Reliability assessment of fiber optic communication lines depending on external factors and diagnostic errors

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Abstract. The article deals with the method for the assessment of the fiber optic communication lines (FOCL) reliability taking into account the effect of the optical fiber tension, the temperature influence and the built-in diagnostic equipment errors of the first kind. The reliability is assessed in terms of the availability factor using the theory of Markov chains and probabilistic mathematical modeling. To obtain a mathematical model, the following steps are performed: the FOCL state is defined and validated; the state graph and system transitions are described; the system transition of states that occur at a certain point is specified; the real and the observed time of system presence in the considered states are identified. According to the permissible value of the availability factor, it is possible to determine the limiting frequency of FOCL maintenance.

1. Introduction
In the process of operation of fiber optic communication lines (FOCL), it is necessary to monitor their status [1, 2]. Diagnostic and control tools are divided into external, integral and mixed according to the method of communication with a monitoring object. External diagnostic and control tools have neither constructive nor contact electrical connections with the monitoring object. Mixed diagnostic and control facilities have integral transducer-converter, providing information on its status and an analyzed device structurally isolated from the unit under test. A number of factors such as errors in measurement and control devices, the diagnosis equipment failure, and the human-operator participation lead to the need to take into account the real possibility of errors with testing status.

The operating practice of FOCL reveals that an optical cable life depends on the magnitude and duration of external influences on it [1 – 4]. These stresses include the action of temperature and strain on optical fibers (OF). The mechanical stresses inside the OF are a result of a number of causes: noncompliance with form of the optical cable (OC) laying, seasonal and daily temperature changes, ground distortion, foundation settlement of engineering structures, boom optical cable deflection as a result of icing or snow build-up [2 – 4].

In addition, the strain of the OF varies with the temperature. Any heating or cooling of the OF lead to the OC strain. This is due to the fact that cable construction consists of different materials with various factors of thermal expansion. The appreciable stresses with sharp variations in temperature due to unequal thermal expansion of the contacting materials inside the optical cable may occur [2 – 5].

Monitoring of FOCL in service is provided by means of monitoring and diagnostic facilities [1, 6].
2. Statement of the problem
The path is considered to be ready for operation only when both of its directions are in a state of readiness. There are the following parameters of availability in G.821 recommendation: availability factor $K_A$ is defined as the ratio of time, during which the path is in the ready state to the total period of monitoring; the factor of unavailability $K_U$, which is defined as the ratio between the time during which the tract is in a state of unavailability and the total time of monitoring [6 – 8].

The external factors include temperature fluctuations and strain. Appearance causes of mechanical stresses inside the optical fiber (OF) can be: breakdown in the technological production process of optical cable (OC); violation of rules of OC laying; daily temperature changes; ground distortion; the overhead cable icing; foundation settlement of high-rise buildings, bridges, overpasses and other engineer constructions [1, 2].

The stringing of OC on telegraph and high-voltage power line poles identified such a problem: strain of OF inside the OC is considerably increased due to wind force or icing of some optical cable sections in winter. If the strain of the optical fiber exceeds a critical value (0.2 % – 0.3 %, depending on exposure duration), the OF will have irreversible changes. It can significantly decrease the lifetime of OF and OC in general [1 – 3].

Temperature effects on the OC result in changes the strain of the OF. As quartz, cable shielding, attach hardware, ground and communication materials have different thermal expansion factors, so significant OF strain with strong changes in temperature can occur due to unequal expansion of mating materials [4, 5].

For detection of fiber sections with increased strain and changed temperature, the Brillouin optical time-domain reflectometers (BOTDR) are applied. In BOTDR the distribution of Mandelstam – Brillouin backscattering spectrum along the OF is registered and analyzed [1 – 4].

The BOTDR application in the monitoring system of OF in FOCL makes it possible to increase the detection efficiency of sections with a modified strain or temperature.

The BOTDR-reflectogram is presented in Fig. 1, wherein the distribution of Mandelstam – Brillouin backscattering spectrum along the optical waveguide is composed of different OF: G. 652 & G. 657 & G. 655, with some sections heated to +70 °C (shown by markers 1-2 (G. 652), 3-4 (G. 657) 5-6 (G. 655)). These characteristics are attained in a Brillouin optical time-domain reflectometer (BOTDR) “Ando AQ 8603”.

![Figure 1. Distribution of Mandelstam – Brillouin backscattering spectrum along the optical waveguide with some sections heated to +70 °C](image)

The suitable distribution of the strain along the fiber length is shown in Fig. 2.
3. A construction of the mathematical model

Let us consider the method of determination of an availability factor of FOCL depending on external actions and diagnosis errors [7–10].

The authors performed the following steps to obtain a mathematical model.

1. The FOCL state is defined and validated.
2. State graph and system transitions are described.
3. The system transition from $S_i$ state to $S_j$ that occur at a certain point are specified.
4. The real and the observed time of system presence in the considered states are identified.

A perfect and up state $S_0$ is initial status of a system. After random time $\tau$ a critical failure can happen in the system. It will be detected with a probability of $F_{\alpha}(T)$ and the system will pass into state $S_2$ and then after recovery time $t_r$ it will pass to the perfect state $S_0$ with probability one. If the failure is not detected by the integral diagnostic tools, the system will go into fictitious failure state $S_3$ with a probability of $(1 - \alpha(T)) \cdot F_{\alpha}(T)$. After fault correction time $t_c$, the system will move to operational condition $S_0$ with probability one. If during maintenance period $T$, the system does not have failures, it will pass into the maintenance state $S_{TO}$ with a probability of $(1 - \alpha(T)) \cdot [1 - F_{\alpha}(T)]$. During the maintenance period actions of personnel can lead to the failure in the system, so it can go into a state of critical failure $S_2$. If during the reconstruction work of the system failures are not occurred, the system will return to up state $S_0$ and its operation will start in a new cycle.

The matrix of the transition probability graph of this system is given by:
The further calculation is the same as the definition of dependence $\alpha_r(T)$ [6, 7].
Let us write a row matrix for final probabilities:

$$\pi = [\pi_o(T), \pi_s(T), \pi_4(T), \pi_{\tau_0}(T)]$$

The follow conditions must be satisfied to find final probability of system presence in the $S_i$ states:

$$\begin{align*}
\pi_o(T) &= \pi_s(T) + \pi_{\tau_0}(T), \\
\pi_s(T) &= \pi_o(T) \cdot (1 - \beta_1(T)) \cdot F_{o_2}(T), \\
\pi_4(T) &= \pi_o(T) \cdot \beta_1(T) \cdot F_{o_2}(T), \\
\pi_{\tau_0}(T) &= \pi_o(T) \cdot [1 - F_{o_2}(T)] + \pi_s(T), \\
\pi_o(T) + \pi_s(T) + \pi_4(T) + \pi_{\tau_0}(T) &= 1.
\end{align*}$$

Let us solve combined equation (3) and get an expression for the final probability:

$$\pi_o(T) = \frac{1}{A}. \quad (4)$$

For convenience, let us represent the expression as shown in Eq.(4):

$$\pi_o(T) = \pi_s(T) = \frac{1}{A}. \quad (5)$$

Thus, one can write the equations for the final probability based on the (4):

$$\begin{align*}
\pi_s(T) &= (1 - \beta_1(T)) \cdot F_{o_2}(T) \cdot \frac{1}{A}, \\
\pi_4(T) &= \beta_1(T) \cdot F_{o_2}(T) \cdot \frac{1}{A}, \\
\pi_{\tau_0}(T) &= [1 - F_{o_2}(T)] \cdot \frac{1}{A} + \beta_1(T) \cdot F_{o_2}(T) \cdot \frac{1}{A}.
\end{align*}$$

The real time of system presence in state $S_0$ is given by:

$$\omega_0(T) = p_{o_2} \int_0^\infty \tau_{o_2} dF_{o_2} (\tau_{o_2}) + p_{o_4} \int_0^\infty \tau_{o_4} dF_{o_4} (\tau_{o_4}) + p_{\tau_0} \int_0^\infty \tau_{\tau_0} dF_{\tau_0} (\tau_{\tau_0}). \quad (9)$$

Let us write the distribution function for a single step of the process:

$$F_{o_2}(\tau) = \begin{cases} 
F_{o_2}(\tau) \cdot \frac{\tau}{F_{o_2}(\tau)}, & \text{npu } \tau < T \\
1, & \text{npu } \tau \geq T.
\end{cases} \quad (10)$$

$$F_{o_4}(\tau) = \begin{cases} 
F_{o_4}(\tau) \cdot \frac{\tau}{F_{o_4}(\tau)}, & \text{npu } \tau < T \\
1, & \text{npu } \tau \geq T.
\end{cases} \quad (11)$$
\[ F_{\text{o}_0}(\tau) = \begin{cases} 0, & \text{npu } \tau < T \\ 1, & \text{npu } \tau \geq T \end{cases}. \tag{12} \]

Let us substitute the obtained distribution functions for a single step of process in (9) to obtain the following expression:
\[ \omega_0(T) = (1 - \beta_i(T)) \cdot F_{\text{o}_2}(T) \int_0^T \frac{\partial}{\partial \tau} F_{\text{o}_2}(\tau) \, d\tau + \beta_i(T) \cdot F_{\text{o}_2}(T) \int_0^T \frac{\partial}{\partial \tau} F_{\text{o}_2}(\tau) \, d\tau + [1 - F_{\text{o}_2}(T)] \cdot T. \tag{13} \]

Modified equation (13):
\[ \omega_0(T) = (1 - \beta_i(T)) \left[ \int_0^T \partial \! F_{\text{o}_2}(\tau) \, d\tau + \beta_i(T) \left[ \int_0^T \partial \! F_{\text{o}_2}(\tau) \, d\tau + [1 - F_{\text{o}_2}(T)] \cdot T. \right. \tag{14} \]
\[ \omega_0(T) = (1 - \beta_i(T)) \left( T \cdot F_{\text{o}_2}(T) - \int_0^T F_{\text{o}}(\tau) \, d\tau \right) + \beta_i(T) \left( T \cdot F_{\text{o}_2}(T) - \int_0^T F_{\text{o}}(\tau) \, d\tau \right) + 
\[ + [1 - F_{\text{o}_2}(T)] \cdot T. \right) \tag{15} \]

After simplification, expression \( \omega_0(T) \) becomes:
\[ \omega_0(T) = T - \int_0^T F_{\text{o}_2}(\tau) \, d\tau. \tag{16} \]

The observed time of presence in state \( S_0 \) is:
\[ \nu_0(T) = p_{\text{o}_2} \int_0^T \tau \, dF_{\text{o}_2}(\tau) + p_{\text{o}_4} \int_0^T \tau \, dF_{\text{o}_4}(\tau) + p_{\text{e}_{\text{o}_0}} \int_0^T \tau \, dF_{\text{e}_{\text{o}_0}}(\tau). \tag{17} \]

The distribution functions for a single step of the process are:
\[ F_{\text{o}_2}(\tau) = \begin{cases} \frac{F_{\text{o}_2}(\tau)}{F_{\text{o}_2}(T)}, & \text{npu } \tau < T \\ 1, & \text{npu } \tau \geq T \end{cases}. \tag{18} \]
\[ F_{\text{o}_4}(\tau) = \begin{cases} 0, & \text{npu } \tau < T \\ 1, & \text{npu } \tau \geq T \end{cases}. \tag{19} \]
\[ F_{\text{e}_{\text{o}_0}}(\tau) = \begin{cases} 0, & \text{npu } \tau < T \\ 1, & \text{npu } \tau \geq T \end{cases}. \tag{20} \]

Let us substitute the determined distribution functions for a single step of the process in (17) to get the following equation:
\[ \nu_0(T) = (1 - \beta_i(T)) \cdot F_{\text{o}_2}(T) \int_0^T \frac{\partial}{\partial \tau} F_{\text{o}_2}(\tau) \, d\tau + \beta_i(T) \cdot F_{\text{o}_2}(T) \cdot T + [1 - F_{\text{o}_2}(T)] \cdot T. \tag{21} \]

Thus:
\[ \nu_0(T) = (1 - \beta_i(T)) \left[ \int_0^T \partial \! F_{\text{o}_2}(\tau) \, d\tau + \beta_i(T) \left[ \int_0^T \partial \! F_{\text{o}_2}(\tau) \, d\tau + [1 - F_{\text{o}_2}(T)] \cdot T. \right. \tag{22} \]
\[ \nu_0(T) = (1 - \beta_i(T)) \cdot \left[ T \cdot F_{\text{o}_2}(T) - \int_0^T F_{\text{o}}(\tau) \, d\tau \right] + \beta_i(T) \cdot F_{\text{o}_2}(T) \cdot T + [1 - F_{\text{o}_2}(T)] \cdot T. \tag{23} \]

After conversion, equation \( \nu_0(T) \) becomes:
\[ \nu_0(T) = T - \int_0^T F_{\text{o}_2}(\tau) \, d\tau + \beta_i(T) \int_0^T F_{\text{o}_2}(\tau) \, d\tau. \tag{24} \]
The observed time of the system presence in a state of critical failure $S_2$ is determined by components of recovery time:

$$\nu_2(T) = t_c.$$  \hspace{1cm} (25)

The time in a state of dormant failure $S_4$ is equal to an operating lifetime of the system as a built-in diagnostic system is not able to detect failures of this type:

$$\nu_4(T) = T.$$  \hspace{1cm} (26)

Availability factor for this system is:

$$K_4(T) = \frac{\pi_0(T)\omega_1(T)}{\pi_0(T)\nu_0(T) + \pi_2(T)\nu_2(T) + \pi_4(T)\nu_4(T)}.$$  \hspace{1cm} (27)

4. The research results

A graph of simulation results of the availability factor as a function of maintenance rate of FOCL is shown in Fig. 3.

![Graph of simulation results of the availability factor as a function of maintenance rate of FOCL](image)

**Figure 3.** The graph of simulation results of the availability factor as a function of FOCL maintenance rate

The simulation results are estimated by the value of $K_4(T)$, which corresponds to maintenance rate $T_m$.

The less the maintenance rate of the system, the closer the availability factor value to unity. The uprating of FOCL availability by reducing the time between services leads to loss of system efficiency. Therefore, there is a question on requirements for the maintenance rate of FOCL to ensure a sufficient level of system availability.

The model takes into account external factors such as mechanical and temperature effects on the OF and diagnostic errors. The permitted value of the availability factor gives the possibility to define allowed time of operation at which the system is still in upstate. Let us denote the allowed operating time as the maintenance rate. For the experimental data obtained with the allowed value of $K_{Am} = 0.999$, the recommended maintenance rate is 5600 hours.

5. Conclusion

Modeling of the relationship between the availability factor and the maintenance rate of the system allows us to answer the questions raised.
The use of the developed mathematical model makes it possible to evaluate the availability factor, increase the reliability, efficiency of FOCL operation, as well as to reduce the complexity in drafting recommendations for planned maintenance and repair of FOCL.

One of the reasons of FOCL failures is the critical OF strain. The reasons for this are the temperature and mechanical effects on FOCL. To improve the efficiency of detection of sections with changed temperature or strain in the OF monitoring system of FOCL, it is necessary to use BOTDR.

The mathematical model helps to determine the permitted maintenance rate of FOCL. The model considers the diagnostic errors, temperature and mechanical effects on the FOCL. This model is more accurate than models that do not take these factors into account. Improving the efficiency of FOCL operation is achieved by determining scientific-based timing of the maintenance.

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