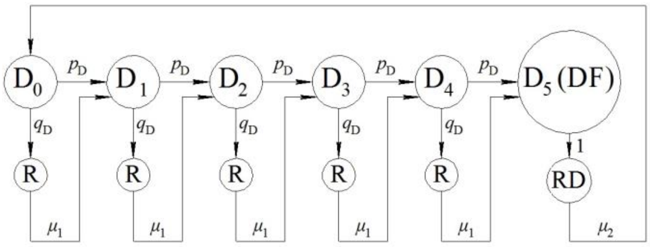

Figure 3. Diagram of states-transitions on one degradation cycle

In the states D_0, D_1, D_2, D_3, D_4, there is an increase in attenuation, and in the state D_5, a degradation failure occurs. After a degradation failure, the degradation cycle ends and a new cycle begin. In this case, the optical cable is restored with the recovery rate μ_2.

The transition from the current state degradation state to the next state occurs provided there was no sudden failure or control error of the first kind in the current degradation state.

D. Signal Attenuation During Degradation

A sudden failure or control error of the first kind in any degradation state leads to the attenuation parameter increasing in the next state.

The attenuation parameter increment in one state Δb is transferred to the next state when switching to it.

A sudden failure or control error of the first kind can cause a different change in the attenuation parameter. This effect is taken into account using the coefficient η. At η = 0, sudden failures and control errors of the first kind do not affect the degradation process; at η = 1, sudden failures and control errors of the first kind have the same effect as the degradation process in one degradation state; at η > 1, sudden failures and control errors of the first kind have a greater impact compared to the degradation the process in one state.

So, the increase in the signal attenuation parameter during the transition $D_i \rightarrow D_{i+1}$ occurs due to the following factors:

1) transition with the attenuation parameter b_i from the state D_i to the state D_{i+1};

2) an increase in the attenuation parameter by the value Δb due to the degradation process in the state D_i;

3) an increase in the attenuation parameter due to a sudden failure or control error of the first kind by the value $\eta \cdot \Delta b$.

The transition $D_i \rightarrow D_{i+1}$ occurs both in the absence and in the case of a sudden failure or control error of the first kind. In any situation, the attenuation parameter in the state D_{i+1} increases by the value Δb due to the degradation process in the state D_i. However, an increase in the attenuation parameter because of a sudden failure or control error occurs only if these events happen. Since the probability of these events is q_D, the increase in the attenuation parameter on average will be equal to $\eta \cdot \Delta b \cdot q_D$.

So, the increase in the attenuation parameter during the transition $D_i \rightarrow D_{i+1}$ is expressed as:

$$b_{i+1} = b_i + \Delta b + \eta \cdot \Delta b \cdot q_D, \quad (9)$$

where b_i is the signal attenuation parameter in the *i*-th degradation state; q_D is defined in (7).

It follows from (9) that if the attenuation parameter in the state D_i is calculated under the condition $b_0 = 0$, then:

$$b_{i+1} = i \cdot (1 + \eta \cdot q_D) \Delta b, \quad i = 0, 1, 2, ..., n. \quad (10)$$

Thus, the attenuation parameter of the signal (10) in the state D_i depends on the state number, the coefficient η and the probability of recovery after a sudden failure or control error of the first kind q_D.

At sudden failure rate $\lambda \neq 0$ and $\eta \neq 0$, the increase in the signal attenuation parameter during the transition from state to state will be greater than the planned value Δb. The planned degradation failure occurs at the attenuation parameter value $n \cdot \Delta b$. Therefore, degradation failure will occur when the condition is met: $b_i \geq n \cdot \Delta b$. This condition is expressed by inequality:

$$I \geq \frac{n}{1 + \eta \cdot q_D} = \frac{n}{1 + \eta \cdot \left[1 - (1 - \alpha)^m \cdot \exp(-\lambda \cdot T_D)\right]}, \quad (11)$$

where I is the critical number of condition with degradation failure, T_D is defined in (2).

The number I is the smallest integer satisfying condition (11), as well as the number of states included in the degradation cycle.

When condition (11) is fulfilled, the degradation cycle ends in the state D_I. At the same time, the optical cable is replaced, and then its further operation with a new planned degradation cycle.

So, the degradation failure caused by the influence of sudden failures can occur in a certain state D_I, where $I \leq n$, that is, the number of the degradation cycle states decreases compared to the planned T_{CD} defined in (1).

E. Duration of States and Subsets of States

The average time spent in a up and down states during one testing period after a sudden failure, θ_{UT} and θ_{DT}, respectively, is calculated using formulas given in [15]:

$$\theta_{UT} = \int_0^{T_{TP}} \exp(-\lambda \cdot t) dt ,$$

$$\theta_{DT} = \int_0^{T_{TP}} [1 - \exp(-\lambda \cdot t)] dt . \qquad (12)$$

The average duration of one degradation state t_D is determined by [15]:

$$t_D = m_{TP} \cdot T_{TP} = \frac{1 - p_{TP}^5}{1 - p_{TP}} \cdot T_{TP} , \qquad (13)$$

where m_{TP} is defined in (8).

Taking into account the probability of transition to recovery, the duration of one degradation state can be represented in two parts:

$$t_D^{UT} = m_{TP} \cdot T_{TP} - q_D \cdot q_F \cdot \theta_{DT} ; \; t_D^{DT} = q_D \cdot q_F \cdot \theta_{DT} , (14)$$

where θ_{DT} is defined in (12).

Let correspond the recovery time to the state of degradation from which the transition to recovery occurred. The average degradation time and the average recovery time in total is $t_D + q_D / \mu_1$, where t_D is defined in (13).

This average time can be represented by the sum of two parts:

1) a workable part $t_D - q_D \cdot q_F \cdot \theta_{DT}$;

2) a non-workable part $t_D^{DT} + q_D/\mu_1 = q_D \cdot (q_F \cdot \theta_{DT} + 1/\mu_1)$ taking into account (14).

The average duration of the degradation cycle depends on I and the average recovery time after degradation failure:

$$t_{CD} = I \cdot (t_D + q_D / \mu_1) + 1/\mu_2 . \qquad (15)$$

The average duration of the degradation cycle also consists of two parts, taking into account (15):

1) a workable part $t_{CD}^{UT} = I \cdot t_D^{UT} = I \cdot (m_{TP} \cdot T_{TP} - q_D \cdot q_F \cdot \theta_{DT})$;

2) a non-workable part $t_{CD}^{DT} = I \cdot (t_D^{DT} + q_D/\mu_1) + 1/\mu_2 =$ $= I \cdot q_D \cdot (q_F \cdot \theta_{DT} + 1/\mu_1) + 1/\mu_2$.

F. Reliability Measures of the Optical Cable

The availability factor and the unavailability factor are the main integrated reliability measures of optical cable. The availability (unavailability) factor is the probability an object will be in up (down) state at any given time, except for planned periods during which its use is not provided [1]. These measures allow estimating the level of reliability for one degradation state and for the degradation cycle.

The availability factor F_D^{AV} and the unavailability factor F_D^{UN} in the same degradation state (taking into account the recovery time after the degradation state) are calculated using the formulas:

$$F_D^{AV} = \frac{t_D^{UT}}{t_D + q_D / \mu_1} ; \; F_D^{UN} = \frac{t_D^{DT} + q_D / \mu_1}{t_D + q_D / \mu_1} .$$

When calculating these measures for the degradation cycle, a decrease in the number of degradation states ($I \leq n$) and the average recovery time after degradation failure ($1/\mu_2$) should be taken into account:

$$F_{CD}^{AV} = \frac{t_{CD}^{UT}}{t_{CD}} = \frac{t_D^{UT}}{t_D + q_D / \mu_1 + 1/(I \cdot \mu_2)} ;$$

$$F_{CD}^{UN} = \frac{t_{CD}^{DT}}{t_{CD}} = \frac{t_D^{DT} + q_D / \mu_1 + 1/(I \cdot \mu_2)}{t_D + q_D / \mu_1 + 1/(I \cdot \mu_2)} . \qquad (16)$$

V. NUMERICAL CALCULATIONS RESULTS

To explore the behavior of the unavailability factor (16) of an optical cable in the degradation process, depending on the influence of sudden failures and control errors of the first kind under periodic monitoring conditions, let introduce the following initial data:

- the planned number of degradation states $n = 30$;
- the planned duration of one degradation state $T_D = 1$ year = 8760 hours;
- the recovery rate after a sudden failure $\mu_1 = 1/4$ 1/hour;
- the recovery rate after degradation failure $\mu_2 = 1/10$ 1/hour [19].

At given values of n and T_D, in the absence of sudden failures over the entire interval of the planned degradation cycle, an increase in the attenuation parameter due to degradation in one state can be assumed to be equal to $\Delta b =$ = 0.2 dB with an energy reserve of 6 dB [20], when a planned degradation failure occurs. In the presence of sudden failures, the restoration of the optical cable after failure increases the attenuation parameter by 0.05 dB for the welded method of connecting optical fibers and by 0.5 dB for the mechanical connection of optical fibers [20]. Then the influence coefficient of sudden failure or control error of the first kind $\eta = 0.25$ and 2.5, respectively.

Tables IV and V show the values of the unavailability factor of the optical cable during the degradation cycle for different values of the testing period and two values of η at the sudden failures rate $\lambda = 10^{-5}$ 1/hour [19].

Changing the duration of the testing period under the specified conditions has a negligible effect on the unavailability factor. The longer the testing period, the slower the unavailability factor decreases. This is due to failures will be detected less frequently with a longer testing period.

Table IV. Unavailability factor for degradation cycle at η = 0.25

Parameter	Value						
α	0	5·10-6					
T_{TP}, min	10-120	10	20	30	60	90	120
F_{CD}^{UN} ·10-4	0.866	2.14	1.5	1.29	1.08	1.01	0.972

Table V. Unavailability factor for degradation cycle at η = 2.5

Parameter	Value						
α	0	5·10-6					
T_{TP}, min	10-120	10	20	30	60	90	120
F_{CD}^{UN} ·10-4	0.952	2.45	1.7	1.45	1.2	1.19	1.08

Figure 4 shows the dependence of the unavailability factor on the type I error probability at T_{TP} = 30 min, λ = 10^{-5} 1/hour and η = 0.25; 2.5.

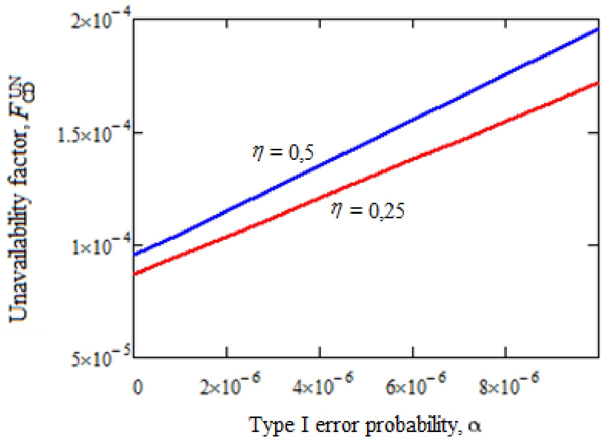

Figure 4. Dependence of the unavailability factor of an optical cable for the degradation cycle on type I error probability

From Figure 4 it can be seen an increase in the type I error probability leads to an increase in the unavailability factor.

Figure 5 shows plots of the dependence of the unavailability factor on the sudden failures rate at T_{TP} = 30 min, α = 5·10^{-6} and η = 0.25; 2.5.

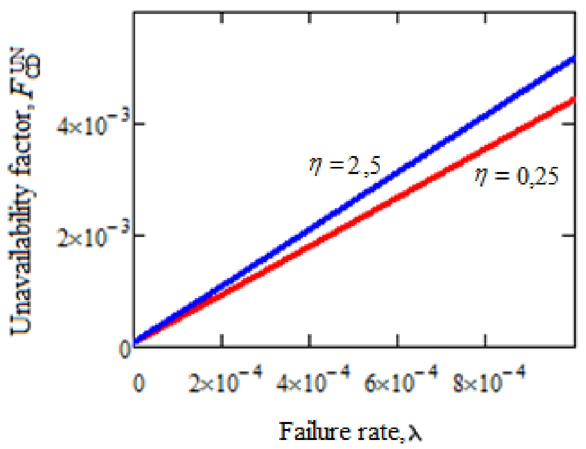

Figure 5. Dependence of the unavailability factor of an optical cable for the degradation cycle on sudden failure rate λ = 0, 10^{-7}… 10^{-3} 1/hour

According to the plots on Figure 5, it can be concluded that at low values of the sudden failures rate, the value of the unavailability factor practically does not differ with different methods of restoring an optical cable after a failure. Frequent failures lead to frequent recoveries and an increase in the signal attenuation parameter in the cable, as a result of which the unavailability factor increases.

VI. Conclusion

Based on the mathematical model, the following conclusions can be drawn:

1. Periodic monitoring of the optical cable condition allows fixing a sudden failure as early as possible and restoring communication, however, the presence of errors in the monitoring system increases the value of the unavailability factor, that should be taken into account optical cable operation during the degradation cycle.
2. The value of integrated reliability measures of optical cable depend on the chosen method of cable recovery after a sudden failure. This permits to choose one or another strategy for maintenance and repair of the optical cable, which will be optimal at the required value of the availability factor or the unavailability factor.

Based on the above approach, a methodology for evaluating the degradation cycle of an optical cable can be developed, taking into account signal attenuation as one of the main parameters reflecting the optical cable degradation process.

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