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Insulating properties of optical fiber current sensor with external conversion

***Abstract**. In the article are presented results of investigations on insulating properties of an optical fiber current sensor with external conversion (OFCS-EC). Its design and characterization were presented in our papers [1, 2]. The aim of studies presented in this paper is to verify good isolation properties and correct operation of the presented sensor exposed to very high voltage. Sensor's response was tested at alternating voltage of magnitude up to 30 kV. Our tests fully confirmed very good isolation properties of the investigated OFCS-EC.*

***Streszczenie.** W pracy przedstawiono badania nad własnościami izolacyjnymi światłowodowego czujnika prądu z przetwarzaniem zewnętrznym (OFCS-EC). Czujnik został wcześniej zaprojektowany i przebadany [1, 2]. Celem prezentowanych w artykule badań jest weryfikacja dobrych własności izolacyjnych czujnika oraz poprawności pracy czujnika pod wysokim napięciem. Przetestowano odpowiedź czujnika przy napięciu przemiennym do 30 kV. Wykonane testy w pełni potwierdziły bardzo dobre własności izolacyjne czujnika OFCS-EC. (**Właściwości izolacyjne światłowodowego czujnika prądu z przetwarzaniem zewnętrznym**)*

Keywords: optical fiber current sensor, instrument current transformer, insulation properties, high voltage engineering.
Słowa kluczowe: światłowodowy czujnik prądu, przekładnik prądowy, własności izolacyjne, technika wysokich napięć.

Introduction

Unconventional instrument transformers of current and voltage have been known for years. First articles concerning fiber optical current sensors which can serve as instrument current transformers appeared in the '80 of the last century [3 - 7]. For this reason they are called optical fiber current transducers. Such sensors are fully optical, which means that nearby a conductor with electric current there are only insulating materials (most commonly glasses or polymers). Basic configuration of such a sensor consist of a waveguide loop placed around the conductor with electric current in such a way, that magnetic field lines created by the current are parallel to coils of the loop [3, 8]. A light source and a detector are grounded and are placed at a safe distance from the conductor, which may be highly electrified. However there is an fiber-optical connection between a head of the sensor and its electronic part responsible for signal processing. This ensures full galvanic separation. Such sensors are characterized by very short response times (less than 10^{-9} s) and immunity to overload [9]. The latter property is especially important and useful for instrument current transformers applied in power systems [10-13]. Despite these benefits the fiber waveguide current sensors are not commonly used in power systems. The reason for this are most probably their interdisciplinary nature, standards and well established conviction about the credibility of electric methods.

The optical fiber current sensor with external conversion is a subject of studies presented in this article. It was designed and tested in the Department of Optoelectronics of the Silesian University of Technology [1]. Its working principle consist on rotation of polarization plane of an optical wave propagating in magneto-optical medium placed in external magnetic field (the Faraday effect). An electric current that flows in a busbar induces magnetic field whose magnitude is directly proportional to a magnitude of the electric current intensity. This field interacts with the head of the OFCS-EC, at the output of which there is a polarizer acting as a analyzer. This polarizer transforms rotation of a polarization plane into variations of intensity of light passing through it. Finally, a light beam returning from the sensor head via the fiber is converted to electric domain in a photodetector. A schematic view of the sensor is presented in Fig. 1.

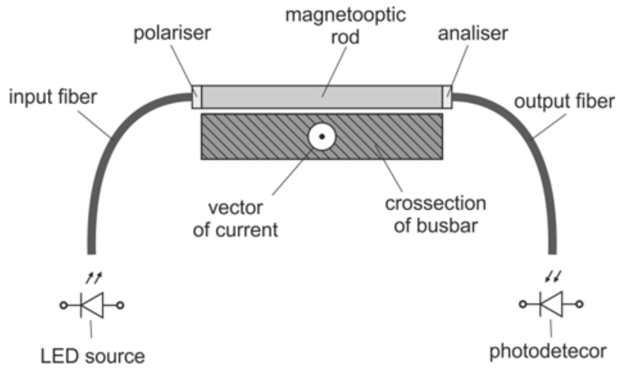

Fig.1. A schematic drawing of the optical fiber current sensor with external conversion investigated in this paper

Insulating properties of those sensors are crucial if they are to be applied in power systems, especially in high-voltage environments. For this reason, this article focuses on investigations carried out in the presence of high voltage. The sensor have already been investigated in alternating electric field (the article with these investigations was submitted for publishing). These investigations allowed to determine leakage currents and proved its very good insulating properties. Now they are extended of a measurements of a insulation resistance, whose results are presented below.

Further, after determination and verification of insulating properties, operation of the sensor was tested when the electric potential of the busbar was very high. These tests were one of the main goal of this work. Their positive results opened up possibility of further investigations of the presented sensor in operating conditions close to those that are typical for power systems.

Insulating properties

The investigations in alternating electric field showed that the OFCS-EC sensor have very good insulating properties. They were carried out using a supporting insulator at the end of which, was mounted the busbar with the OFCS-EC sensor head (Fig. 2a). For the purpose of comparison the leakage currents was measured for isolator itself (Fig. 2b). Investigations involving measurements of the leakage current were performed for voltage varying from 0 to 38 kV. Additionally was carried out a test lasting 1 minute for effective voltage 70 kV. Such a value of test voltage is required if any insulating systems being tested is intended for operation in power grids operating at rated voltage 30 kV [14]. The test was successful (optical fibers and their cover acting as the isolation withstand required voltage).

Characteristics of the leakage current as a function of voltage allowed to determine the impedance of the circuit. This impedance in configuration presented in Fig. 2, normalized to the unit length was equal to 18,5 MΩ/cm. Whereas its value for the supporting insulator was 14,5 MΩ/cm (the article with these results was submitted for publishing).

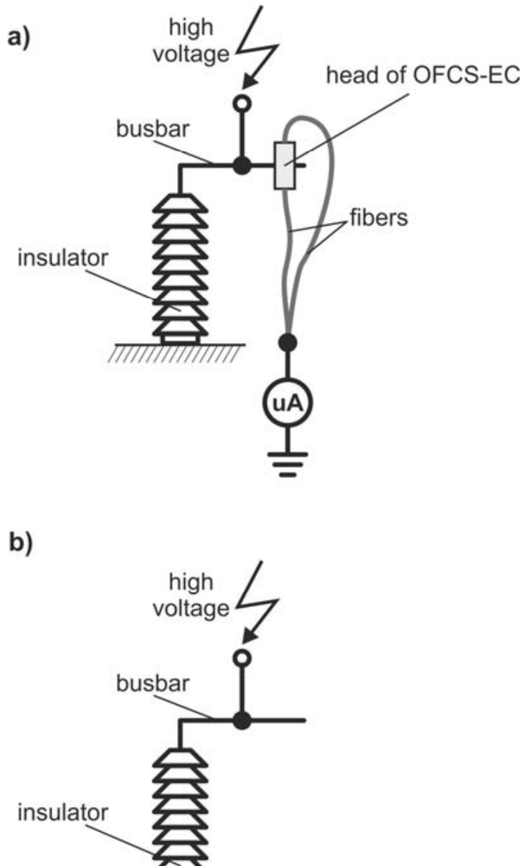

Fig.2. Schematic view of setup for leakage current measurements: a) OFCS-EC sensor, b) supporting insulator

As demonstrated in Fig. 2, insulating properties of the sensor are mainly determined by optical fibers leading optical signal to and from the head of the OFCS-EC. These fibers connect a grounded area and an area in which electric potential is very high. The values of leakage current determined during the measurements do not reveal the resistance itself, because the measurements were carried out for alternating current. In fact, we dealt with a circuit connecting in parallel resistance and capacitance. The latter is associated with a geometry of the measurement setup (distance, shape of electrodes) and relative permeability of optical fibers and air. Therefore, for the purpose of this article, additionally were performed measurements of isolation resistance of the OFCS-EC input/output optical waveguides. These are PCS (Plastic Clad Silica) waveguides composed of a silica core, hard polymer cladding and ETFE coating (it is a copolymer of Ethylene and TetraFluoroEthylene better known as Tefzel®). These fibers are placed in PVC tubes. It is well known that PVC has very good electro-insulating properties [15]. However, in considered case it is connected with other materials (e.g. hard polymer cladding), whose insulating properties are not known. For this reason, a short section of optical fiber was tested. A schematic view of a setup for measurements of isolation resistance is presented in Fig. 3.

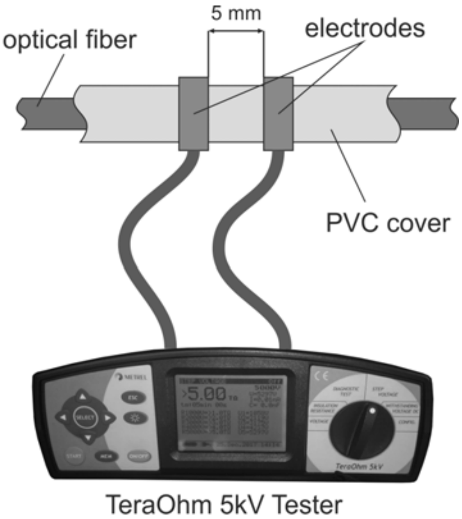

Fig.3. A schematic view of a setup for measurements of isolation resistance of optical fibers

The tests were carried out for voltage varying from 1 kV to 5 kV. Based on their results the determined value of isolation resistance and its uncertainty is R_i = 22,0(25) GΩ.

In fact, a resistance of the optical fiber is mainly determined by insulation properties of PVC,

Investigation in high voltage environment

Positive results of tests performed in high voltage conditions allowed to run tests of sensor's response in operating conditions similar to conditions typical for power systems. In subsequent investigation stages the decision was made about the determination of a measuring range of alternating current and permissible magnitudes of alternating voltage. It is directly related to rated values of current and voltage in a circuit in which a sensor is going to operate. Chosen values of rated current and voltage were 200 A and 30 kV, respectively [2]. As was mentioned in the introduction, a response of the OFCS-EC is directly proportional to the magnetic field induction, which in turn is directly proportional to intensity of electric current flowing in a electric conductor. Therefore a magnitude of sensor's response is strictly dependent on a location of the sensor head as well as a shape and size of its cross-section. Considering a geometry of the OFCS-EC sensor head, the most favorable is rectangle cross-section. Typical copper busbar of cross-section dimensions 3 mm x 20 mm was selected for assumed current intensity 200 A [2]. Maximum permissible magnitude of alternating voltage 30 kV has been already determined and checked above.

Tests in conditions similar to conditions typical for power systems supply current of intensity 200 A at voltage of 30 kV. For this purpose a special laboratory setup was designed and constructed. It is shown in Fig. 4. In this setup flow of high current is yielded separately from simultaneously applied high voltage. It was not necessary to use a generator allowing to give 6 MVA of electric power. In proposed setup the busbar was supplied from a low-voltage source of alternating voltage (up to 230 V) through an insulating transformer, allowing insulation up to 110 kV, and a current source isolated from ground potential (placed on the insulating base). A high electric potential from a test transformer (having rated voltage 60 kV) is connected to the busbar. The test transformer was supplied from the low-voltage source (up to 230 V). High voltage is present along the waveguides because the light source and photodetector are grounded. The current transformer is also under high voltage, however its isolation from the ground do not expose its isolation to danger. Application of insulating transformer ensures safe operation of that part of the measuring setup which, powered from low voltage grid, is a source of the high electric current. In Fig. 4 is shown only electric part of this setup.

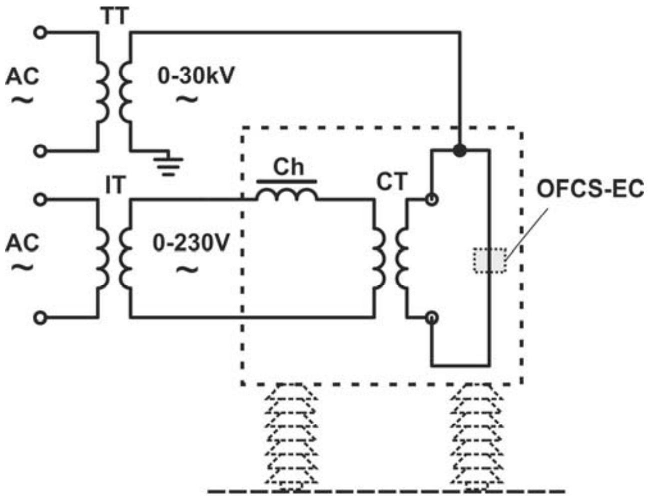

Fig.4. Electrical scheme of a setup used for tests under high voltage and current conditions.
(TT – test transformer; IT – insulating transformer; Ch – choke; CT – current transformer)

The purpose of the investigations was to determine what is the influence of high voltage on operation of the sensor and confirmation that it can be applied in real power system. The test was composed of several cycles of measurement of sensor's response for the following values of voltage: 0 kV, 10 kV, 20 kV and 30 kV (Fig.5, Fig.6, Fig.7).

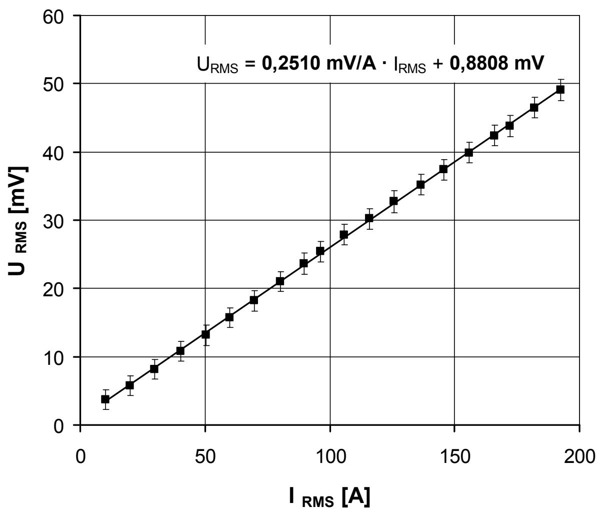

Fig.5. The response of the sensor as a function of electric current intensity in busbar for voltage 0 kV

Determined characteristics of the sensor's response for voltage varying from 0 kV to 30 kV are shown in Fig. 5 and Fig. 6. One can see the characteristics are almost identical. A difference between slope values of approximating linear functions is twice less than measurement uncertainties (a_{0kV} = 0,2510(10) mV/A; a_{30kV} = 0,2505(10) mV/A). In Fig. 7 are presented results obtained for chosen values of voltage. For voltage 10 kV and 20 kV measurements were carried out increasing busbar current of 50 A. In the plot there are only visible small differences between subsequent series falling within the scope of measurement uncertainties.

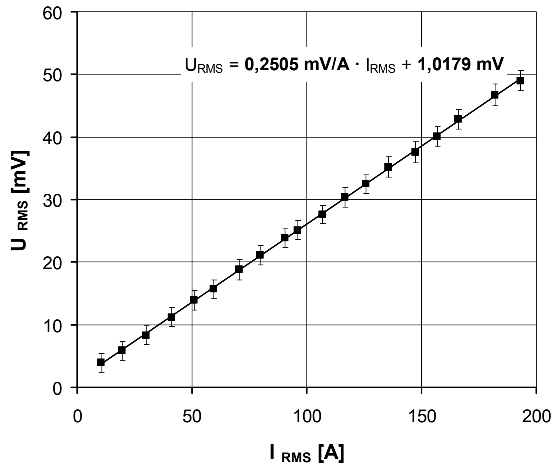

Fig.6. The response of the sensor as a function of electric current intensity in busbar for voltage 30 kV

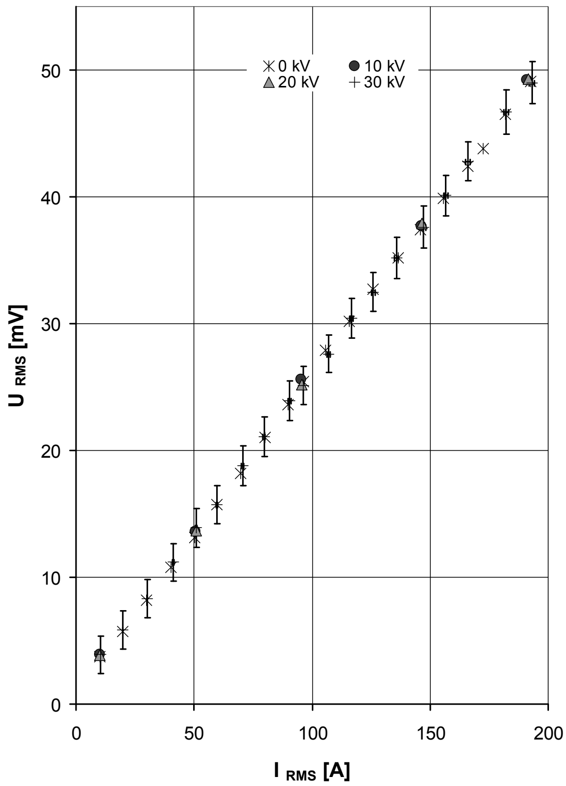

Fig.7. Collective plot of sensor's response registered for the following values of voltage: 0 kV, 10 kV, 20 kV and 30 kV

Summary

The carried out measurements of leakage current and insulation resistance fully confirmed excellent insulating properties of the OFCS-EC sensor. In particular, optical fibers were tested. They link the sensor head and the opto-electronic signal processing unit.

The sensors was also tested in high voltage/current operating. The results of these tests confirmed that the sensor is working properly when its head is mounted on the busbar connected to high electric potential 30 kV.

For the purpose of the investigations reported in this paper designed and constructed a measurement setup allowing investigations of the OFCS-EC sensor in conditions typical for power systems. The electric current and high electric potential can be regulated up to 200 A and 30 кV, respectively. The range of the electric potential values can be extended to 70 kV, which allows Authors to expand their research opportunities.

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