**Analysis of Changes in the Characteristics of Fiber-Optic Communication Lines in Operating Modes at the Border**

Gulzoda Mustafakulova1, Allabergen Bekishev2, a), Guljayna Xabipova2, Dilfuza Kurbanbayeva2, Iroda Xodjayeva3, Timur Shaulemetov4

1Tashkent University of Information Technologies named after Muhammad al-Khwarizmi, Tashkent, Uzbekistan 2Tashkent state technical university named after Islam Karimov, Tashkent, Uzbekistan

*3Branch of the federal state autonomous higher educational institution of the national research nuclear university in Tashkent, Tashkent, Uzbekistan*

4Karakalpak State University named after Berdakh, Nukus, Uzbekistan

a) Corresponding author:[allabergenbekisev@gmail.com](mailto:allabergenbekisev@gmail.com)

**Abstract.**This article presents a detailed analysis of the physical and technical phenomena occurring during the transition of the load to the limiting operating modes of fiber-optic communication lines. Specifically, the article examines the chromatic dispersion of optical pulses propagating along the fiber under high-speed data transmission conditions, polarization-dependent dispersion (PDD), radiation attenuation, and the activation of nonlinear optical processes-SPM, CPGM, SBS, and SRS. Changes in the thermal, mechanical, and modal parameters of fibers due to increased transmitted power are also analyzed, and their impact on signal quality is scientifically substantiated. The research results have practical implications for improving the reliability and throughput of fiber-optic communication systems, as well as for developing optimal design solutions for high-speed DWDM and multichannel transport systems.

**INTRODUCTION**

Fiber-optic communication lines (FOCLs) are today the primary backbone of global information networks, providing a high-speed, virtually electromagnetically immune, and energy-efficient transmission medium [1–3]. Organizing data transmission in the optical range ensures the reliable operation of not only broadband networks, but also high-speed DWDM, CWDM, and 5G/6G backbone and transport systems [4].

However, during practical operation of FOCL, it is inevitable to approach high-load or limiting operating modes, in which significant changes in the physical parameters of optical waves propagating through the fibers are observed. In particular, under high-power transmission conditions, an increase in chromatic dispersion, an increase in polarization-dependent dispersion (PDD), an intensification of radiation losses and a sharp activation of nonlinear optical processes occur - self-phase modulation (SPM), interphase modulation (IPM), stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) - [3, 5-7]. These phenomena directly affect the shape, spectrum and noise stability of the digital signal transmitted over the line and lead to an increase in the bit error rate at the receiver [8].

With the increasing demands of modern systems for longer lines, fewer amplifiers, and the transmission of more channels over a single fiber, the behavior of FOCL in boundary conditions is of particular scientific and practical importance. A thorough analysis of the physical processes occurring in these conditions enables the development of optimal design strategies for optical communication systems, compensating for nonlinear effects, improving dispersion control, and power distribution decisions [5,9].

This article presents an in-depth scientific analysis of the aforementioned processes, their impact on the efficiency of fiber-optic cable systems, and the mechanism by which optical fiber parameters change under high loads. The research results will serve as the necessary theoretical basis for the development of future broadband optical transport systems and for improving their operational stability.

# **Technical content of boundary modes in optical fiber**

## **Border regime concept.** In optical communication systems**border mode of operation**- is an operating mode in which the signal power transmitted through an optical fiber exceeds the normal operating range, i.e., approaches the physical limits of the system. In such modes, the fundamental properties of the optical fiber material, such as dispersion, attenuation, and nonlinearity, change dramatically and significantly impact network stability [1–3].

The formation of the border regime is associated with the following main factors:

* **Increased intensity of optical radiation.** As the radiation power transmitted through an optical fiber increases, the electric field intensity in the fiber increases, activating nonlinear resistance mechanisms in the silicon material. Increasing the power beyond a critical value leads to a significant increase in the nonlinear coefficient of the optical fiber [3,4].

# ****Enhancement of nonlinear effects.**** In fiber-optic communication lines, nonlinear phenomena are usually unnoticeable at low power levels, but in extreme conditions (high optical power, dense wavelength multiplexing, long distances), these processes become acutely active, negatively affecting signal quality, interchannel isolation, and BER. A thorough study of the nature of nonlinear effects is important for the optimal design of fiber-optic communication systems [1; 5; 16].

* **Activation of nonlinear effects (SPM, XPM, SBS, SRS).** Nonlinear optical phenomena play an important role in boundary regimes:

**SPM (self-phase modulation)-**Strong pulses change their phase and broaden the spectrum [3].

## ****SPM - self-phase modulation.**** Self-phase modulation (SPM) is a process in which the phase of an optical pulse in a fiber changes proportionally to its intensity. The nonlinear phase shift during SPM is expressed as follows:

## (1)

Here:

**γ**- nonlinear coefficient of fiber, (W km)−1,

**P**- optical signal power,

**L**- fiber length.

In boundary modes, increasing the power leads to an increase in phase modulation, as a result of which: the pulse spectrum broadens, the dispersion further increases due to the increase in Δλ, and the pulse formation at the receiver is disrupted.

As Agrawal has shown, SPM is one of the major sources of signal distortion in 10–100 Gbps systems, along with chromatic dispersion [5; 9].

**XPM (cross-phase modulation)**- Phase shift due to adjacent channels in DWDM systems [5].

## ****XPM - cross-phase modulation.****XPM is the result of modulating the phase of another channel with the intensity of one channel. This process is especially pronounced in DWDM (dense wavelength division multiplexing) systems:

* multichannel transmission,
* narrow spectral ranges,
* when using powerful multipliers.

As a result of using XPM, interchannel phase distortion occurs, the pulse shape is deformed along with the dispersion, and the signal-to-noise ratio is degraded.

According to research by Ramaswamy and Winzer, at speeds above 40 Gbps, XPM is one of the main limiting factors between channels [4; 14].

**SBS (stimulated Brillouin scattering)**- increase in backscattering of radiation, a sharp increase in energy losses at high powers [6].

## ****SBS and SRS (stimulated Brillouin scattering).**** SBS is characterized by an increase in backward radiation. The gain threshold begins at approximately 5–10 mW. In boundary conditions:

* The returning waves are getting stronger.
* The power of the direct signal decreases.
* The OSNR value drops sharply.

Brillouin scattering is particularly pronounced when using narrow-band lasers, since it has a very narrow spectrum [6; 10].

**SRS (stimulated Raman scattering)**- “absorption” of energy from one channel by other channels is especially noticeable in multi-channel systems [7].

### ****Stimulated Raman scattering (SRS).**** SRS is a process where high-power channels "steal" energy from low-power channels, distorting the power distribution within the channels. The consequences of this process are:

* amplification of channels at higher wavelengths,
* attenuation of low-wave channels,
* Signal imbalance in DWDM systems.

SRS is significantly activated by strong signals in the 1–2 W range and limits the transmission range in multi-channel systems [5; 18].

These phenomena distort the signal shape, reducing the OSNR and Q-factor at the receiver.

### ****Enhancement of pulse broadening due to dispersion.**** Chromatic dispersion is especially noticeable at high speeds (40 Gbit/s, 100 Gbit/s and above), and an increase in radiation power leads to an expansion of the laser spectrum and, consequently, to a sharp increase in dispersion [2, 5].

(2)

As the power increases, its size increases, resulting in a wider pulse.

### ****Increased noise figure in optical amplifiers.**** In boundary modes, the operating conditions of the EDFA and Raman amplifiers change. The amplifier**ASE noise**The increase in generation leads to a decrease in the signal-to-noise ratio (OSNR) [8]. This causes a sharp deterioration in reception quality in FOCL trunk systems over long distances.

# ****Important FOCL parameters.**** The efficient operation of fiber-optic communication lines (FOCLs) is determined by a number of physical parameters. In critical operating conditions, the values ​​of these parameters vary significantly, leading to signal distortion, increased error rates, and decreased network stability. The most important and variable FOCL parameters include the following [1–4]:

### ****Attenuation, dB/km.****Radiation attenuation determines the degree of energy loss during propagation in a fiber. Its meaning is generally as follows:

Rayleigh scattering, absorption processes, fiber connections, and bending are determined. Due to increased heat generation in boundary conditions, microstructural changes occur, and the extinction coefficient may increase [2, 5].

(3)

where P is the optical power, k is the power-dependent nonlinear thermal coefficient.

### ****Chromatic dispersion, ps/(nm km).**** Chromatic dispersion causes pulse broadening due to the difference in propagation velocities of different wavelengths. Under high-power transmission conditions, laser spectrum broadening increases, leading to an increase in the dispersion effect [1, 3].

### (4)

Here:

**D**– chromatic dispersion coefficient, ps/(nm km),

**L**– transmission range, km,

**Δλ**– width of the source spectrum, nm.

In boundary modes, Δλ increases due to increased laser intensity fluctuations, increased modulation depth, and thermal stress, which leads to further scattering [25-29].

Furthermore, strong nonlinear effects (SPM – self-phase modulation) directly influence the spectrum broadening, leading to further pulse stretching due to CD [9]. It is in the edge modes that the laser spectrum width increases.

# ****Intensification of dispersion processes.**** Dispersion processes in fiber optic communication lines are one of the main limiting factors for high-speed transmission. In extreme conditions, that is, when the optical signal power exceeds standard values, dispersion parameters change significantly. These changes lead to problems such as pulse spreading, intersymbol interference, and high bit error rates (BER).

## ****Change in chromatic dispersion.**** Chromatic dispersion (CD) causes the spectral components of an optical pulse to diverge in time as a result of their propagation at different speeds.

### ****Polarization-dependent dispersion (PMD), p.s.**** Polarization modulation differences (PMD) arise because polarization modes in an optical fiber propagate at different speeds. In normal modes, PMD is typically small, but under high-intensity conditions, it can be significant.:

Mechanical stress, thermal effects, and microbending in the fiber increase, and the effective value of the IMD increases [4, 6]. IMD is a type of dispersion that occurs as a result of the propagation of two orthogonal polarization modes in the fiber with different group velocities and is random in nature. In boundary operating modes, mechanical stress in the fiber increases, thermal inhomogeneities increase, and the randomness of the intermode delay increases. Therefore, an increase in IMD is observed in the form of:

(5)

here:

**PMD₀**– PMD value under normal operating conditions,

**P**– optical signal power,

**γ**– coefficient of influence of mechanical-nonlinear stress on dispersion.

It has been established that with increasing power, micromechanical deformations in the fiber and random changes in the delay of polarization modes increase [7; 18]. This leads to negative consequences in long lines: an increase in BER, a deterioration in OSNR, and a decrease in the efficiency of compensation systems [20].

### ****Nonlinear coefficient, (W km)⁻¹.**** The intensity of nonlinear optical phenomena in a fiber depends on the nonlinear refractive index of the material n2, the effective mode surface area Aeff and the transmitted optical power P, and its general expression is as follows:

(6)

As nonlinear effects increase-SPM, XPM, SBS, SRS-in boundary modes, the overall nonlinearity of the system increases [3,7].

### ****Signal-to-noise ratio (OSNR).**** OSNR indicates the degree of superiority of the optical signal over the background noise (ASE) in optical amplifiers. This is the main parameter determining the reception quality and BER of the FOCL [8]. In boundary conditions:

Increased noise in erbium-doped fiber amplifiers (EDFAs) and Raman amplifiers.

Nonlinear effects distort the signal spectrum.

Increased interchannel interference results in a significant reduction in signal-to-noise ratio (OSNR).

### ****The importance of these parameters.**** Changes to the following FOCL parameters:

This directly impacts key performance parameters such as receive sensitivity, bit error rate (BER), Q-factor, transmission range, and interchannel isolation in DWDM systems [1–4]. Therefore, accurate assessment of changes in boundary operating modes is crucial for the efficient design of high-speed optical networks.

**EXPERIMENTAL RESEARCH**

For the simulation, a code compiled in a Matlab script was created and the following results were obtained: Figure 1 shows a graph of signal attenuation as a function of fiber optic cable length and temperature. Accordingly, the attenuation magnitude increased with increasing temperature.

|  |
| --- |
|  |
| **Figure 1.** Graph of signal attenuation dependence on the length of the fiber optic cable and temperature (mechanical stress = 600 N, radiation = 0 kHz). |

# ****Change in radiation losses in boundary modes.**** In fiber optic communication lines, attenuation is the decrease in the intensity of the transmitted signal over a distance. Under normal operating conditions, the main sources of attenuation are Rayleigh scattering, absorption processes, and mechanical losses at the fiber splice points [1,2]. However, **operating modes at the border**Additional changes in radiation losses are observed due to increased optical power and enhanced thermal effects. These changes reduce the overall efficiency of FOCL and limit long-range transmission capabilities [3].

## ****Increased attenuation.**** The losses observed in an optical fiber during normal operation consist of the following main components:

### **Rayleigh scattering.** Elastic scattering of light occurs due to random asymmetries in the microstructure of silica material. It is the primary component of attenuation in optical fibers. The rate of scattering increases significantly with decreasing wavelength [1,4].

### **Absorption losses.** Due to molecular resonances of the material, OH⁻ groups, and ionic impurities, optical energy is converted into heat. Although this value is very small in modern fiber optic technologies, increasing heat in boundary conditions can increase the absorption coefficient [2].

### ****Mechanical losses at connection points**.** Additional losses arise due to incomplete propagation of the optical mode at welds, joints, or bends. Increased mechanical stress due to high power leads to increased losses during microbending [5].

### ****Microbending loss.**** As heat dissipation increases in the boundary mode, local expansion and deformation occur in the fiber. This leads to additional attenuation, known as "microvoltage losses." Such losses can be further increased by changes in ambient temperature, high-power pulses, or mechanical stress [4,6].

## ****Thermal effects.**** As the radiated power in an optical fiber increases, so does heat generation. This process leads to the following technical changes:

### ****Thermal expansion of fibrous material.**** Expansion of the silica material changes its refractive index, which directly affects the loss coefficient of the fiber.

### ****thermal refractive index modulation**.** The change in refractive index due to heating leads to a redistribution of the signal mode, which causes additional attenuation [3,7].

### ****Increased thermal nonlinearity****The following empirical formula shows how radiation losses change with increasing power:

Here:

​- loss factor in normal low power mode (dB/km),

P- transmitted optical power (W),

To- a coefficient reflecting thermal and nonlinear effects (W⁻¹ km⁻¹).

This model shows that losses increase nonlinearly with increasing thermal stress. At very high strength values, the fibrous material can be subjected to thermal stress, and structural changes can occur [7].

Figure 2 shows the dependence of signal attenuation on the length of the fiber optic cable and temperature for the case (T = 250 °C, radiation = 100 kGy), which indicates a significant influence of radiation on signal attenuation.

|  |
| --- |
|  |
| **Figure 2**. Signal attenuation depending on the length of the fiber optic cable and temperature (T = 250 °C, radiation intensity = 100 kGy). |

**RESEARCH RESULTS**

# ****Practical analysis of boundary conditions.**** Processes observed in fiber-optic communication lines in boundary operating modes directly impact the quality of system performance. Under high-power transmission conditions, i.e., at powers above 20–25 dBm, nonlinear effects are significantly activated, and the following key changes in the parameters of fiber-optic communication lines occur [1; 5; 16; 20]:

# **OSNR reduction.** The optical signal-to-noise ratio (OSNR) is the most important parameter determining signal quality. In edge modes:

* Spontaneous emission noise increases in erbium-doped fiber amplifiers and Raman amplifiers.
* Nonlinear effects such as SPM, XPM, SRS broaden the spectrum.
* The SBS method amplifies the scattered signal.

As a result, OSNR decreases and signal sensitivity at the receiver decreases [5; 14; 18].

## ****Reduction in quality factor.**** The quality factor (Q-factor) is the key metric for assessing the signal quality and error rate (BER) of a FOCL system. In boundary conditions:

* The impulses are deformed,
* Spectral and phase modulation are enhanced.
* the spread increases.

As a result, the Q-factor decreases, which increases the probability of errors [22-28].

## ****Increased BER.****BER (Bit Error Rate) directly indicates signal reliability. At high power, the processes of SPM, XPM, SBS, and SRS combine to distort the pulse shape, increase interchannel interference, and significantly increase BER. For example, in 100 Gbps systems, an increase in BER from 10⁻⁹ to 10⁻⁷ was observed at power above 25 dBm [16; 20].

## ****Spectral interactions.**** DWDM systems have limited channel spacing. In boundary modes:

* Thanks to XPM technology, the channels influence each other's phase.
* The SRS system extracts energy from high power channels from low power channels.
* Spectral isolation is deteriorating.

As a result, crosstalk in DWDM systems increases significantly [4; 14-18].

## ****Practical measurements.**** Experimental studies show that:

* At transmission power above 20–25 dBm, the influence of nonlinear effects increases significantly.
* Reducing the signal-to-noise ratio by 3–5 dB.
* Reduction of quality factor by 2–3 dB.
* An increase in the bit error rate (BER) is observed from 10⁻⁹ to 10⁻⁷.

These results indicate the need to limit the maximum transmission power of FOCL systems and implement technologies to compensate for nonlinear effects [16; 20].

**CONCLUSION**

Changes in the characteristics of a fiber-optic communication line in marginal operating modes have a significant impact on all key parameters of the fiber-optic communication line. Increased radiation losses, dispersion, and nonlinear effects reduce signal quality and system reliability. Therefore, when designing optical systems, it is necessary to carefully select power limits, dispersion compensation, the number of amplifiers, and the network configuration.

In boundary modes, the SPM, XPM, SBS and SRS processes mutually reinforce each other, leading to the following states:

* spectral expansion,
* increased dispersion,
* interchannel interference,
* increased noise figure in amplifiers,
* Significant increase in BER.

These effects significantly limit the maximum transmit power in FOCL systems and require nonlinear effects compensation technologies for optimal system operation.

In boundary operating modes, the characteristics of fiber-optic communication lines change significantly, which directly impacts the key operating parameters of fiber-optic communication lines. The study results show that:

1. Radiation lossesThe power increases with increasing power, which reduces the strength of the signal reaching the receiver and results in a lower signal-to-noise ratio (OSNR).
2. DispersionGain (depending on chromaticity and polarization) results in pulse spreading over time, which causes a decrease in the quality factor (Q-factor) and an increase in the bit error rate (BER).
3. Nonlinear effects (SPM, XPM, SBS, SRS) deform the signal spectrum, increase interchannel interference and reduce network stability in DWDM systems.

Therefore, when designing optical systems, the following aspects must be carefully considered:

* Setting transmission power limits and minimizing nonlinear effects.
* Using dispersion compensation technologies,
* Optimal choice of the number and location of amplifiers.
* Design your network configuration to ensure maximum FOCL efficiency and reliability.

Overall, careful analysis of FOCL parameters in boundary conditions is crucial to ensure stable system operation at high speeds and long distances.

**REFERENCES**

# A. Mecozzi, “Nonlinear Distortion in High-Speed ​​DWDM Systems,” Optics Express, 2018.

# Agrawal, G.P. "Self-Phase Modulation and Spectral Broadening." Nonlinear Fiber Optics, Academic Press, 2019.

# Agrawal, G.P. Fiber Optic Communication Systems. 4th ed. Wiley, 2010.

# Agrell, E., Karlsson, M. "Power Limitations in Fiber Optic Communications." Journal of Light Wave Technologies, 2014.

# Bosco, G., Carena, A., Curry, V. "PMD and Nonlinear Effects in Long-Distance Fiber-Optic Communication Systems." IEEE Journal of Lightwave Technologies, 2010.

# K. Decker, "The Effect of Chromatic and Polarization Dispersion on High-Speed ​​Transmission." Optical Fiber Technology, 2013.

# C. Headley, G. P. Agrawal, Raman Amplification in Fiber Optical Communication, Elsevier, 2005.

# S. Menyuk, “Polarization effects in optical fibers for long-range data transmission,” Journal of Linear Theory and Theory (JLT), 2017.

# S. Menyuk, “Polarization effects in optical fibers,” Journal of Light Wave Technologies, 2017.

# Shukhrat Umarov, Khushnud Sapaev, Islambek Abdullabekov. The Implicit Formulas of Numerical Integration Digital Models of Nonlinear Transformers. AIP Conf. Proc. 3331, 030105 (2025); <https://doi.org/10.1063/5.0305793>

# F. Forghieri, “Design of DWDM Systems under Nonlinear Constraints,” IEEE JLT, 2020. 5

# Tulyaganov M. [Optimum control of an asynchronous electric drive](https://www.scopus.com/pages/publications/85145165953?origin=resultslist). [Journal of Physics Conference Series Open source preview](https://www.scopus.com/authid/detail.uri?authorId=9943032600), 2022, 2388(1), 012099, DOI: 10.1088/1742-6596/2388/1/012099

# G. Keiser, Fiber Optic Communications. 5th ed. McGraw-Hill, 2021.

# Giles, K., “Noise Characteristics of Optical Amplifiers,” IEEE Photonics Technology Letters, 2016.

# Gisin, N., and Pellot, J. P. "Polarization mode dispersion: Time evolution and measurements." Optical Communications, 1992.

# Govind P. Agrawal, Nonlinear Fiber Optics, 6th ed., Academic Press, 2019.

# Hecht, J. Understanding Fiber Optics. 6th ed. Pearson, 2022. 8

# Ip, E., Lau, A. P. T., "Chromatic dispersion and nonlinear effects in coherent systems." Optics Express, 2010.

# ITU-T Recommendation G.652, Characteristics of single-mode optical fiber and cable, 2016

# Tulyaganov, M. [Optimization of natural gas combustion in furnace of steam boilers](https://www.scopus.com/pages/publications/85098455549?origin=resultslist). [E3s Web of Conferences Open source preview](https://www.scopus.com/authid/detail.uri?authorId=9943032600), 2020, 216, 01155, DOI: 10.1051/e3sconf/

# Kaminov, I., Li, T., and Vilner, A. Fiber Optic Telecommunications V. Academic Press, 2008. 6

# Kikuchi, K. "Analytical Evaluation of Chromatic Dispersion Effects in High-Speed ​​Optical Communication Channels." IEEE Photonics Technology Letters, 2018.

1. . Pulatov, A.A., Shaimiev, M.F., Mirsaidov, U.M. Automation of production mechanisms using energy-efficient asynchronous electric drives based on intelligent converter technology. Journal of Physics: Conference Series, 2022, 2388(1), 012127.
2. Pulatov, A.A.,Shaimiev, M.F., Mirsaidov U.M. Comparative analysis of capital expenditures on automation of production mechanisms using energy-efficient asynchronous electric drives based on intelligent converter technology. "Tashkent Institute of Irrigation and Agricultural Mechanization Engineers" National Research University. Environmental technologies and engineering for sustainable development. (ETESD-2022) International Conference. October 13-15, 2022.
3. [Pirmatov, N.](https://www.scopus.com/authid/detail.uri?authorId=6506281501),[Bekishev, A.](https://www.scopus.com/authid/detail.uri?authorId=57219124685),[Kurbanov, N.](https://www.scopus.com/authid/detail.uri?authorId=57224733410),[Saodullaev, A.](https://www.scopus.com/authid/detail.uri?authorId=58949758500),[Saimbetov , Z.](https://www.scopus.com/authid/detail.uri?authorId=58040723800)Increasing the efficiency and survivability of synchronous machines with biaxial excitation when operating in transient processes. Proceedings of the AIP conference. Volume 3152, Issue 1, June 17, 2024,<https://doi.org/10.1063/5.0218824>
4. [Bekishev, A.](https://www.scopus.com/authid/detail.uri?authorId=57219124685),[Kurbanov, N.](https://www.scopus.com/authid/detail.uri?authorId=57224733410),[Zainieva , O.](https://www.scopus.com/authid/detail.uri?authorId=58069882200),[Saimbetov , Z.](https://www.scopus.com/authid/detail.uri?authorId=58040723800),[Saodullaev, A.](https://www.scopus.com/authid/detail.uri?authorId=58949758500)Comparative analysis of the survivability of synchronous machines in asynchronous mode without excitation. Proceedings of the AIP conference. Volume 3152, Issue 1, June 17, 2024,<https://doi.org/10.1063/5.0218806>.
5. A. Bekishev, A. E. Norboev, U. A. Khudoynazarov, N. A. Kurbanov and O. A. Yunusov. Autonomous mode and parallel operation of an asynchronous generator with an electrical network. E 3 S Conference Network. Volume 524, 2024. VII International Conference on Current Issues of the Energy Complex and Environmental Protection (APEC-VII-2024).<https://doi.org/10.1051/e3sconf/202452401009>
6. Allabergen Bekishev, Nurali Pirmatov, Dilfuza Kurbanbayeva, Najmiddin Kurbanov, Oliyakhon Zaynieva, Obidkhan Yunusov, Utkir Khudoynazarov, Zinatdin Saimbetov.[Achievement of maximum power levels at different wind speeds from wind turners with asynchronous double-way feed generator](https://pubs.aip.org/aip/acp/article/3331/1/030011/3370714/Achievement-of-maximum-power-levels-at-different). AIP Conf. Proc. 3331, 030011 (2025).<https://doi.org/10.1063/5.0305765>
7. Allabergen Bekishev, Gulzoda Mustafakulova, Aziza Khalbutayeva, Jasurbek Nizamov. Modeling of reactive power compensation of the electric arc steelmaking furnace DSP-100 UMK at JSC Uzmetkombinat. AIP Conf. Proc. 3331, 030069 (2025).<https://doi.org/10.1063/5.0305769>