Торайғыров университетінің хабаршысы
ҒЫЛЫМИ ЖУРНАЛЫ

НАУЧНЫЙ ЖУРНАЛ
Вестник Торайгыров университета

Торайғыров университетінің ХАБАРШЫСЫ

Энергетикалық сериясы

1997 жылдан бастап шығады

ВЕСТНИК Торайгыров университета

Энергетическая серия

Издается с 1997 года

ISSN 2710-3420

№3 (2026)

ПАВЛОДАР

НАУЧНЫЙ ЖУРНАЛ
Вестник Торайгыров университета

Энергетическая серия
выходит 4 раза в год

СВИДЕТЕЛЬСТВО
о постановке на переучет периодического печатного издания,
информационного агентства и сетевого издания
№ 14310-Ж
выдано
Министерство информации и общественного развития
Республики Казахстан

Тематическая направленность
публикация материалов в области электроэнергетики,
электротехнологии, автоматизации, автоматизированных и
информационных систем, электромеханики и теплоэнергетики

Подписной индекс – 76136

---

https://doi.org/10.48081/BTOUEn3.2026/2710-3420

Бас редакторы – главный редактор
Талипов О. М.
доктор PhD, ассоц. профессор (доцент)

Заместитель главного редактора — Калтаев А.Г., *доктор PhD*
Ответственный секретарь — Сағындық Ә.Б., *доктор PhD*

Редакция алқасы – Редакционная коллегия

Клецель М. Я.,	*д.т.н., профессор*
Никифоров А. С.,	*д.т.н., профессор*
Новожилов А. Н.,	*д.т.н., профессор*
Алиферов А. И.,	*д.т.н., профессор (Российская Федерация)*
Кошеков К. Т.,	*д.т.н., профессор*
Приходько Е. В.,	*к.т.н., профессор*
Кислов А. П.,	*к.т.н., доцент*
Нефтисов А. В.,	*доктор PhD*
Шерьязов С. К.	т.ғ.д., *профессор (Российская Федерация)*
Искакова З. С.	*технический редактор*

За достоверность материалов и рекламы ответственность несут авторы и рекламодатели
Редакция оставляет за собой право на отклонение материалов
При использовании материалов журнала ссылка на «Вестник Торайгыров университета» обязательна

© Торайгыров университет

SRSTI 50.01.81

https://doi.org/10.48081/BTOUEn3.2026/340-352

I. M. Kazambaev[1], A. D. Mekhtiyev[2],
U. K. Zhalmagambetova[3], N. N. Kylyshkozha[4]
[1,2]S. Seifullin Kazakh Agrotechnical Research University,
Republic of Kazakhstan, Astana;
[1]Astana IT University,
Republic of Kazakhstan, Astana;
[2] Abylkas Saginov Karaganda Technical University,
Republic of Kazakhstan, Karaganda;
[3]Toraighyrov University,
Republic of Kazakhstan, Pavlodar;
[4]University of Padua,
Italian Republic, Veneto.
[1]ORCID: https://orcid.org/0000-0003-0850-7490
[2]ORCID: https://orcid.org/0000-0002-2633-3976
[3]ORCID: https://orcid.org/0000-0002-2261-2222
[4]ORCID: https://orcid.org/0009-0002-4340-178X
*e-mail: ilyaskazambayev@gmail.com

DEVELOPMENT OF A MODEL OF A FIBER-OPTIC MONITORING SYSTEM

Currently, due to the increased demand for electricity, all components of the energy supply system play an important role in the industry of the Republic of Kazakhstan. This article discusses the main solutions for monitoring the technical condition of a power cable. One of the most accurate integrity monitoring solutions is a fiber-optic monitoring system based on a reflectometer. The purpose of this work is to develop a model of an OTDR-based fiber-optic system. The initial data for the simulation was set, and the main physical parameters were determined. Mathematical expressions were formalized for the main events, namely vibration, stretching, bending, overheating, joint defects, shock effects and mechanical damage. In order to achieve the reliability of the results, white Gaussian noise and speckle noise were additionally introduced. During the implementation, several methods for filtering the optical signal were considered and compared. Among all the proposed methods, the Wavelet method and the method based on the decomposition of a function

into a Fourier series with further integration are the most effective. As a result, it was revealed that stretching, heating, and compression of the optical fiber are insignificant events. In turn, the developed program allows you to scale the signal to study phenomena in order to increase sensitivity.

Keywords: mathematical model, fiber-optic sensor, OTDR, monitoring system, power cable.

Introduction

At present, due to the growth of electricity consumption and the increased demand of consumers of the first category, monitoring the integrity and condition of power systems is becoming the most important, due to the need to provide reliable measurements for effective decision-making [1]. Relay protection currently plays an important role in preventing the spread of damage by localizing it [2]. However, the provision of high-precision monitoring of the state of objects to predict their failure and timely warning of possible intentional damage increases the cost of the solution several times [3]. One of the main areas is fiber-optic systems for monitoring the technical condition, both point for the installations themselves and distributed, most often used for power cables [4]. It is worth noting that power cables are not only prone to damage, but also to vandalism [5]. Moreover, damage to this element of power supply, thus disconnecting important components of the power system. Therefore, to ensure that the integrity of the power cable is maintained, it is necessary to build an optical fiber solution that allows you to determine the exact location of the impact. For example, [6] offers a non-volatile monitoring system that monitors the state of the power cable by partial discharges in the connections. The method is based on the developed algorithm for simplified phase-resolved analysis of partial discharges, which differs from the traditional one in the absence of a network phase synchronization sensor. This approach provides low power consumption and simplified hardware implementation. However, due to the decrease in the complexity of the system, there is a decrease in accuracy in comparison with PRPD systems. Another method with greater sensitivity and noise reduction is the use of the Mach-Zender interferometer and the slime mold algorithm combined with the signal decomposition method [7]. The advantages of this approach are increased immunity to noise and high accuracy of isolation of frequency components. The disadvantages are the need to set parameters in advance, namely the number of modes and the penalty coefficient.

In turn, the most popular methods are based on the use of reflectometers. For example, [8] proposes a method for observing partial discharges using a coherent optical time domain reflectometer (COTDR). In order to implement it, a hardware improvement of the scheme was proposed using a two-stage approach. The main advantages are a long monitoring range, distributed control along the entire length

of the optical cable, and a reduction in false alarms. The disadvantages are the high cost and complexity of the system, the large amount of data and sensitivity to external vibrations. Another approach involves the use of a phase-sensitive reflectometer (P-OTDR) [9]. The system has been improved in hardware by adding a Polarization Compensation Module (PCM) to improve measurement stability. The advantages of the method are high localization accuracy, continuous monitoring, increased stability and reliability of measurements. The main disadvantages are the high complexity and cost of the solution, the need for accurate installation and calibration. Another example is the solution [10], which is a passive optical network (PON) monitoring technology. The method is based on the application of a unique identification frequency generated by a piezoelectric transducer at the end of the branch. This solution features fast identification, no need to install new fiber, and reduced inter-branch interference. Despite this, the proposed method is expensive, as well as the presence of a limited number of unique frequencies.

In general, the use of phase-sensitive reflectometer techniques is an expensive solution. At the same time, not all technologies allow you to determine the nature of impacts. Currently, the presence of artificial intelligence makes it possible to eliminate noise in the signal, as well as classify, reconstruct and make a decision. Among these are [11], which uses a convolutional neural network (CNN) to improve the accuracy of measurement and error correction, the solution from [12] uses CNN to classify events.

Moreover, in order to develop practical solutions, it is necessary to develop a fundamental model based on the main analytical tools.

Materials and methods

The main goal of the study is to develop a model of a fiber-optic system to determine the impact of various events on the signal in order to further classify them. Therefore, it is necessary to specify the initial data, namely the characteristics of the optical cable (Table 1)

Table 1 – Initial data for the design of the system

Parameter	Significance
Wavelength	850 nm
Core Radius	4.5 μm
Refractive Index of Core	1.45
Refractive Index of Shell	1.445
Optical Cable Length	6000 m
Laser Power	5 mW

Next, you need to define the basic expressions to model the signal to be measured:

$$\begin{cases} E(x,\ y) = \exp\left[-\left(\dfrac{r}{w_{eff}} \right)^2 \right]; \\ r = \sqrt{x^2 + y^2}; \\ w_{eff} = 0.65 \cdot a_{core} \end{cases} \quad (1)$$

where r is the radius of the cross-section; *WEFF* is the effective radius of the mode field, a_{core} is the radius of the core.

Then, given the expression for the light wave in the optical cable [x]:

$$P(z) = P_0 - \alpha z + \sum_{i=1}^{N_r} R_i \delta(z - z_i) - \sum_{j=1}^{N_r} L_j H(z - z_i) + n(z) \quad (2)$$

where P_0 is the laser power, α is the attenuation coefficient, z is the longitudinal length of the optical cable, R_i is the reflecting events, N_r is the number of events, L_i is the reflecting events, N_l is the number of connectors, $\delta(z\text{-}zi)$ is the Dirac function, $H(z\text{-}zi)$ is a Heaviside function.

It is possible to determine what losses will be in the optical cable.

In the future, mathematical expressions are used to simulate events:

– for reflection from the connector

$$P_{i+1}(z) = \zeta P_i \quad (3)$$

where P_i is the power at the input to the connector, ζ is the refractive ratio coefficient;

– for vibration

$$V(z) = 1 + A_v \sin\left(2\pi f_v \frac{10z}{L} \right) \quad (4)$$

where A_v is the amplitude of vibration oscillations, L is the length of the section, f_v is the frequency of vibrations

– for stretching

$$\begin{cases} w' = \rho w_{eff}, \\ E_s(x,y) = \exp\left[-\left(\dfrac{r}{w'} \right)^2 \right], \end{cases} \quad (5)$$

where *w'* is the effective radius of the mode field in tension, ρ is the tensile coefficient;

– for bending

$$\begin{cases} E_s(x,y) = \exp\left[-\left(\dfrac{\sqrt{(x-\Delta x)^2 + y^2}}{w_{eff}}\right)^2\right] \\ \Delta x = 0.6a_{core} \end{cases} \tag{6}$$

– for overheating

$$\begin{cases} T(z) = T_0 + \Delta T \sin\left(\dfrac{2\pi z}{L}\right), \\ n(T) = n_0 + \alpha_T \Delta T, \\ \alpha_T = 10^{-5}, \\ z_T = z(1 + \gamma\Delta T), \\ \gamma = 5 \cdot 10^7, \end{cases} \tag{7}$$

where α is the thermo-optical coefficient, γ is the coefficient of thermal expansion;

– for poor adhesion

$$\begin{cases} P(z_i^+) = 0.6P(z_i^-), \\ P(z) = P(z_i^+)e^{-\beta(z-z_i)}, \end{cases} \tag{8}$$

where $P(z_i^+)$ is the power after the jump, $P(z_i^-)$ is the power before the jump, β is the attenuation coefficient;

– for a strong impact

$$I' = 0.5I \exp\left[-\left(\frac{r}{2.5a_{core}}\right)^2\right], \tag{9}$$

where *I* is the intensity of the optical signal;

– for chipping

$$\begin{cases} C = \exp\left[-\left(\dfrac{r}{1.5a_{core}}\right)^2\right], \\ I'' = I(1-0.6C), \end{cases} \tag{10}$$

where I is the intensity of the optical signal.

In this way, various events can be simulated based on the above expressions and source data.

Results and discussion

As a result of the simulation, it is possible to track the behavior of the light wave to create a practical solution using artificial intelligence, both to determine the physical parameters of the impact and to classify phenomena. Moreover, additive white Gaussian noise and speckle noise [x+1] were used to generate noise. Figure 1 shows a three-dimensional image of an optical fiber with an intensity display.

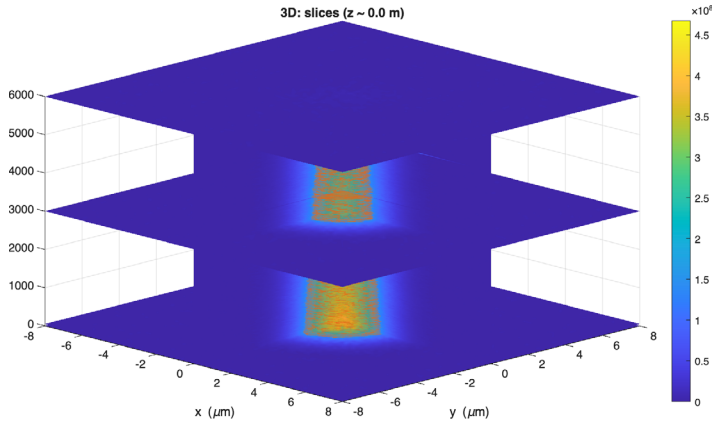


Figure 1 – Three-dimensional image of optical signal propagation

The presence of noise in the signal is indicated by slight oscillations, which can be seen in Figure 2. At the same time, strong impacts can be seen on the three-dimensional representation of the signal.

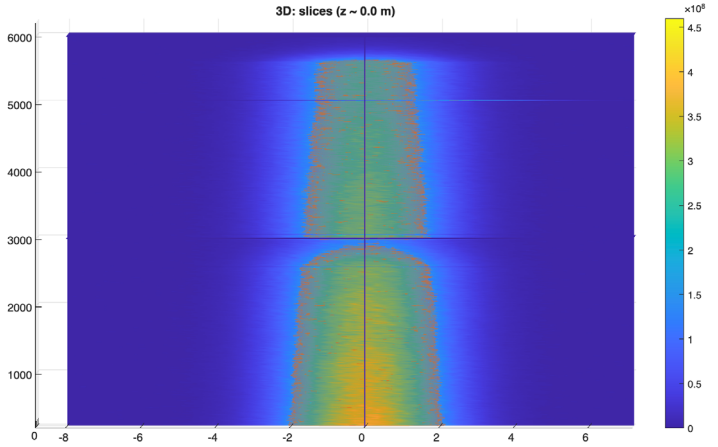


Figure 2 – Transverse intensity graph relative to z and y

The effects on the optical cable are often pronounced, however, it is worth noting that a stronger reflection occurs when bending or breaking.

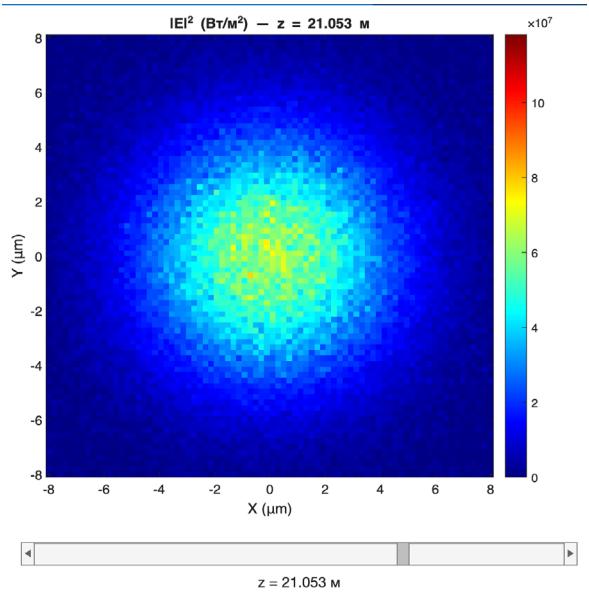


Figure 3 – Transverse intensity in x and y

By analyzing a mathematical model, a clear classification can only be achieved if the signal is filtered accurately, since even a slight noise can be superimposed on a minor event, preventing the prediction of a possible failure. For example, Figure 4 shows a reflectogram with a number of different physical events.

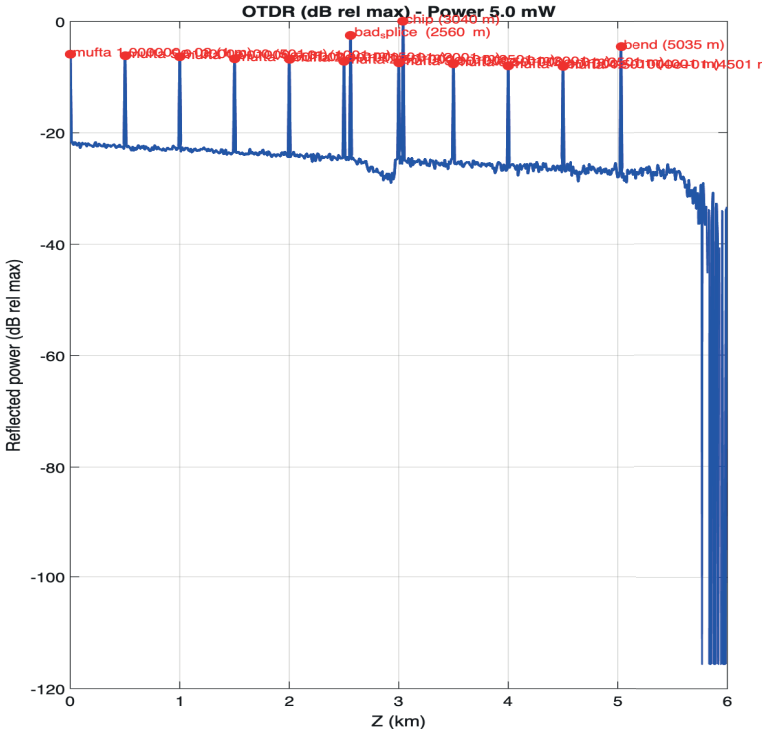


Figure 4 – A reflectogram with events

Moreover, the most common are connectors, represented as mufta, and alternating every 500 m, imitating an optical cable with a length of 500 m. Other events, namely overheating, stretching, vibration, are almost impossible to determine. On the other hand, the inflection event is distinguished relative to the connectors, but in order to determine accurately, it is necessary to introduce a flexible and sensitive mathematical apparatus with a combined setting, namely manual and automatic, which allows you to first be determined by an operator or a specialist.

Using standard methods of signal denoising, it is possible to clearly distinguish the boundaries between events and thus increase the sensitivity of the system and the accuracy of both measurement and classification (Figure 5).

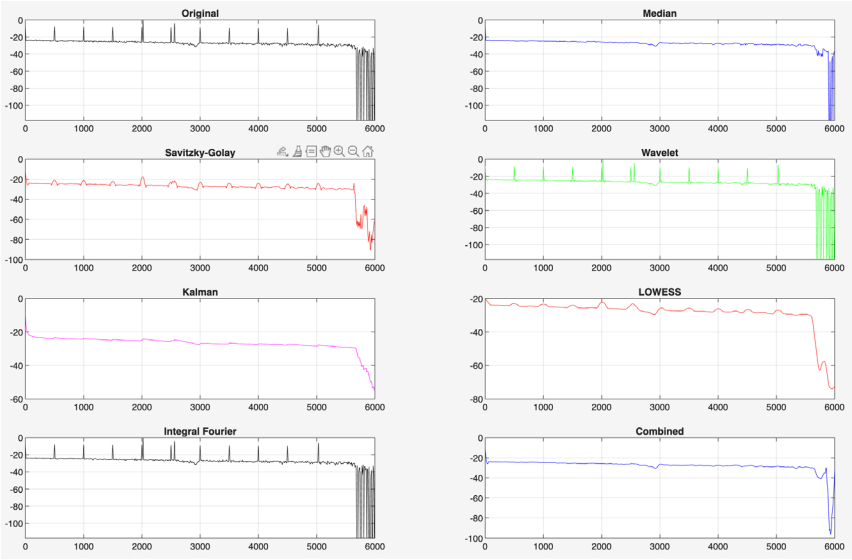


Figure 5 – Comparison of the main types of filtration

Compared to the original method, the median method reduces the impact of significant events and connectors. Also, the combined and Kalman filters smooth the signal too much, leading to the loss of useful information. The Savitsky-Golay and Local Regression (LOWESS) filters highlight the connector but smooth out the other events too much, making it impossible to accurately identify events. Therefore, the optimal solution is to use the Fourier and Wavelet decomposition methods.

Conclusions

Within the framework of this work, the main solutions for monitoring the technical condition of a power cable based on an optical time domain reflectometer were considered. A model based on mathematical expressions was developed to further analyze existing events before implementing the solution in practice. In turn, the analysis of the results showed that the most pronounced changes in the signal are observed in mechanical damage and defects in the connections, while weak effects (vibration, slight stretching and temperature change) require the use of intelligent filtering and spectral analysis methods for their proper isolation. A comparison of signal processing methods has shown that the most effective

approaches are those based on Fourier transform and waves, which provide an optimal balance between noise suppression and preservation of information components.

Thus, the proposed model can become the basis for the development of intelligent monitoring systems for fiber-optic communication lines and power cables, which can increase diagnostic accuracy, improve event positioning and reduce the likelihood of false alarms. A promising area for further research is the integration of the developed model with machine learning methods for automatic classification and prediction of the state of the cable infrastructure in real time.

REFERENCES

1 **Dincer, I., Erdemir, D.** Introduction to Energy Systems [Text]. – Hoboken, NJ, USA : Wiley, 2023. – 576 p. – ISBN: 978-1-119-82576-0.

2 **Blackburn, J. L., Domin, T. J.** Protective Relaying: Principles and Applications [Text]. – 3rd ed. – Boca Raton, FL, USA : CRC Press (Taylor & Francis Group), 2006.

3 **Yang, Y., Chen, K., Gupta, N.** Fiber-Optic Sensors [Text] // In Material-Integrated Intelligent Systems: Technology and Applications. – Hoboken : Wiley, 2018. – P. 107–136. – https://doi.org/10.1002/9783527679249.ch5

4 **Carlino, A., Godio, A.** Laboratory Testing of FBGs for Pipeline Monitoring [Text] // In Sensors. – 2020. – Vol. 20, No. 13. – P. 3797. – https://doi.org/10.3390/s20133797

5 **Udd, E., Spillman, W. B.** Fiber Optic Sensors: An Introduction for Engineers and Scientists [Text]. – Hoboken : Wiley, 2011. – 512 p. – https://doi.org/10.1002/9781118014103.

6 **Wang, J., Zhang, Zh., Zhou, R., Fan, A., Zhai, T., Guo, T.** A Novel Fiber-Optically Powered Partial Discharge Monitoring System for Cable Joints Based on Acoustic Emission [Text] // In IEEE Sensors Journal. – 2025. – Vol. 25, No. 20. – P. 38809–38819. – https://doi.org/10.1109/JSEN.2025.3605966.

7 **Tian, H., Wang, J., Zhang, W., Liu, H., Song, Y., Chen, W.** 110 kV Power Cable External Disturbance Optical Fiber Sensing Detection and Identification Method Based on ResNeXt and Attention Mechanism [Text] // In IEEE Transactions on Instrumentation and Measurement. – 2025. – Vol. 74. – Art. no. 9004111. – https://doi.org/10.1109/TIM.2025.3560744.

8 **Qin, W., Ma, G., Wang, S., Guo, T., Hu, J., Liu, H.** Improving SNR and Sensing Distance of COTDR for Distributed Partial Discharge Detection in Power Cable Joints [Text] // In IEEE Transactions on Instrumentation and Measurement. – 2024. – Vol. 73. – Art. no. 9004309. – https://doi.org/10.1109/TIM.2024.3419085.

9 **Wang, Z., Zhu G.** Phase-Sensitive OTDR Monitoring for Fault Detection in High-Density Multi-Branch Passive Optical Networks [Text] // In Journal of Lightwave Technology. – 2025. – Vol. 43, No. 22. – P. 9962–9969. – https://doi.org/10.1109/JLT.2025.3608722.

10 **Liu, Z., Yang, S., Chen, Q., Liu, Zh., Zhang, Zh., Li, Z.** Partial Discharge Distributed Locating in Power Cable Joints Using Φ-OTDR Optical Fiber System [Text] // In IEEE Sensors Journal. – 2024. – Vol. 24, No. 9. – P. 14404–14412. – https://doi.org/10.1109/JSEN.2024.3378273.

11 **Xu, S., Wen, Zh., Wang, Y., Tong, Sh., Li, M., Yang, H.** Cable Fault Maintenance and Troubleshooting Method Based on OTDR Combined with Wavelet Transform and CNN [Text] // In 2025 5th International Conference on Electrical Engineering and Mechatronics Technology (ICEEMT). – Shenzhen, China, 2025. – P. 433–436. – https://doi.org/10.1109/ICEEMT66565.2025.11280721.

12 **Li, C., Chen, X., Shi, Y.** An Event Recognition Method for a Φ-OTDR System Based on CNN-BiGRU Network Model with Attention [Text] // In Photonics. – 2025. – Vol. 12. – P. 313. – https://doi.org/10.3390/photonics12040313

13 **Fouda, B. M. T., Yang, B., Han, D., An, B.** Pattern recognition of optical fiber vibration signal of the submarine cable for its safety [Text] // In IEEE Sensors Journal. – 2021. – Vol. 21, No. 5. – P. 6510–6519. – https://doi.org/10.1109/JSEN.2020.3041318.

14 **Abufana, S. A., Dalveren, Y., Aghnaiya, A., Kara, A.** Variational mode decomposition-based threat classification for fiber optic distributed acoustic sensing [Text] // In IEEE Access. – 2020. – Vol. 8. – P. 100152–100158. – https://doi.org/10.1109/ACCESS.2020.2997941.

Received 10.06.26.
Received in revised form 10.06.26.
Accepted for publication 31.08.26.

**И. М. Казамбаев[1], А. Д. Мехтиев[2],*
У. К. Жалмагамбетова[3], Н. Н. Қылышқожа[4]
[1,2]С. Сейфуллин атындағы Қазақ агротехникалық зерттеу университеті, Қазақстан Республикасы, Астана қ.;
[1]Astana IT University, Қазақстан Республикасы, Астана қ.;
[2]Әбілқас Сағынов атындағы Қарағанды техникалық университеті, Қазақстан Республикасы, Қарағанды қ.;
[3]Торайғыров университеті, Қазақстан Республикасы, Павлодар қ.;
[4]Падова университетінің, Италия Республикасы, Венето.

10.06.26 ж. баспаға түсті.
10.06.26 ж. түзетулерімен түсті.
31.08.26 ж. басып шығаруға қабылданды.

ТАЛШЫҚ-ОПТИКАЛЫҚ МОНИТОРИНГ ЖҮЙЕСІНІҢ МОДЕЛІН ӘЗІРЛЕУ

Қазіргі уақытта электр энергиясына сұраныстың артуына байланысты энергиямен жабдықтау жүйесінің барлық компоненттері Қазақстан Республикасының өнеркәсібінде маңызды рөл атқарады. Бұл мақалада қуат кабелінің техникалық жағдайын бақылаудың негізгі шешімдері қарастырылады. Тұтастықты бақылаудың ең дәл шешімдерінің бірі–рефлектометрге негізделген талшықты-оптикалық бақылау жүйесі. Бұл жұмыстың мақсаты–OTDR негізінде талшықты-оптикалық жүйенің моделін жасау. Модельдеу үшін бастапқы деректер берілді, негізгі физикалық параметрлер анықталды. Негізгі оқиғаларға арналған математикалық өрнектер рәсімделді, атап айтқанда діріл, созылу, иілу, қызып кету, қосылыс ақаулары, соққы әсерлері және механикалық зақымданулар. Нәтижелердің дұрыстығына қол жеткізу мақсатында қосымша ақ Гаусс шуы, дақ–шу енгізілді. Іске асыру барысында оптикалық сигналды сүзудің бірнеше әдісі қарастырылды және салыстырылды. Ұсынылғандардың ішінде ең тиімдісі-толқын әдісі және функцияны одан әрі интеграциялаумен Фурье қатарына ыдыратуға негізделген әдіс. Нәтижесінде оптикалық талшықтың созылуы, қызуы, қысылуы аз әсер ететін оқиғалар екені анықталды. Өз кезегінде, әзірленген бағдарлама сезімталдықты арттыру мақсатында құбылыстарды зерттеу үшін сигналды масштабтауға мүмкіндік береді.

Кілтті сөздер: математикалық модель, талшықты-оптикалық датчик, OTDR, мониторинг жүйесі, күштік кабель.

**И. М. Казамбаев[1], А. Д. Мехтиев[2],*
У. К. Жалмагамбетова[3], Н. Н. Қылышқожа[5]
[1,2]Казахский агротехнический исследовательский университет
имени С. Сейфуллина, Республика Казахстан, г. Астана;
[1]Astana IT University, Республика Казахстан, г. Астана;
[2]Карагандинский технический университет
имени Абылкаса Сагинова, Республика Казахстан, г. Караганда;
[3]Торайгыров университет, Республика Казахстан, г. Павлодар;
[4]Университет Падовы,Итальянская Республика, Венето.

Поступило в редакцию 10.06.26.
Поступило с исправлениями 10.06.26.
Принято в печать 31.08.26.

РАЗРАБОТКА МОДЕЛИ ВОЛОКОННО-ОПТИЧЕСКОЙ СИСТЕМЫ МОНИТОРИНГА

В настоящее время в связи с повышенным спросом на электроэнергию, все компоненты системы энергоснабжения играют важную роль в промышленности Республики Казахстан. В данной статье рассматриваются основные решения по мониторингу технического состояния силового кабеля. Одним из самых точных решений по контролю целостности является волоконно-оптическая система мониторинга на основе рефлектометра. Целью данной работы является разработка модели волоконно-оптической системы на основе OTDR. Были заданы исходные данные для моделирования, определены основные физические параметры. Были формализованы математические выражения для основных событий, а именно вибрации, растяжения, перегиба, перегрева, дефектов соединений, ударных воздействий и механических повреждений. В целях достижения достоверности результатов были дополнительно введены белый гауссовый шум, спекл-шум. В ходе реализации были рассмотрены и сравнены несколько способов для фильтрации оптического сигнала. Среди всех предложенных наиболее эффективными являются метод Вейвлет и метод на основе разложения функции в ряд Фурье с дальнейшим интегрированием. В результате было выявлено, что растяжение, нагрев, сжатие оптического волокна являются слабозначимыми событиями. В свою очередь разработанная программа позволяет масштабировать сигнал для исследования явлений в целях повышения чувствительности.

Ключевые слова: математическая модель, волоконно-оптический датчик, OTDR, система мониторинга, силовой кабель.

Теруге 07.09.2026 ж. жіберілді. Басуға 30.09.2026 ж. қол қойылды.
Электронды баспа
19,0 Mb RAM
Шартты баспа табағы 34,4. Таралымы 300 дана. Бағасы келісім бойынша.
Компьютерде беттеген: Шукитова А. Б.
Корректор: А. Р. Омарова, Д. А. Кожас
Тапсырыс № 4601

Сдано в набор 07.09.2026 г. Подписано в печать 30.09.2026 г.
Электронное издание
19,0 Mb RAM
Усл. печ. л. 34,4. Тираж 300 экз. Цена договорная.
Компьютерная верстка: Шукитова А. Б.
Корректор: А. Р. Омарова, Д. А. Кожас
Заказ № 4601

«Toraighyrov University» баспасынан басылып шығарылған
Торайғыров университеті
140008, Павлодар қ., Ломов к., 64, 137 каб.

«Toraighyrov University» баспасы
Торайғыров университеті
140008, Павлодар қ., Ломов к., 64, 137 каб.
67-36-69
E-mail: kereku@tou.edu.kz
www.vestnik-energy.tou.edu.kz