Energy Reports 11 (2024) 5227–5234

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Review article

Review of the usage of fiber optic technologies in electrical power engineering and a development outline in Poland

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ARTICLE INFO

Keywords:
Fiber optic
Fiber optic sensors
Electric power
Electric transmission lines
Transmission lines
Fiber optic networks

ABSTRACT

This article provides an overview of fiber optic technology applications in the broad field of electrical power engineering. Various constructions of power transmission lines integrated with optical fibers are described. The article presents the applications of optical fibers in electrical power engineering beyond typical digital data transmission, such as detecting line faults, monitoring the overheating of components, and powering devices. Subsequent sections detail the inception of the first fiber optic networks in Poland and their development over the years, including their reliance on power infrastructure. In the conclusion, the authors address the prospects for further development and legal regulatory issues.

1. Introduction

The broad field of energy, particularly electric power systems, constitutes an indispensable element of the contemporary world. The widespread electrification has established global power transmission lines, ranging from low to high voltages, as a standard practice in moderately and highly developed nations. Increasingly stringent technical requirements for electric power grids, coupled with heightened electricity demand, have prompted the gradual modernization, replacement, or augmentation of power transmission lines as needed. Consequently, the integration of novel technologies into the realm of electric power transmission lines is relatively straightforward, while concurrently minimizing additional financial and temporal investments. The invention of optical fiber and its utilization for signal transmission marked a significant breakthrough in the IT and data transmission industry. One of the earliest practical applications of optical fibers was introduced by NASA in the late 1960s. In 1977, the BICC company patented the integration of optical fiber technology with grounding wires, known as OPGW (Moore, 1997), thereby laying the foundation for the current IEEE 1138-2021 standard (previously IEEE 1138-2009). The basis for the development of the OPGW standard was the patent filed by BICC Ltd. in 1977 in UK (Anon, 1977). Practical utilization of OPGW occurred in the early 1980s. The technology of optical data transmission (fiber optics) in electrical transmission lines has been in development for over 40 years, resulting in numerous standards and solutions that are still in use today (Nanda and Kothari, 1995). In Poland, some of the earliest implementations of these technologies were carried out by the Tel-Energo company (now Exatel). This infrastructure was used to launch the POL-34 nationwide network in 1997, connecting major academic and research institutions. Further modernizations and the development of POL-34 served as the foundation for the PIONIER academic network, which is still in use today. The following section discusses the applications of optical fibers in various structures of electrical transmission lines (including for data transmission purposes and as sensors). Section 3 presents several solutions related to the use of optical fibers as components of measurement systems (e.g., sensors and power supply). Section 4 outlines the development of optical-fiber-equipped electrical transmission lines in Poland. Section 5 outlines prospects and possibilities for further development. Section 6 provides a summary.

2. Optical fiber technology in power engineering

The use of optical fibers in conjunction with power transmission lines has been employed and developed for several decades. Numerous standards and solutions have emerged and are widely adopted (Moore, 1997; Nanda and Kothari, 1995). Special fiber optic bundles encompassing anywhere from a few to even several dozen optical fibers are commonplace, typically organized into one to four bundles. These cables (comprising fiber optic bundles) can serve one of three primary functions:

- Self-supporting cables made of non-conductive (or insulated) material;

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https://doi.org/10.1016/j.egyr.2024.04.068
Received 27 October 2023; Received in revised form 5 April 2024; Accepted 30 April 2024
Available online 14 May 2024
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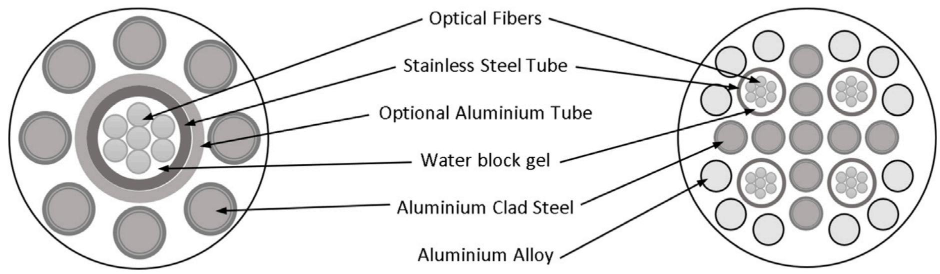

Fig. 1. Central loose (left) and Multi lose (right) tube type.

- Phase cables;
- Lightning protection cables.

In the following subsections, several technologies representing the most frequently encountered solutions are presented.

2.1. Optical Ground Wire (OPGW)

OPGW, which stands for Optical Ground Wire, refers to overhead protective (grounding) cables containing optical fibers (Pardiñas et al.). These cables are utilized in high-voltage power transmission lines, typically with voltages starting at 110 kV. The cable is composed almost entirely of metal components, either aluminum or steel. Due to their intended use OPGW cables are exposed to high short-circuit currents and atmospheric discharges. Consequently, it necessitates adjusting the parameters of the transmission lines to accommodate the thermal durability of the fiber optic bundles. Simultaneously, when designing the cable, the fiber optic bundles cannot be placed on the external side of the transmission line. Two fundamental OPGW solutions are utilized, where:

- There is one fiber optic bundle placed within a single core of the cable in the form of a metal tube. External layers consist of metal (twisted) wires arranged around the core.
- There are several fiber optic bundles – the core of the cable is a metal wire, and the tubes (multiple) containing fiber optic bundles are positioned around the core (sometimes alternating with wires). The outer layer also comprises metal (twisted) wires.

Internal structures of the OPGW cable for both cases are shown in Fig. 1. OPGW cables are characterized by their high durability and reliability. It is also worth noting that they can be used in place of standard AFL grounding cables, without interfering with supporting structures (poles).

2.2. All-Dielectric Self Supporting (ADSS)

ADSS cables are fiber optic cables constructed solely from non-metallic (non-conductive) materials. ADSS cables exhibit low susceptibility to thermal expansion. Simultaneously, these cables are prone to stretching under additional loads, such as snow or ice. Therefore, the utilization of ADSS cables necessitates additional technical requirements for supporting elements (poles) to be considered. The core of such a cable is composed of Fiber Reinforced Polymer (FRP) composite. Surrounding the core are tubes containing fiber optic bundles, encapsulated within waterproof insulation. Surrounding this layer are Aramid Reinforcement Plastic (ARP) fibers, which ensure high cable strength. The outer insulation is typically made of High-Density Polyethylene (HDPE) material. A notable drawback of these cables is their susceptibility to surface micro-discharges (e.g., under high humidity conditions), which accelerates the deterioration of insulating layers. Consequently, ADSS cables are usually employed in low and medium voltage power transmission lines. Optionally, cables made of materials resistant to high electrical fields are available. In general, two types of ADSS cable interactions in high-voltage lines are distinguished (Kaiser, 2005; Dodd et al., 2003):

- tracking effect (dry banding, electrical arborescence) - refers to the destruction of the insulating dielectric by partial discharges on the surface and inside the material (with prolonged influence of high voltage).
- corona discharge (ionization of air surrounding a charged conductor) - this effect is quite common, but at low voltages it is practically imperceptible. Only at high voltages this effect is so intense that it has a destructive effect on various materials.

In addition to high humidity, higher air pollution also causes a greater destructive process of the mentioned effects (particles of “dirt” are trapped in condensing water). Protection against these activities can be achieved by using anti-tracking materials, usually selected according to guidelines:

- under the IEEE P1222 2011 standard,
- non-standard - prepared according to individual guidelines, on special order usually for worse working conditions.

One of the key suppliers of ADSS cables with anti-tracking protection is FONCS (Online, 2024t).

2.3. Optical Phase Conductor (OPPC)

OPPC is a self-supporting cable made of metal components. Structurally similar to OPGW cables, OPPC is designed to function as a phase power transmission line. OPPC cables are used in cases where the power distribution network lacks a grounding conductor, making the use of OPGW cables unfeasible. Technical specifications for OPPC cables meet the mechanical and electrical requirements associated with replacing phase power lines. An important drawback is the necessity of employing dedicated mounting and connection elements that support fiber optic bundles and fibers while simultaneously enabling work on high-voltage phase lines.

2.4. Optical Attached Cable (OPAC) - Sky Wrap

OPAC is a non-metallic cable associated with optical fibers and lacks a self-supporting structure. The absence of a self-supporting core or durable composite fibers significantly reduces the cost of implementing such cables. Typically, a phase or grounding cable is used as a supporting line, around which the OPAC cable is wrapped. Cable installation is performed using specialized remote-controlled robots that can be operated from the ground (eliminating the need for work at heights). This solution can be applied both to standard power transmission lines and to OPGW and OPPC cables. A significant advantage of these cables is their relatively low weight, allowing them to be used on transmission lines without the need for supporting structure modifications.

2.5. All-Dielectric Lashed Cable (ADL)

ADL is an optical fiber cable made of synthetic materials, structurally free of self-supporting elements. It closely resembles the OPAC standard, with the main difference lying in the method of attachment to the supporting line, which involves suspending it beneath the supporting cable and wrapping both cables with Kevlar tape.

2.6. Metallic Aerial Self Supporting (MASS)

MASS cables are self-supporting cables with fiber optic bundles, made of metal materials. They are structurally similar to OPGW cables. However, the key difference is that MASS cables do not serve as electrical or grounding conductors. The practical use of MASS cables is often contingent on financial considerations and technical conditions. They offer increased fiber optic capacity on a given line at a lower cost compared to OPGW, OPPC, or ADSS cables. MASS cables provide very high line strength.

The presented designs of optical fiber lines used in power transmission lines in power engineering are not the only ones available. However, other solutions are specialized (dedicated) and are therefore much less commonly employed.

2.7. Hybrid power fiber cable

Hybrid cables have fiber optic bundles for data transmission and copper or aluminum bundles to provide power (Online, 2024i). Fiber optics are usually one to four. Power conductors are two wires usually 12-22AWG. They are designed to simultaneously transmit data and provide DC power to devices (such as IP cameras). Unlike PoE, transmission speeds are much higher, so the cables can be used to connect critical network infrastructure. They come in indoor and outdoor versions (including underground).

These cables are not available in versions for medium and high AC voltages. Also, it is not recommended to use them for low-voltage AC, due to the lack of a PE protection wire (some manufacturers declare the possibility of ordering cables with three power bundles for low-voltage AC).

The key parameters of the presented power cables with embedded fiber optics (Lazaropoulos and Leligou, 2022; Vasileiou et al., 2004; Baoping et al., 2021; Ezeh and Ibe, 2013; Online, 2024e,u,k,c,j,d,a) are summarized in Table 1

3. Applications of optical fibers in power engineering (beyond data transmission)

Optical fibers can be employed not only for the conventional data transmission but also due to the specificity of their operation, they find widespread use in detecting changes in beam performance and alterations in technical parameters resulting from external factors (Chai et al., 2019). Several different measurement methods within the field of optical fiber technology are utilized:

- Fiber-Optic Interferometry (Wang and Fang, 2017);
- Fiber Bragg Grating (FBG) based on polimer (POF) (Litong et al., 2018; Zhang and Xiaoming, 2021) or silica (Litong et al., 2018; Oliveira et al., 2018);
- Distributed sensing technology (Distributed optical fiber sensing (Lu et al., 2019)).

The measurement capabilities vary, and below, we present the most commonly encountered solutions (Chai et al., 2019). N'cho and Fofana (2020) also provides a broader classification of solutions in which optical fibers are used as sensors (referred to as fiber optic sensors - FOS), and a schematic representation is depicted in Fig. 2.

3.1. Detection of overheating in power lines

The application of specialized optical fibers (with a crucial consideration for the maximum operating temperature) allows for the creation of a system to monitor the temperature of cable lines (DTS - Distributed Temperature Sensing) (Hartog, 2017). Such optical fibers exhibit changes in attenuation depending on the temperature of the fiber optic bundle itself. The temperature distribution can be reconstructed by measuring only a few locations of the spatial (García et al.,

Table 1
Summary of typical properties of cables with optic fibers.

Type of a cable	Properties
OPGW	– Installation on overhead transmission lines; – Sheathed in a metal jacket, typically aluminum or steel; – Designed with a central loose tube; – Engineered to withstand temperatures ranging from −40 °C to 85 °C; – Positioned predominantly atop high-voltage power lines; – Exhibits a complex structure contributing to relatively high production costs;
ADSS	– Installation on the side of transmission towers; – Typically sheathed in a layer of aramid yarn; – Utilize a tightly buffered design, with each fiber wrapped in a protective material; – Designed for temperatures typically ranging from −40 °C to 70 °C; – Self-supporting and installed on transmission and distribution towers and poles separately from the power lines; – Externally composed of two layers of sheath (aramid yarn and water blocking tape) to protect the inner fiber optic cable; – Wires are a completely independent communications network that may coexist with the power grid;
OPPC	– Comprised of multiple layers of metal foil, effectively preventing the spread of fire; – Predominantly utilized on lower-voltage power lines; – Structure is relatively simple, contributing to relatively low production costs; – Optical cables are housed within the wire, typically contained within a stainless steel tube filled with gel; – Self-supporting due to inner aluminum-clad steel conductors; – Replaces a phase conductor, implying that any maintenance activities affect the operations of the power grid;
OPAC	– Optic cables are located inside the wire, typically contained within a stainless steel tube filled with gel; – Replaces a phase conductor, implying that any maintenance activities affect the operations of the power grid and the communications network; – Self-supporting due to their inner aluminum-clad steel conductors; – Fiber optic cables that are small in size, flexible, and all-dielectric; – Water blocking tape (aramid yarn) and outer sheath surround an optic cable; – Has little impact on their mechanical and electrical performance of grid;
ADL	– Lightweight optical cable; – Used with automatic bundling and winding machines for quick installation; – Can be installed on phase lines without power failure; – Outer sheathing made of organic synthetic materials (unable to withstand high temperatures generated during line short circuit); – Aging problem of external sheathing material; – Installation requires special machinery;
MASS	– Metal structure (electrical corrosion issue easily solved through proper grounding treatment); – Central Stainless Steel loose tube design (center tube type); – Deployed on lines without ground wires, often installed without an outage; – Deployed in regions with high lightning activity; – Compact, lightweight solution with no electrical function; – Designed to provide a telecommunications path without interfering with existing power lines and infrastructure; – Completely self-supporting to meet sag and tension requirements (small size);

(continued on next page)

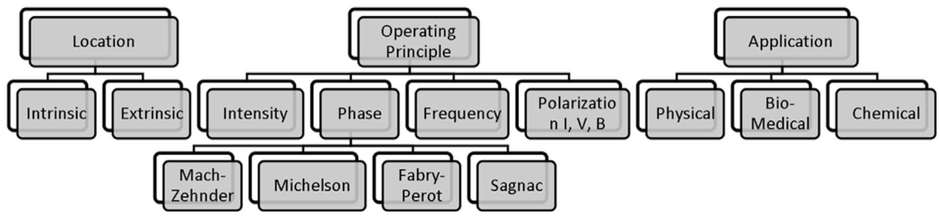

Fig. 2. Fiber optic sensors classification.
Source: N'cho and Fofana (2020).

Table 1 (*continued*).

Type of a cable	Properties
Hybrid Power Fiber Cable	– Reduces the number of required cables (only one cable to pull and manage); – Usually recommended for low-voltage DC power supply; – Custom cables are typically more expensive than single-media cables, with longer delivery periods; – Not as adaptable as fiber when technology changes; – Used to establish a flexible network environment (efficient, scalable, versatile); – A hybrid network topology requires more maintenance (usually several topologies interconnect within a hybrid);

2007). Currently, technologies are available that allow measurements with a spatial resolution of 1 m for cables over 10 km (Hausner et al., 2011; Online, 2024f). Temperature resolution can be as 0.1 °C (Hausner et al., 2011), but for distances of several kilometers it is usually about 0.5 °C (Online, 2024f) to 1 °C (Online, 2024s). Some equipment manufacturers even declare sensing resolution down to 0.01 °C (Online, 2024f) - presumably only for short distances. Monitoring such parameters must be carried out using dedicated measuring equipment, making this system reliant on specific instrumentation. Typically, control and monitoring can be performed remotely (online). The essence of this solution lies in the ability to monitor the actual temperature of power lines under current environmental conditions. At the same time, it enables dynamic adjustment of the line's load to the current demand and transmission capabilities or in emergency situations when the line is temporarily under increased load. This solution is also valuable for designing so-called Smart Grids. The DTS system can be applied to both overhead and underground lines. There are two basic temperature measurement technologies for optical fiber lines (Nazarathy et al., 1998):

- Optical Time Domain Reflectometry (OTDR);
- Optical Frequency Domain Reflectometry (OFDR).

Usually, DTS combines elements of both OTDR and OFDR technologies using Code Correlation (Nazarathy et al., 1998; Anon, 2004, 2007). DTS systems are most commonly used for OPPC phase lines (see Section 2.3), but they are occasionally encountered in OPGW lines (see Section 2.1).

3.2. Detection of transformer failures

In N'cho and Fofana (2020), the use of optical fibers for measuring parameters of network transformers is presented. Transformer damages primarily result from electrical and thermal stress. Verification can be performed by analyzing discharges, the presence of specific gases, or temperature anomalies. Selected parameters can be monitored using optical fibers. The article (N'cho and Fofana, 2020) provides information about monitoring the following parameters through optical fiber technology:

- Electrical parameters (Partial discharges, Breakdown voltage, Current, Voltage);
- Mechanical parameters (Winding deformation and vibration Sound);
- Thermal parameters (Temperature - similar to Section 3.1);
- Chemical parameters (Hydrogen, Acetylene, Methane, Moisture, Furfural, Oil level, Oil aging).

Partial discharges can be verified using sensors based on sensitive optical fiber interferometers. Prolonged discharges (e.g., due to insulation voids or bubbles in oil) are a typical assessment of potential transformer damage. Temperature and gas anomalies (the presence of H2) are also widely recognized as early signs of failure. Mechanical anomalies resulting from:

- Tension in transmission lines (galloping lines, icing);
- Tower structure stresses (torsional deformation, uneven loads);
- Ground conditions (soil) – landslides, foundation settling

can be monitored using optical fibers. The following subsection addresses the measurement of power line tensions using fiber optic sensors.

3.3. Detection of tensions (and damage) in power lines

An essential aspect of the proper functioning of power lines is the continuous monitoring of damage and changes in the fiber bundle's position or arrangement. Using specific optical fibers, it is possible to detect attenuation changes resulting from deformation (damage) of the line through the use of OTDR technology (Chai et al., 2019). This technology is employed to monitor the bundle's condition during work near transmission lines. It enables precise location of damage, thereby reducing the time required for line verification and repair. Also, coherent OFDR (Floris et al., 2021; Khadour and Waeytens, 2018; Online, 2024n) technology is widely used to detect defects in optical fibers. Commercial OCDR (polarization optimized white light interferometer) systems are also available to determine the point and level of distortion in a fiber (Online, 2024m). These technologies are constantly being modified and improved, information on the technologies mentioned is also collected in Zhu et al. (2023). Furthermore, detecting insulation damage that may cause incomplete discharges (Partial Discharge - PD) is possible through the use of technology employing fiber optic sensors.

In Drissi-Habti and Carvelli (2022), a prototype simulated project for analyzing and verifying underwater power line damage using "Fiber Optic Services" (FOS) is also presented. According to Drissi-Habti and Carvelli (2022), the amount of energy produced by wind farms in Europe around 2050 will range from 230–450 GW (currently only 20 GW). Between 2012 and 2019, approximately 90 underwater power line damages were documented, resulting in a total loss of approximately 350 million Euros (Drissi-Habti and Carvelli, 2022). Offshore wind farms pose additional challenges to the reliability of transmission lines. Even the cable laying process can significantly impact efficiency. Unfavorable environmental conditions (saltwater, pressure) further compound the issue. The shape of the seabed also directly affects the occurrence of stresses and damage. Decreased efficiency of power cables mainly arises from deformations of copper conductors, which can occur even at very low loads. They simultaneously affect other physical properties. Thus, continuous verification of high-voltage cable conditions is necessary through the placement of sensors (monitoring, e.g., deformations, temperature changes) near the cables. Articles (Chai et al., 2019; Drissi-Habti and Carvelli, 2022) describe simulations for cable monitoring using FOS sensors placed inside the cable core. The analysis included deformations caused by stretching, and the results obtained are very promising. Simulations were also conducted to determine the optimal placement of FOS inside the cable for measuring bending deformations. In this way, locations where the cable is excessively deformed (e.g., due to the seabed shape) can be identified, allowing for the application of additional supports to mitigate the resulting stresses.

Numerical analyses (and simulations) presented in Drissi-Habti and Carvelli (2022) indicate that linear placement of FOS parallel to the copper core of the cable yields the best results. However, this approach is associated with significant friction between FOS and the copper core. A proposed solution involves coating FOS with additional protective layers, although these may impact operating parameters and measurement quality. Another proposed arrangement for FOS is to position it at a depth of 1 mm (relative to the core) within the XLPE insulation. This is a straightforward solution to implement, but the resulting measurement data may deviate to some extent from the actual core stresses.

Another proposed FOS placement involves spirally winding it around the copper core of the cable. In this case, friction may be lower, but additional protective coating may still be necessary. Analysis and simulations in Drissi-Habti and Carvelli (2022) suggests that such FOS placement provides the best measurement information for both longitudinal and transverse deformations.

3.4. Powering devices through fiber optics (power over fiber, PoF)

Article (Cheng et al., 2019) presents the possibility of using optical fiber to power low-power receivers, employing the Photovoltaic Power Converter (PPC) technology. In a typical application, a DC-DC converter must also be included alongside PPC to adjust voltage levels for the powered devices. Attention was paid to the conversion efficiency of PPC, which is approximately 50%.

Simultaneously, for an optical power of 1 W (resulting in an output of 500 mW from PPC), it was determined that the effective core area of the optical fiber must be at least $205\ \mu m^2$ (with a wavelength of 810 nm). For this application, a seven-core optical fiber with a suitably larger core area was designed. In a multi-core fiber, the cores are in the same cladding, which can lead to inter-core crosstalk. Therefore, factors such as core spacing and mode count are significant. It was assumed that the fiber is responsible for power transmission, not data transmission, so crosstalk may not be as critical.

Additionally, the RLH company offers PoF devices for industrial power solutions (Online, 2024r). MH (MIH) also offers ready-made PoF modules for deployment and prototyping (Online, 2024l).

According to Online (2024r), the achievable current at a distance of 32.8 ft is 45 mA, while for a distance of 3280 ft it is only 14 mA. It is a complete system (transmitter and receiver) that enables powering target devices with 24VDC voltage. The parameters are very similar to those presented in Cheng et al. (2019):

- 24 V DC, 45 mA (1.08 Watts) at a distance of 10 m;
- Multimode Fiber (62.5/125 μm);
- Wavelength 830 nm.

In Rosolem (2017) concept of PoF is reviewed, technology and applications are also presented. Implementations in access networks and smart grids (with power cables) are included. Distance is a key aspect for efficient PoF. Simulation research shows the potential to achieve 350 mW over a distance of 1 km (Varlamov et al., 2023). In López-Cardona et al. (2021b), it was demonstrated that devices can be powered by PoF over distances as long as 10 km, but up to an optical power of 133 mW (at reception) - showing negligible negative impact on data transmission. Also in López-Cardona et al. (2021b) the bit error rate (BER) is analised for different levels of energy transmitted. The same team of researchers obtained a power of 226 mW over a distance of 14.43 km (López-Cardona et al., 2021a). At the same time, the infrastructure for PoE is very demanding. Altuna et al. (2023) describes monitoring technique of PoF signals in Spatial Division Multiplexing optical networks.

Solutions presented in Sections 3.1–3.4 can be used for monitoring various parameters in the field of power engineering (e.g., the condition of transmission lines or transformers). Thanks to the outlined technologies, it is possible to determine the precise locations of potential damages and, to some extent, assess the extent of these damages. Implementing the Power over Fiber technology additionally allows for powering small measuring devices and sensors using optical fibers. There is a possibility that, with the right transmission parameters (low speed, short distance), a multi-core optical fiber can serve as both PoF and transmit data, e.g. from measurements. Obtaining relatively rapid information about potential damages enables operators to plan repair work more quickly and minimize associated costs (losses).

4. TEL-ENERGO and the POL-34 network, and PIONIER

The initial tests and trials related to the establishment of the nationwide academic network date back to 1995 and the project "Program for the Development of Information Infrastructure for Polish Academic Communities" (pol. "Program rozwoju infrastruktury informatycznej dla polskich środowisk naukowych"). Innovative solutions based on fiber-optic networks utilizing power transmission lines quickly gained attention. The potential and possibilities of using OPGW (and related) technologies led to the creation and development of the first Polish academic network, POL-34.

4.1. Inception and development of the POL-34 network

The pivotal years for the inception of the POL-34 project were 1997–1998. During the Polman exhibition and the Infosystem fair in Poznań, several entities, including PCSS, presented an experiment involving the creation of a heterogeneous, extensive ATM 34 network within the SDH 622 Mb/s telecommunications environment of the Tel-Energo operator. During the fair, an experimental 155 Mb/s connection was established between Gdańsk, Gliwice, Łódź, and Poznań. Satisfactory results from these trials and positive reactions from the academic community led to the signing of an agreement between Tel-Energo and key operators of academic MAN networks in 1997, regarding the establishment of the national broadband scientific network, POL-34. The Tel-Energo infrastructure was based on fiber optics in both underground and overhead power transmission lines, making this technology the foundation of a full-fledged scientific network in Poland. Over the years, the POL-34 network underwent modernization and expansion, connecting additional centers across the country, as well as European scientific networks (e.g., TEN-155 in 1999). Subsequent work primarily focused on increasing accessibility and bandwidth, eventually reaching 622 Mb/s. Many academic units also locally utilized OPGW/ADSS/OPPC technology (leasing fiber optic links from regional power utility operators), enabling the interconnection of various campuses and entities within the MAN network. Often, such a solution was the only way to establish a broadband urban academic network with a limited budget. This approach was favored by the fact that university campuses and research units often have direct and independent connections to power substations (due to increased electrical energy demand).

In 2000, the PIONIER program was launched, and building on the success of POL-34, the construction of a new-generation national optical network (largely using own fiber optic lines) began in 2001. In 2003, the PIONIER Consortium was formally established, taking over the management of the emerging network. The PIONIER National Optical Network was officially launched on January 1, 2004, and it formally replaced the POL-34 network.

4.2. Current status of the PIONIER network

The PIONIER project, thanks to the widespread use of fiber optic connections, enabled the implementation of modern network technologies and their general utilization across Poland. The PIONIER network is continuously modernized, serving as the fundamental network for the Polish academic and scientific community. The infrastructure is often used for testing and deploying innovative network services, cloud computing, and various IT-related applications. The operational network, spanning approximately 10,000 kilometers, primarily relies on its own fiber optics (often shared with other operators). However, over 600 kilometers of the network still consists of OPGW and ADSS lines leased from power utility operators. This solution is particularly suitable for regions where laying one's own fiber optic cables is cost-prohibitive or infeasible due to location and regulatory constraints. Currently, modernization work is underway as part of the PIONIER-LAB project (Online, 2024q), which will meet the Polish scientific community's demand for various network services in the coming years.

Exatel (formerly Tel-Energo) is currently one of the largest teleinformatics infrastructure operators in Poland utilizing power transmission lines. The total length of the Exatel network exceeds 20,000 kilometers.

5. Perspectives and opportunities for further development

Fiber-optic cables associated with power transmission lines have been a continually evolving solution for 45 years. Leading global manufacturers, including AFL Company (Online, 2024p), TW-SCIE (Online, 2024b), and LUMPI-BERNDORF (Online, 2024o), are still conducting research and introducing new products related to this technology. It is essential to remember that the use of OPGW (and similar) lines involves not only the cable itself but also the entire technological infrastructure. The proper operation of a teleinformatics network depends on other elements, such as cable connectors, splice closures (fiber optic joints), vibration dampers, and more. Manufacturers and suppliers also offer comprehensive systems for deploying and installing such cables while considering the requirements related to fiber optic usage. The introduction of new fiber optic solutions is just one component of such a system. Modernizing and improving the parameters (properties) of other infrastructure elements have an almost equally significant impact on the network's final performance. The specificity of using fiber optic technology in power transmission lines, however, necessitates a somewhat different approach and poses additional challenges compared to standard fiber optic networks.

Promising fields of development also encompass optical technologies in the broadest sense, including the mentioned Fiber-Optic Sensors and Power over Fiber. Various fiber optic sensors are already quite readily available, and ongoing research allows for improvements in measurement parameters. Regarding Power over Fiber (PoF), it is only a matter of time until higher-power solutions become available. Currently, devices allowing optical power transmission up to 16 W are already accessible (Online, 2024h). However, for over applications than fiber optic networks, there are fiber coupled modules with power outputs of up to several hundred watts (Online, 2024g). But the diameter of the optical fiber is as large as 800um. Typical applications are Pumping DPSSL and resonant pumping or practical use in fat reduction, lung and liver surgery, varicose vein treatment, materials processing and over (Online, 2024g).

The latest research in the field of fiber optic sensors also pertains to measurements beyond power engineering or mere networks. Currently, intensive research is also being conducted in the utilization for medical purposes (Wang et al., 2021; Chen et al., 2017, 2023, 2021b; Yang et al., 2020; Shen et al., 2018) or measurements such as gas pressure (Yang et al., 2022; Chen et al., 2021a; Li et al., 2023). In many of these applications, the phenomenon of interferometry is utilized (Chen et al., 2021b; Yang et al., 2020; Shen et al., 2018; Yang et al., 2022; Chen et al., 2021a).

5.1. Signal amplification for optical fibers

Distance is one of the key parameters for optical fiber lines. Despite the relatively small attenuation, due to large distances, it becomes a crucial factor. Optical fibers are often used over distances of hundreds or even thousands of kilometers. In such situations, it is necessary to use signal amplifiers for optical fiber lines. Two solutions are commonly employed:

- Electro-optical repeater - a system comprising a receiver and a transmitter. A weak optical signal is received and converted into electrical form. Subsequently, the transmitter converts appropriate electrical signals into optical form (with suitable power). Between the receiver and transmitter, appropriate feeding and amplifying circuits are typically placed (signal regeneration occurs).
- Optical amplifiers - directly amplify the optical signal without typical signal regeneration. Noise is also amplified in the process. The advantage of this approach is its low cost. The construction of an optical amplifier utilizes rare-earth elements ion-doped materials such as:
  - erbium - Erbium-Doped Fiber Amplifier (EDFA) - operating in the range of 1550 nm;
  - praseodymium - Praseodymium-Doped Fiber Amplifier (PDFA) operating in the range of 1300 nm;
  - ytterbium - Ytterbium-Doped Fiber Amplifier (YDFA) - operating in the range of 1 μm;
  - neodymium - Neodymium-Doped Fiber Amplifier (NDFA) - operating in the range of 1 μm;
  - thulium - Thulium-Doped Fiber Amplifier (TDFA) - operating in the range of 2 μm;
  - holmium - Holmium-Doped Fibre Amplifier (HDFA) - operating in the range of 3 μm;
- Brillouin Fibre Amplifier (BFA) - based on the stimulated Brillouin scattering (SBS).
- Raman Fibre Amplifier (RFA) - based on the stimulated Raman scattering (SRS).

RFA, an ultra-wideband optical amplifier, continues to be developed and improved. Current research on RFA includes, among others:

- Raman amplifier-based long-distance sensing system for simultaneous measurement of temperature, strain and vibration - obtained a remote sensing operation of simultaneous at a location to 150 km (Hu et al., 2012; Ju et al., 2005);
- a combination of Raman amplifier and remotely optical pumped amplifier (ROPA) - a second-order remote pump laser can effectively transfer the pump power to the first-order remote pump wavelength (Ronghua et al., 2022; Ronghua and Lei, 2021);
- realization a optical transport network with using bidirectional Raman amplifier and auxiliary laser without remotely pump amplifier (Lei et al., 2022).

5.2. Regulations and availability

The development and accessibility of these technologies are significantly influenced by the adaptation of legal regulations to the possibilities of utilizing power infrastructure for building teleinformatics networks. Unfortunately, despite the use and implementation of power transmission lines with fiber optics for several decades, many countries still face challenges with commercializing such solutions and their legal regulation. This is typically justified by the need to ensure user safety and the integrity of the power grid, which is achieved by limiting access to the infrastructure. Limited accessibility and practically non-existent competition (compared to major power utility operators) result in relatively high usage costs (lease fees) compared to, for example, radio technologies. Gradual changes in regulations, however, can enable greater accessibility and competitiveness, which should have a noticeable impact on more favorable pricing.

6. Summary

The continuous development of power transmission networks has allowed for the widespread implementation of fiber optic technologies in power lines and supply systems. In recent years, these solutions may seem less attractive compared to competing telecommunications technologies (e.g., wireless transmissions). However, this is primarily applicable to metropolitan and highly urbanized areas, where the overall infrastructure does not always permit extensive modernization of power lines.

The application of OPGW (and similar) cables appears to be the most attractive method for introducing fiber optic technology in rapidly developing regions, where electrification is not yet as widespread or requires extensive modernization. Fiber optic-associated power transmission lines have been and continue to be the backbone of many national broadband networks (forming the core infrastructure connecting smaller urban networks). A prime example of this is the scientific networks in Poland (POL-34 and PIONIER), where fiber optic-associated networks are still utilized within urban areas. Thanks to continuous development and the utilization of other fiber optic applications (e.g., sensors, measurements), this technology remains attractive, especially in terms of performance parameters. In the coming years, many entities plan further investments and the development of power infrastructure associated with fiber optics.

CRediT authorship contribution statement

Paweł Poczekajło: Writing – original draft, Formal analysis, Data curation, Conceptualization. **Robert Suszyński:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation. **Andrzej Antosz:** Writing – original draft, Resources, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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