Rev. Roum. Sci. Techn.– Électrotechn. et Énerg.
Vol. 65, 1-2, pp. 11–14, Bucarest, 2020

Dedicated to the memory of Academician Gleb Drăgan

HIGH VOLTAGE POLYMER LINE INSULATOR AS FIBRE OPTIC POWER AND DATA TRANSMITTER

ANDREI MARINESCU[1]

Key words: High voltage, Fiber optic (FO) link, FO line insulator, Nonconventional instrument transformer.

The measurement technique used in modern high-voltage networks is currently marked by a transition from the classical, inductive or capacitive analog systems to the nonconventional systems based on embedded or hybrid sensors and digital fiber optic transmissions. The paper presents the achievement of a high voltage insulator with embedded fiber optic, dimensionally and dielectrically identical with a common insulator with the same operating voltage. It represents the physical support required for the digital transmission of any electrical or non-electrical quantity from high potential, it has 4 optical fiber channels and the possibility of supplying a sensor at high potential by power over fiber (PoF). The paper describes the design of the FO insulator and its qualification testing.

1. INTRODUCTION

The traditional high voltage (HV) electrical substation uses electromechanical relays, programmed logic and microprocessors, master-slave protocols and copper wire interfaces. In this century there is a gradual transition to the intelligent substation, which uses digital input from optical transducer, Ethernet communications between intelligent electronic devices (IEDs), peer-to-peer messages over process bus and a small numbers of fibre optic cables replacing large bundles of copper wire [1].

There are worldwide concerns in the field of data transmission, directly by fiber optic (FO) [2], from the sensors located on HV lines to earth potential, for measuring, control and monitoring purposes [3,4], related to the functional parameters specific to HV networks or to the associated electric power equipment. In Romania, since the 80s these have also determined the beginning of the research in this field, materialized in numerous practical applications [5].

The operational reliability of the power transmission and distribution networks increases due to the presence of FO nonconventional instrument transformers (NCIT) [6–8] as compared to classical instrument transformers. This is explained, among other things, by the total reduction of high-voltage oil-paper insulation, which is the main cause of defects occurring in operation. In addition, in FO NCITs, the destructive effects of thermal and electrodynamic stresses are eliminated [9].

NCIT is made entirely of series of prefabricated components (polymeric insulator, fiber optic, electronic components, sensors, etc.), which reduces the manufacturing cost and does not neglect the weight of the product.

The paper analyzes the essential constructive element of any NCIT, namely the polymeric insulator with integrated/embedded FOs, which largely determines the signal transmission stability at and from high potential. It presents the multi-mode FO positioning that allows the active sensors to be supplied at high potential through the PoF technology and the multi-channel structure, based on the ribbon FO. Finally, the test of the optical insulator is presented, both as independent insulating structure and as ~~a~~ digital data transfer medium.

2. APPLICATION OF THE FO-BASED MEASUREMENT SYSTEMS IN THE POWER GRIDS. ROMANIAN ACHIEVEMENTS

In Romania, the designing activity in the field of measurements based on the use of FO as a medium for transmitting information from high-voltage networks has started in 1980, by establishing a research group in ICMET's HV and HP labs [5]. This group was and still is today the only one of its kind in Romania, which has close ties with the national electricity companies "Electrica" and "Transelectrica" and with their specialists in the measurement technique.

This group achieved and put into operation in 1981 the first 123 kV, 1000 A optical current transformer with U/F-F/U conversion based on the patent [10]. Based on the same principle, a 24 kV, 200 A current transformer was achieved during 2006 – 2010 as an industrial prototype, using latest generation integrated modules [11].

The activity is focused on studying and applying methods of optical measurement and monitoring for electrical quantities (partial discharge [12], on-load tap changers [13]) as well as non-electric quantities (static and dynamic axial forces in transformers [14–16].

Another field where the optical transmission of the signals was used is in the development of HV switchgears for the measurement of temperature and pressure variation in the quenching chamber, usually at high potential. It is practically impossible to measure the above-mentioned quantities by means of other methods due to the strong electromagnetic disturbances generated by the power arc extinguishing process. This technique was developed through a joint project with Karlsruhe Institute for Technology (KIT) [17].

The NCITs developed by this research group were made with Rogowski sensors [18,19] or low power current transformers (LPCT) according to the standards in force [20,21] and the delicate problems of supplying the signal conversion modules were treated either with saturated transformers [11] or with PoF [22].

Finally, by holding the three Optotech national conferences with international participation in 2009, 2011 and 2015 [23], the background was created for scientific collaboration and raising awareness of specialists in this top field.

[1] ASTR (Romanian Academy of Technical Sciences), Craiova Branch, 107 Decebal Av., Craiova 200440, Romania

3. THE DESIGN AND IMPLEMENTATION OF THE HV FO INSULATOR

The decision to achieve a stable mechanical support for the FO used in a high-performance optical transmission was determined primarily by the need to ensure its protection from any mechanical stress that could alter more or less its transmission qualities in operation. This category includes the accidental stretching and/or bending of the FO. Under these conditions, the simplest solution is to integrate the FO in a standard line insulator [24], without changing its withstand voltage. The research carried out has shown that the polymeric insulator is the most suitable as a support for the FO, provided that its integration is done on the composite (fiberglass) core. The design must ensure that the FOs are kept in position when injecting the silicone rubber layer and prevent the voids, which modify the partial discharge level and the operating life of the insulating structure.

A favorable situation for laying out and fastening the FO on the insulator core with adhesive is determined by the use of a ribbon type structure. [25]. A ribbon cable (also known as multi-wire planar cable) is a cable with several FOs parallel to each other on the same flat plane. As a result, they are smaller in size and weight and easier for the installation crew to handle and layout [26].

A ribbon with 4 x 62.5 / 125 µm multimode fiber was used in the achieved structure. This type of FO ensures a sufficiently low attenuation over 1 km of transmission distance and at the same time it is the only one which allows the transmission of power at high potential through PoF. This gives a complete system for measuring voltage, current, temperature and PoF.

Figure 1 shows, for exemplification, the block diagram of optical transmission with a single signal channel and PoF supply channel.

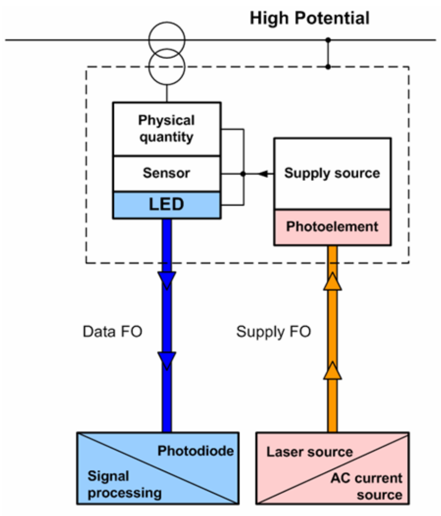


Fig. 1 – Single channel optical system with PoF. Typical values: Laser source, 1–2 W, 820 nm with power feedback loop; Signal processing: sampling rate higher as 80 samples per cycle acc. IEC 61850-9-2; A/D resolution 16 bit.

The physical realization of the optical transmission was achieved by winding the FO ribbon on the rigid fiberglass core of the insulator prepared for the silicone rubber casting like in Fig. 2.

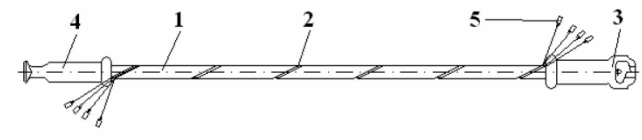


Fig. 2 — FO Insulator support before silicone rubber casting: 1–core, 2–FO ribbon, 3, 4–metallic end fittings, 5–FO input/output.

After the achievement of the optical insulator, the integral structure of the optical system is presented schematically in Fig. 3 and physically in Fig. 4.

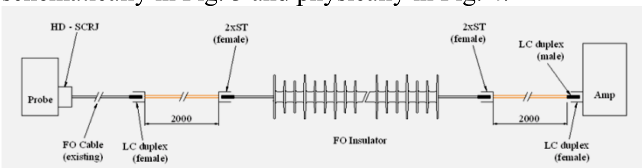


Fig. 3 — FO insulator cable supply. Dimensions are in mm.

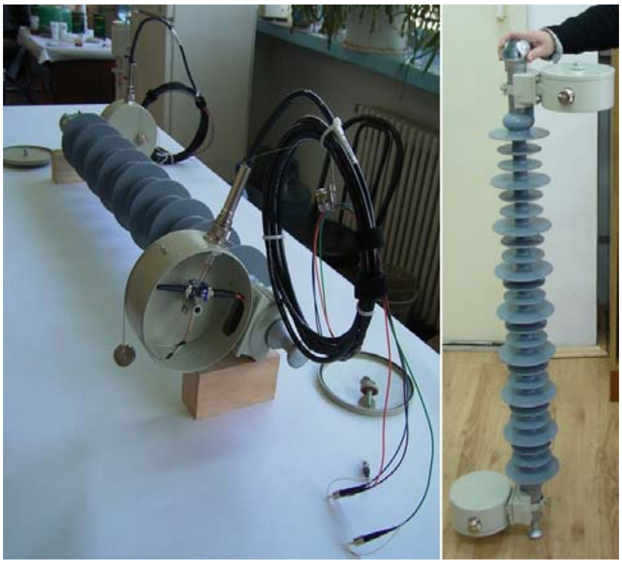
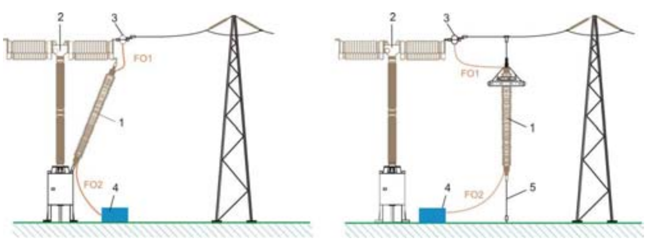


Fig. 4 – Pictures of the 123 kV FO insulator. The two cylindrical boxes placed at the bottom/top are used for the connection between the internal ribbon cable and the external flexible heavy-duty cables (black), 2 m long each.

Figure 5 outlines two alternatives of using the FO insulator developed in this paper to achieve NCITs, which can be used in substations for high and very high voltages.



a b

Fig. 5 – NCIT solutions for HV electrical substations: a – near connection box, b – independent. 1 – FO insulator, 2 – circuit breaker, 3 – current NCIT, 4 – acquisition and PoF unit, 5 – tension cable.

In Fig. 5a the FO insulator 1 is associated with the pole of the circuit breaker 2 in inclined position. In Fig. 5b the FO insulator is used as an independent construction with a field uniformization electrode. This version takes up much space, but it has universal application, irrespective of the constructive type of the substation equipment.

4. QUALITY OF INFORMATION TRANSMISSION THROUGH THE FO INSULATOR

First, the FO insulator was subjected to successful dielectric withstand tests: ac (230 kVRMS, 1 minute), (550 kVpeak) and partial discharge test at 1.5 $(U_N)^{1/3}$, the measured level being below 10 pC (Fig. 6).

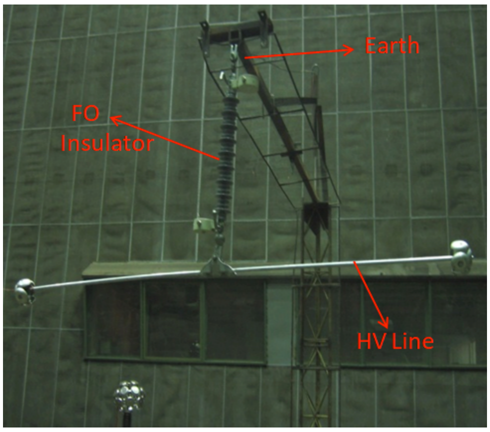


Fig. 6 – FO Insulator under test in the HV Lab.

The diagram (Fig. 7) and the ways of checking the conditions for the transmission of the digital information in terms of the desired quality performance, depending on the transmission distance are presented further below.

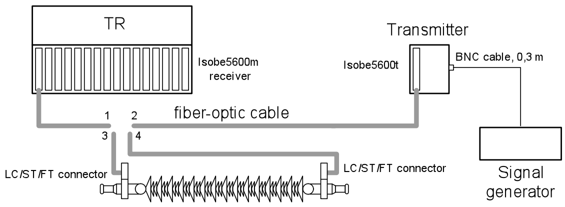


Fig. 7 – Diagram for the determination of the digital information transmission through the optical insulator.

The insulator FO was checked with a signal generator and a transient recorder by means of the substitution method. Initial measurements were carried out by setting up the connection (1-2) using a FO cable of different lengths (up to 40 m), and then measurements were performed with the FO insulator by making the connections (1-3) and (2-4) with different types of connectors: ST, FC and LC. The signals applied were sinusoidal and rectangular.

The analysis of the results led to the following voltage deviations:

– regardless of the type of optical connector and the 50 Hz – 1 MHz frequency range, sinusoidal or rectangular, deviations below 0.2 %;

– maximum deviations for the optical cables up to 40 m, below 1 %;

– repeatability of measurements for a given FO link length, regardless of the length, below 0.3 %;

– repeatability of measurements for the insulator with embedded FO (about 1.5 m) with an external heavy duty FO link of 2x2 m, below 0.1 %.

The last result characterizes the optical insulator link similarly to a wired link.

In the case of digital optical transmission, it is mandatory to determine the bit error rate (BER) for any embedded FO system. BER = 0 was obtained, as shown in Fig. 10, paragraph 5. This result shows that the FO ribbon embedded in the insulator was not deteriorated and the technological process can be validated.

This result is equally important for the FO used for PoF.

5. DESCRIPTION OF THE RECORDING EQUIPMENT

The setup used for the FO insulator signal transmission is shown in Fig. 8.

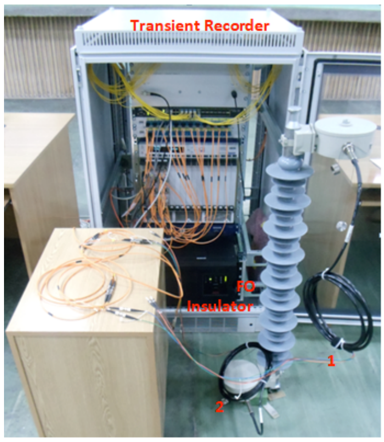


Fig. 8 – FO insulator in the Electronic Lab. 1,2 – input and output heavy duty multiple FO Cable.

Figure 9 depicts the simplified diagram of a recording channel, which includes the following functional blocks:

– *a signal conditioning block*, which allows the achieving of signals from ac supply (through a capacitor) or directly from dc supply. It also offers "auto-zero" function and it is able to determine and remove the offset by using numerical algorithms applied to the input data;

– *a programmable input amplifier*, which allows signals up to ±40 V. The zero level signal can be shifted by a summing block to obtain several input domains. The output signal from a bipolar digital-analog converter can be used to shift the zero level, which, together with the recorder signal are algebraic summation within the "offset" block;

– *a low-pass filter*, with f_{-3dB} frequency, set at 10 MHz.

– *an analog-digital converter* (16 bits) and 100 MS/s maximum sampling rate, fitted with digital filter modules.

The recorded data and status data are digitally transmitted through the FO.

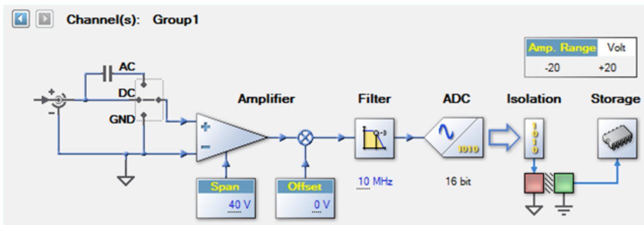


Fig. 9 – Recording channel.

The main controlling PC communicates with the remote blocks to obtain, among other things, the status of each optical link in a template like in Fig. 10.

Link status	Link quality (BER)	Cable length	Front-end temperature (°C)	Front-end power level
OK	0.0E+000	37 m	43.3 °C	OK

Fig. 10 – Parameters calculated using the communication between the remote blocks and the main controlling PC.

6. **CONCLUSIONS**

The paper presents a nonconventional use of the polymeric insulators as optical links for signals measured at high voltages.

It presents the construction of the optical insulator with embedded FO for the rated voltage of 123 kV, achieved based on a standard line insulator, and the necessary measures for the insulator to meet the requirements set, both dielectrically and in terms of information transmission. The solution of using the 4-fiber multimode FO ribbon allows the achievement of three measurement channels and an electric power supply channel for the high-potential sensors by using the PoF technology.

The insulator represents a stable support for transferring the information from electrical and non-electrical sensors at high potential, by eliminating the random changes of the light attenuation produced by mechanical deformation (vibration, stretching, bending, etc.) created by thermal and electrodynamics stress.

The polymeric FO insulator can be considered a universal component for the achievement of nonconventional instrument transformers, including combined (voltage and current) transformers, due to the possibility to include several FO.

ACKNOWLEDGEMENTS

The author warmly thanks former collaborators from the optoelectronics group in ICMET: Engineers E. Gaber, St. Catana†, I. Dumbrava, N. Paduraru, A. Vintila, M. Popescu†, A. Manta†, H. Ionescu†, D. Truta, C. Caramida, who passionately contributed to the development and practical applications and of this new technology, but also to IPROEB SA company, in Bistrita, which made available its facilities for the achievement of the FO composite insulator described in the paper.

Received on February 22, 2020

REFERENCES

1. ∴IEC TR 61850-1:2013, *Communication networks and systems for power utility* automation - Part 1: Introduction and overview.
2. F. Rahmatian, A. Ortega, *Applications of optical current and voltage sensors in high-voltage system*, IEEE PES T&D Conf. and Expo. Latin Am., Venezuela, 2006.
3 J.N. Blake, A.H. Rose, *Optical current sensors in the modernization of the electric power grid: digital substation challenges*, Proc. of SPIE, **9157,** pp. 1-4 (2014).
4 A.H. Rose, G.W. Day, *Optical fiber current and voltage sensors for the electric power industry*, Chapter 27, *Handbook of Optical Fibre Sensing Technology*, Ed. Jose Miguel Lopez-Higuera, Wiley & Sons, Ltd., pp. 569-618, 2002.
5. A. Marinescu, Optoelectronic Measurements in the Era of Intelligent Electrical Networks, Tutorial, 3rd OptoTech Conf., 16-19 June, 2015, Tulcea, Romania.
6. K. Bohnert, P.Gabus, H.Brändle, *Fiber optic current and voltage sensors for high-voltage substations*, Int. Conf. Optical Fiber Sensors, October 13-17, Nara, Japan, 2003.
7. J. Nedoma, M. Fajkus, R. Martinek, *Measurement of electric current using optical fibers: A Review*, Przegląd Elektrotechniczny, **93**, *11*, pp. 140-147 (2017).
8. H. Albert, T. Ene, N. Golovanov, C. Stoicof, L. Elefterescu, *Review of worldwide achievements and trends on optical current and voltage measuring transformers use*, Paper SI-6, 8p, 2nd Optotech Conf., June 8-9, 2011, Calimanesti.
9. T. Bosselmann, *Innovative applications of fiber-optic sensors in energy and transportation*, Proc. SPIE, **5855**, pp. 188-193 (2005).
10. ∴*Unconventional Instrument Transformer for High Voltage Networks*, Patent RO nr.77498 A2/7.03.1980
11. M. Popescu, A. Manta, N. Paduraru, A. Marinescu, *Optoelectronic current transformer for medium voltage networks*, Annals of the Univ. of Craiova, Electrical Engineering Series, **34**, (2010).
12. T. Nicoară, A. Marinescu, I. Pătru, *Partial discharge diagnostics in power and instrument transformer based on acoustic emission method*, Int. Conf. on Appl. Theor. El. ICATE, 6-8 Oct. (2016).
13. A. Marinescu, A. Manta, D. Truta, *Monitoring of MOV protection for power autotransformers*Proc. of 15th ISH, Ljubljana, 2007, Paper T7-527.
14. ∴*Device for measuring and monitoring by fiber optic the axial clamping forces of the transformer windings*, Patent RO nr. 126339 /29.06.2012
15. R. Şchiopu, A. Drăgulinescu, R. Iordănescu, A. Marinescu, *Verification of the windings axial clamping forces for high voltage power transformers by using passively mode-locked fiber lasers*, Proc.SPIE **9258**, Advanced Topics in Optoelectronics, Microelectronics and Nanotechnologies, 2015, Constanta.
16. A. Marinescu, *Integrated axial winding clamping force monitoring system for power transformers*, Proc. of 17th ISH, Hannover, 2011.
17. H.W. Klink, *Simulation der gasdynamischen Vorgänge in der Löschkammer eines SF6-Blaskolben-Leistungsschalters*, Dissertation, KIT-IEH, 1999.
18. A. Marinescu, Transition from shunt to rogowski coil in modern power grid, Simpozionul Omagial de Tehnica Tensiunilor Inalte Dedicat Acad. Prof. Gleb Dragan cu ocazia celei de a 90-aniversări, 22 octombrie 2010, Bucuresti.
19. A. Marinescu, *A calibration laboratory for Rogowski Coil used in energy systems and power electronics*, Proc. 12th Intl. Conf. OPTIM, 20-22 May 2010.
20. ∴IEC 61869-8:2002, *Instrument transformers – Part 8: Electronic current transformers*.
21. ∴IEC 61850-9:2016, *Non-Conventional Instrument Transformers* (Sensors, Merging Units, Protection Relays and Turnkey Schemes).
22. J. Werthen, M. Cohen, *The power of light: photonic power innovations in medical, energy and wireless applications*, Photonics Spectra, May 2006.
23. ∴OptoTech, Series of Conferences 2009, 2011, 2015.
24. ∴IPROEB SA, Bistrita, http://www.iproeb.ro/, Accessed: 2020.02.12
25. ∴IEC 60794-1-31:2018, Part 1-31: Generic specification – Optical cable elements – Optical fiber ribbon.
26. ∴*Multimode FO cable and connectors*, Available: http://www.rosenberger-osi.de, Accessed: 2020.02.05