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Measurement of electric current using optical fibers: A Review

***Abstract**. This article deals with the measurement of electric current in the energy via optical fibers. Nowadays, the measurement of the electrical current by using optical fiber most commonly based on the principle of Faraday effects, thus the magneto-optic effect. FOCS (Fiber-Optic Current Sensor) is very accurate, modular and easy to install. Another advantage is the isolation of the measuring part from the primary technology, which is sensed. Optical fibers can also be used to measure the inside of the transformer. It also offers the possibility of measuring the temperature of winding. The main contribution of the paper is to summarize interesting published results to date, approaches and basic principles leading to the analysis and to defining the electrical values such as electrical current using fiber optic technology.*

Streszczenie.** W artykule opisano możliwości pomiaru prądu przy wykorzystaniu światłowodów. Czujnik FOCS (fiber optic current sensor) jest dokładny I łatwy do instalacji. Inną zaletą jest oddzielenie galwaniczne od toru prądowego. W artkule przedstawiono przegląd prac na ten temat, przegląd rozwiązań konstrukcyjnych I zastosowań oraz analizę właściwości metody. **Pomiar pradu elektrycznego przy wykorzystaniu światłowodów.

Keywords: fiber-optic technology, electrical current, current sensor, magneto-optic effect.
Słowa kluczowe: światłowody, pomiar prądu, zjawisko Faradaya.

Introduction

The fiber-optic sensor is based on the use of Faraday's magneto-optical effect (year of discovery is 1845), in which there is a magnetic rotation of plain of the polarized light, see Figure 1. However, the use of this phenomenon for the measurement of electrical quantities has only occurred thanks to the development of fiber optic technology. The rate of twisting of the polarization plane is directly proportional to the path d, after which the light in the given environment spreads and size of the components of the vector of magnetic induction B in the direction of light propagation. The orientation of the vector determines the meaning of the polarization plane. The size of the angle of rotation β, by which the polarization plane is rotated (see Fig. 1) can easily be calculated by a simple relationship (1):

(1) $$\beta = V * B * d,$$

where: V – Verdet constant, B – density of magnetic induction, d – length of path

The Verdet constant depends on the wavelength of the light and it is an optical "constant" that describes the strength of the Faraday-effect for a particular material.

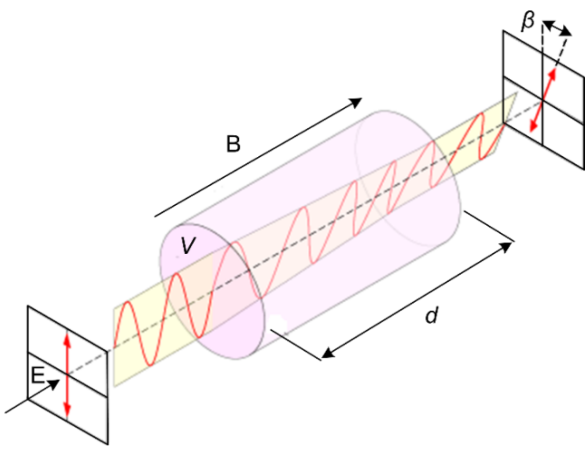

Fig.1. Basic scheme of the Faraday-effect.

Fiber-optic current sensors are referred to as FOCS (Fiber-Optic Current Sensor). Figure 2 shows the principle of the fiber-optic current sensor FOCS. FOCS benefits are high accuracy, high bandwidth: detection of current ripple and transients, wide temperature range, full digital processing, uni- or bi-directional current measurement, analogue and digital outputs, easy to install, adaptable shape of sensing head, small size and weight, no magnetic centering necessary, no magnetic overload problem, immunity to electromagnetic interference and many others.

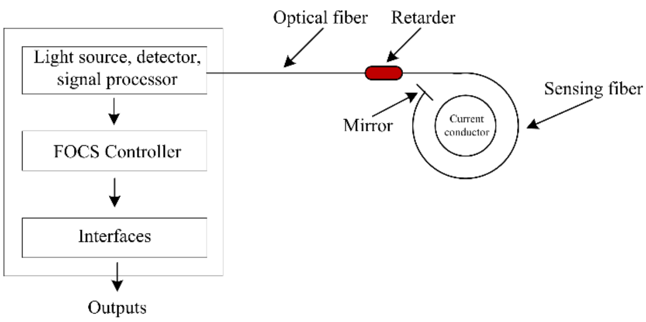

Fig. 2. Principle of the fiber-optic current sensor FOCS

An important application area of FOCS is the metallurgical industry, where an electrolytic process is used to obtain precious metals. Typical electrolyzers work with DC (Direct Current) in the order of several hundred thousand amperes (up to 500 kA). Fiber-optic sensors can be used as measuring transducers and provide a number of benefits, such as easier installation, smaller dimensions and high accuracy of measurement. Nowadays, the target application area for the use of the fiber optic FOCS sensors is to measure, control and protect the substations. Also, the advantage is that due to small dimensions and weight, FOCS can be integrated into an existing device, such as switches and bushings. The application is also in the DC lines of very high voltage (HVDC) used for the transmission of electricity over long distances. From the point of view of the security function of the protection there is a significant advantage that even in the case of high short-circuit currents, there is no overloading and distortion of the output signal, which we encounter with conventional current transformers. Another advantage is the isolation of the measuring part from the primary technology, which is sensed [1-6].

The main contribution of the paper is to summarize interesting published results to date, approaches and basic principles leading to the analysis and to defining the electrical values such as electrical current using fiber optic technology.

Approaches and results

An advanced fiber-optic current sensor is based on the recirculating architecture of fiber loop for significantly enhancing the current sensitivity. The recirculating loop is created by a 2x2 optical switch and the single mode fiber is used as the sensing head, see Fig. 3. Authors experimentally obtained a sensitivity of 11.5 degrees/A for-1000 meters fiber and a sensitivity of 21.2 degrees/A for 500-meters fiber [7].

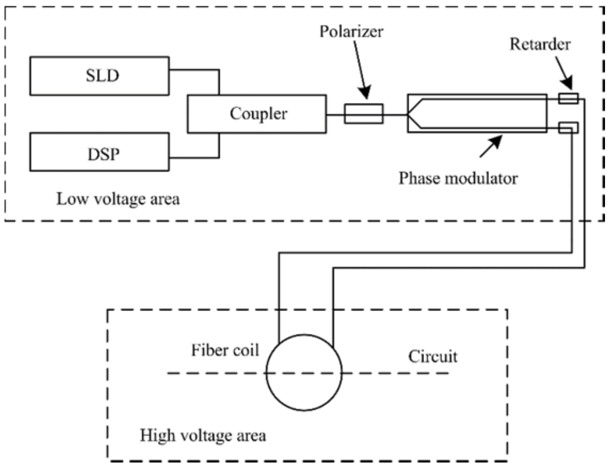

Fig. 3. Basic scheme of Sagnac fiber optic current sensor

A smaller fiber sensing coil is required in order to that the FOCS meet the needs of the high voltage watt-hour meter for measuring smaller current with the better performance. The FOCS sensing coils (<10 cm in diameter) is achieved by the special spun highly birefringent fiber. The ability to resist bending is analyzed in the comparison between the fiber sensing coils by the special spun highly birefringent fiber and the fiber sensing coils by the low birefringent fiber. The measurement error of the FOCS is ± 0.2 % from -40 °C to 70 °C under considering temperature compensation, and the FOCS shows the excellent performance of temperature characteristics, linearity and accuracy in a current range from 1 A to 120 A [8].

Next article studies the using an FOCS for the measurement of plasma current in the fusion reactor (ITER). The sensor is based on a classical FOCS interrogator involving the measurement of the state of polarization rotation when the light in presence of a magnetic field (Faraday effect) in an optical fiber surrounding the current and terminated by a Faraday mirror. The objective of the simulations is to quantify the ratio (beat length over the spun period of the spun fiber) enabling a measurement error in agreement with the ITER specifications. The simulation work showed that a L-B/S-P ratio is 19.2 [9].

The paper [10] researched on the error ratio of FOCS induced by temperature drift. The reason of FOCS error drift was described to explain the relationship among temperature, linear birefringence and error of FOCS ratio. In the range of testing temperature, both the ratio error of FOCS and linear birefringence had a linear relationship with temperature. The FOCS ratio error had a linear relationship with experiment temperature similar to 60 °C.

Complex transforming processes of polarization state induce illegal linear polarization state and illegal circular polarization state in Sagnac fiber-optic current sensor, which, decrease the performance of S-FOCS. Based on polarization state error models of Sagnac fiber-optic current sensor, authors made experiments to evaluate performances of several key components, including polarizer, quarter-wave retarder and sensing head, then, investigate the influence of several main polarization error factors on S-FOCS's performance. The result shows that the changing degree of polarization state causes bias instability, nonlinear of scale ratio, and random noises of S-FOCS, and influents S-FOCS's performance [11].

Paper [12] describes the structure and principle of the FOCS created by Faraday mirror. The performance of the FOCSs is limited by the linear birefringence (LB). Faraday mirror can be employed to compensate the LB using the non-reciprocity of Faraday effect and the reciprocity of LB. The results indicate if that the influence of LB disappears then the current is null. However, if the current is not zero, the LB is not removed and the effect extent is different for different LB. The Faraday rotation can be deduced from the detected signals and the LB need not be compensated physically by employing this technique.

A special spun linear birefringent fiber was designed and created for FOCS based on polarization-rotated reflection interferometers. In contrast with conventional sensing fibers used in FOCS, the fiber uses a function of a quarter wave plate. The output of sensor has a good linearity performance in a wide range of current (10 to 5000 A/rms). The ratio error is ± 0.1 % and the phase error is ± 2 min at AC current of 1000 A [13].

Article [14] investigate the design principle exploiting the geometric rotation effect for the sensing coil of the fiber-optic current sensor (FOCS) on the basis of the polarization-rotated reflection interferometer. The sensing coil is formed by winding the low birefringence single-mode optical fiber in a toroidal spiral. If the rated current is 1200 A/rms, the sensing coil can ensure the scale factor error of the sensor of 0.2 S over a temperature range from -40 °C to 60 °C.

A prototype fiber-optic current sensor (FOCS) created by Sagnac interferometer is designed and tested for monitoring current up to 4000 A. Sensor is tested for nominal current 1 A up to 800 A. The output of sensor has nonlinearity of ± 0.5 % [15].

A highly accurate fiber-optic current sensor for AC and DC up to 100 kA was investigated. Reciprocal optical circuit and method of signal processing based on the relationship of modulation and demodulation of this sensor were analyzed. The sensor achieved accuracy to within ± 0.2 % at -40 °C to 80 °C with inherent temperature compensation, resolving power for small AC current was less than 0.5 A, angle difference was less than ± 2 min [16].

Authors [17] propose a new technique to reduce the bending-induced linear birefringence (LB) by fiber polarization rotator (FPR) in the reflective fiber-optic current sensor (FOCS), see Fig. 4. A comparison was made between the proposed FPR scheme and the conventional scheme on measurement errors. Simulation shows that the proposed scheme has a large improvement on such LB reduction by an order of magnitude.

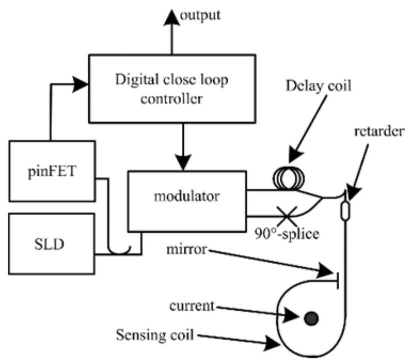

Fig. 4. Basic scheme of FOCS without FPR.

A new method for measurements of lightning on wind turbines by fiber-optic current sensors (FOCS) was developed. FOCS are resistive with respect to electromagnetic interference (EMI), because the magnetic field produced by the current of lightning is directly converted into an optical signal in this device. The sensor cannot be damaged by over-current coming from an unexpected surge caused by a lightning. However, the accuracy of current measurements with FOCS is affected by the environmental perturbations, such as mechanical vibration and temperature changes [18].

A fiber-optic current sensor employs phase shifting algorithms to process the optical signal is described. Here, the sensing element consists of a coil low birefringence fiber which placed between one polarizer and four analyzers. In the polarimeter, the output light from the sensing element of current is divided into 4 beams through 3 non-polarizing beam splitters, and an analyzer and a detector are placed in each beam path. The design of the sensor, results and shift algorithms will be presented [19].

Authors presented fiber-optic current sensor for DC up to 500 kA. The sensor offers significant advantages with regard to performance and ease of installation compared to state-of-the-art Hall-effect-based current transducers. The sensor exploits the Faraday effect in an optical fiber and measures the path integral of the magnetic field along a closed loop around the current-carrying bus bars. The differential magneto-optic phase shift of left and right circular light waves propagating in the fiber is detected by a polarization-rotated reflection interferometer. The sensor achieves accuracy ± 0.1 % over a wide range of currents and temperatures [20].

Next paper presents a fiber-optic current sensor (FOCS), customized for measurement of harmonic current in high-voltage electric power systems. The practical application of this device has been verified experimentally at a thermal power plant. The measurements have been made for the operation of a 6kV induction motor with different load conditions and the thyristor excitation of a 15 kV AC generator [21].

A fiber-optic current sensor (FOCS) created by the Faraday effect is presented. The sensor of current is realized using the all-fiber low-coherent reflection interferometer. An Erbium-doped fiber, a super-fluorescent radiation source, and a sensing spun high-birefringence fiber coil are applied in the interferometer. The sensitivity of the sensor is about 70 mA/root Hz, the scale factor error is about 0.5 %, the range of measured currents is 0.1 A~3000 A, and the bandwidth is up to 10 kHz [22].

Authors [23] present FOCS based on Faraday effects with the magnetic concentrator. According to the measured values of AC up to 1 kA, a calibration procedure was performed. A well-known temperature dependence of the Faraday current sensor and its influence on the measurement accuracy are tested using a special double-layer thermal insulated chamber.

A fiber-optic current sensor (FOCS) based on a Sagnac interferometer is presented to measure high-voltage AC current in electric power systems from 5 A to 3200 A, see Fig. 5. A simple analytical expression for the sensor has been derived, the input-output performance and the temperature dependence of FOCS have been experimentally investigated. The simple geometry of sensor gives high accuracy and sensitivity, wide dynamic range, and immunity to slow-variance temperature and other environmental fluctuations [24].

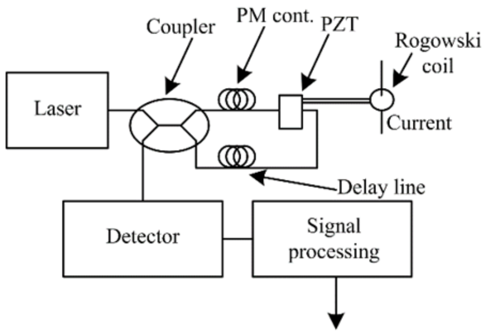

Fig. 5. Basic scheme of FOCS using Differentiating Sagnac Interferometer.

Next, it is discussed a new configuration of FOCS which increases the linearity range of the device without decreasing its sensitivity. In this way, the whole system behaves as a "null-detector". However, the effect of bending-induced linear birefringence is taken into account in the design and optimization of the sensor. It is shown that the response of the experimental apparatus is temperature independent and that its bandwidth gets values higher than 1 MHz [25].

Fiber-optic current sensor based on the Faraday effect of magneto-optic materials, in the isotropic optical transparent medium, and the magnetic field can make the plane polarized light propagating polarization plane rotated along the magnetic field. By mathematical optimization method, paper [26] discusses the end fitting, the average points fitting, least square method, and the optimal linear least absolute deviation method which is applicated to the linear characteristics of the fiber-optic current sensor. The results show that different linear fitting methods have different results. Using the least square method and best linear fitting method (regression line) obtained FOCS's linearity fitting degree is ± 0.069 % and ± 0.071 % respectively.

The error drift caused temperature shift reduces the accuracy of FOCT. Using two models, authors quantitatively researched the error ratio drift, and obtained temperature characteristics of FOCT: within the tested range of temperature (10~60 °C), both the FOCT ratio error and linear birefringence phase difference changes linearly with temperature [27].

The residual linear birefringent of sensing fiber, temperature and vibration sensitivity severely influence the accuracy of Sagnac fiber-optic current sensor. A sensing fiber can be used in FOCS with spun high-birefringent fiber. This S Hi-Bi fiber includes three sections: two terminal sections with variable spin-rate along fiber were utilized to substitute the fiber quarter-wave plates, respectively converting the light polarization state from the linear one to the circle one, and vice versa; and the middle section with a uniform spin-rate was utilized as the current sensing fiber which maintains the circular state polarization and compresses the residual linear birefringent during the light propagation [28].

The fiber-optic current sensors utilize the effects of magnetic-field imposed on the change of polarization state of light in the fibers. This sensor has a lot of advantages over conventional current sensors, see Fig. 6. To eliminate the vibration sensitivity, an improved light path of the reflective fiber-optic current sensor is proposed, which makes the discharge of Sagnac effect with Sagnac effect itself and do not disturb Faraday effects [29].

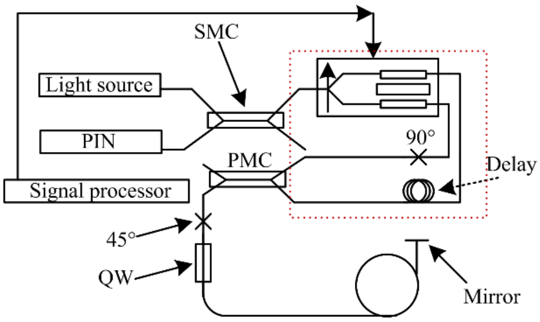

Fig. 6. Basic scheme of a novel fiber-optic current sensor.

To improve the performance, a fiber-optic current sensor was presented and using Jones matrix, its polarization error was studied. By establishing the Jones matrix expression of the main optical devices, an interference expression of this sensor was introduced and the influence of imperfection of optical devices on the measurement accuracy was analyzed [30].

High-precision methods and devices are one of the most important modern engineering development lines in optimal energy consumption sphere. However, there are a few small-sized instruments which allow conducting precision measurements without breaking the circuit. Paper [31] presents information about conducted Faraday Effect research and general construction of the simple fiber-optic current sensor (FOCS).

In 2005, ABB introduced a high-performance fiber-optic current sensor for the measurement of DC up to 600 kA. Recently, ABB has developed the sensor further with a view to implementing it in high-voltage substations. It can be integrated into primary high-voltage equipment such as circuit breakers. By appropriately selecting the number of fiber loops, the measurement range can be optimized for specific applications [32].

According to the polarization coupling model of the polarization-maintaining delay fiber coil, considering the reciprocal parasitic waves with large amplitude, the interference intensity of the optical system in the fiber-optic current sensor (FOCS) is calculated, and the theoretical relationship between the scale factor and the polarization crosstalk of the delay fiber coil is obtained. The effect mechanism of the temperature dependence of the polarization crosstalk on the scale factor is revealed, and the corresponding suppression methods are proposed. The experimental results show that the temperature dependence of the FOCS can be improved greatly when lowering the tension of winding fiber, reducing the quantity of the glue, and utilizing the frame with low-temperature coefficient. The variation of the scale factor is decreased from 0.63 % to 0.07 % over the temperature range from -40 °C to 70 °C [33].

In Sagnac interferometer fiber-optic current sensor, errors from the residual linear birefringence and environmental temperature and vibration sensitivity severely influence the accuracy of this sensor. The spun highly linearly birefringent fiber was designed and the vibration insensitive Sagnac interferometer fiber-optic current sensor scheme was set up. In this scheme, the compensation fiber coil was designed to compensate the error caused by Sagnac effect in sensing fiber coil [34].

The fiber-optic current sensor was presented. According to a characteristic of interference signal, square wave modulation technique was applied to enhance the sensitivity of FOCS, and correlative demodulation scheme was proposed to show phase difference information. The sensor achieved accuracy within ± 0.25 % at -40~60 °C and the bandwidth exceeded 6 kHz [35].

ABB developed a new configuration of air-insulated switchgear (AIS) substations by using new circuit breaker (CB) technologies and optical sensors. The new disconnecting circuit breaker (DCB) 'Combined' placed inside the breaking chamber without any other components. The fiber-optic current sensors based on the Faraday effect is able to determine the current with a fiber-optic loop integrated with the conductors. FOCS also provide an interface with process-level devices for a substation automation system (SAS). The use of new DCB and optical sensors can improve the performance, efficiency, and reduce the footprint of a substation [36].

The nonlinearities of the response of an interferometric fiber-optic current sensor, which is associated with deviations of the light waves from perfect circular polarization, are investigated. The consequences of inherent temperature compensation of the Faraday effect using a non-90°-retarder are investigated for currents up to several 100 kA and temperatures between - 40 °C and 80 °C. The results are of particular interest to sensors for high DC in the electro-winning industry where measurement accuracy of ± 0.1 % is required up to 500 kA [37].

Fiber-optic current sensors (FOCS) based on Faraday magneto-optical effect have plenty of advantages in comparison to the traditional current sensors. However, the residual linear birefringence and environmental vibration sensitive problem are the fatal drawback in Sagnac fiber-optic current sensors. A vibration immunity sensing loop with a function of passive fiber-optic polarization control is proposed, which consist of a spun or twisted fiber with highly birefringence. A spun or twisted fiber possesses two crucial functions: Remove the residual linear birefringence and control polarization of light. It has been demonstrated that this FOCS has high sensitivity, considerable wide dynamic range, resistance to electromagnetic interference, and immunity of vibration [38].

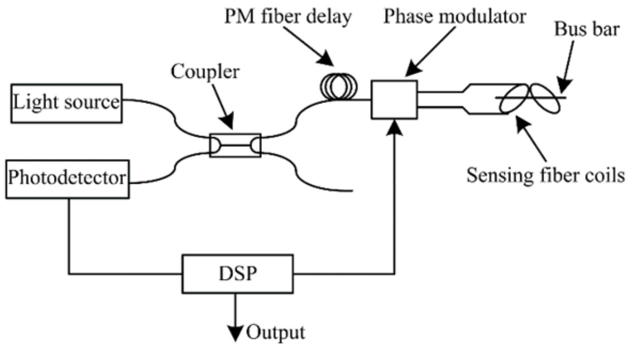

Fig. 7. Basic scheme of principle of S-FOCS.

The intrinsic birefringence of the sensing fiber is the main cause which affects the precision of measurement, and elimination of this cause is the key research topic. In paper [39] an interferometric fiber-optic current sensor configuration with a conjugate reflector is presented. The results show that the configuration with a conjugate reflector is more insensitive to linear birefringence than the configuration with an ordinary reflector. The residual linear birefringence of the sensing coil is about 6 times than that in ordinary mirror configuration for ± 0.2 % measuring accuracy.

Firms require highly accurate DC current sensors to control their processes and operations. FOCS has suitable performance and functionality and is smaller and lighter. Using the FOCS accuracy increased by 10 times, specified accuracy is maintained over a wide temperature range, and large bandwidth to enable rapid response to current ripple and transients. FOCS is also responsible for handling uniand bi-directional DC to ± 500 kA with negligible power consumption [40].

ABB developed a sensor that represents a quantum leap in high DC measurements. This sensor offers outstanding precision and is smaller, lighter and much less complex than traditional transducers and it is about to change the future of high DC measurements. The new fiber-optic current sensor (FOCS) for high DC makes use of the Faraday effects [41].

The problem of polarimetric sensors is not discussed in this paper, but currently polarimetric sensors are also commonly used. Information on polarimetric sensors is available in articles published in the Electrical Review or in article [42].

Conclusion

This article is to summarize the interesting practical and theoretical published results to date, approaches and basic principles based on Faraday effect leading to the analysis and to defining the electrical values such as electrical current using the fiber-optic technology. Fiber-optic current sensor benefits are obvious and very useful for current applications The high accuracy, high bandwidth: detection of current ripple and transients, wide temperature range, no magnetic centering necessary, no magnetic overload problem, immunity to electromagnetic interference and many others.

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References

[1] P. Siddons, N. C. Bell, Y. Cai, C. S. Adams, and I. G. Hughes, “A gigahertz-bandwidth atomic probe based on the slow-light Faraday effect,” Nat. Photonics, vol. 3, no. 4, 2009.
[2] L. Weller, K. S. Kleinbach, M. A. Zentile, S. Knappe, I. G. Hughes, and C. S. Adams, “Optical isolator using an atomic vapor in the hyperfine paschen-back regime,” Opt. Lett., vol. 37, no. 16, 2012.
[3] E. Prati, “Propagation in gyroelectromagnetic guiding systems,” J. Electromagn. Waves Appl., vol. 17, no. 8, 2003.
[4] M. L. Kales, “Modes in wave guides containing ferrites,” J. Appl. Phys., vol. 24, no. 5, 1953.
[5] S. Mancuso and S. R. Spangler, “Faraday rotation and models for the plasma structure of the solar corona,” Astrophys. J., vol. 539, no. 1 PART 1, 2000.
[6] W. F. Magie, “Faraday’s Diary,” Science (80-.)., vol. 77, no. 1995, 1933.
[7] J. Du, Y. Tao, Y. Liu, L. Ma, W. Zhang, and Z. He, “Highly sensitive and reconfigurable fiber optic current sensor by optical recirculating in a fiber loop,” Opt. Express, vol. 24, no. 16, 2016.
[8] F. Yang, X. Hou, Y. Huang, and N. Peng, “Optical fiber current sensor with small size for the high voltage watt-hour meter,” in Proceedings of SPIE - The International Society for Optical Engineering, 2016, vol. 10158.
[9] M. Wuilpart, B. Vanus, A. Andrasan, A. Gusarov, P. Moreau, and P. Mégret, “Study of a fibre optics current sensor for the measurement of plasma current in ITER,” in Proceedings of SPIE - The International Society for Optical Engineering, 2016, vol. 9916.
[10] S. Cheng, Z. Guo, G. Zhang, W. Yu, Y. Shen, and S. Jin, “The analysis on temperature characteristic of fiber optic current sensor ratio error,” in Proceedings - 5th International Conference on Instrumentation and Measurement, Computer, Communication, and Control, IMCCC 2015, 2016.
[11] L. Wang, M. Cao, Q. Liu, G. Wei, B. Li, and C. Lin, “Modeling and experimental verification of polarization errors in Sagnac fiber optic current sensor,” Optik (Stuttg)., vol. 126, no. 20, 2015.
[12] R. Zhang, X. S. Yao, T. Liu, and L. Li, “The effect of linear birefringence on fiber optic current sensor based on Faraday mirror,” in Proceedings of SPIE - The International Society for Optical Engineering, 2014, vol. 9274.
[13] P. Nai, S. Wang, and W. Tao, “A special spun birefringent fiber optic current sensor,” in Proceedings - 2013 12th International Conference on Optical Communications and Networks, ICOCN 2013, 2013.
[14] C. Zhang, C. Li, X. Wang, L. Li, J. Yu, and X. Feng, “Design principle for sensing coil of fiber-optic current sensor based on geometric rotation effect,” Appl. Opt., vol. 51, no. 18, 2012.
[15] A. Prakash et al., “Development of fiber optic current sensor for electric power industry application,” in 2012 International Conference on Fiber Optics and Photonics, PHOTONICS 2012, 2012.
[16] C. Zhang, C. Wang, and S. Chen, “Theory and experimental research of a Y-phase-modulator based optical fiber current sensor,” in Proceedings of SPIE - The International Society for Optical Engineering, 2011, vol. 8199.
[17] S. Zhou and X. Zhang, “Simulation of Linear Birefringence Reduction in Fiber-Optical Current Sensor,” IEEE Photonics Technol. Lett., vol. 19, no. 19, 2007.
[18] S. G. M. Krämer, F. P. León, Y. N. M. Hernández, and B. Lewke, “Integration of a distributed fiber optic current sensor setup for lightning detection in wind turbines,” in Conference Record - IEEE Instrumentation and Measurement Technology Conference, 2007.
[19] J. L. Flores, G. García-Torales, and V. H. Ortiz, “Optical current sensor using phase shift algorithms,” in Proceedings of SPIE - The International Society for Optical Engineering, 2007, vol. 6770.
[20] K. Bohnert, H. Brändle, M. G. Brunzel, P. Gabus, and P. Guggenbach, “Highly accurate fiber-optic dc current sensor for the electrowinning industry,” IEEE Trans. Ind. Appl., vol. 43, no. 1, 2007.
[21] S. J. Petricevic, Z. Stojkovic, and J. B. Radunovic, “Practical application of fiber-optic current sensor in power system harmonic measurement,” IEEE Trans. Instrum. Meas., vol. 55, no. 3, 2006.
[22] V. P. Gubin et al., “All-fiber optical sensor of electrical current with a SPUN fiber sensing element,” in Proceedings of SPIE - The International Society for Optical Engineering, 2006, vol. 6251.
[23] P. Mihailovic, S. Petricevic, Z. Stojkovic, and J. B. Radunovic, “Development of a portable fiber-optic current sensor for power systems monitoring,” IEEE Trans. Instrum. Meas., vol. 53, no. 1, 2004.
[24] T. Wang, C. Luo, and S. Zheng, “A fiber-optic current sensor based on a differentiating Sagnac interferometer,” IEEE Trans. Instrum. Meas., vol. 50, no. 3, 2001.
[25] A. Irace, G. Breglio, A. Luciano, L. Zeni, and A. Cutolo, “A novel configuration for a wide-range high-power fiber-optic current sensor,” Eur. Trans. Electr. Power, vol. 7, no. 5, 1997.

[26] Z. Yue, W. Xiaofei, and M. Hao, “Study on the characteristics of all fibre optical current sensor linear fitting algorithm,” in 2015 IEEE 12th International Conference on Electronic Measurement and Instruments, ICEMI 2015, 2016, vol. 3.
[27] S. Cheng, Z. Guo, G. Zhang, Y. Shen, P. Song, and H. Huang, “Temperature characteristic of fiber optic current sensor,” Gaodianya Jishu/High Volt. Eng., vol. 41, no. 11, 2015.
[28] Y. Wang, M. Kang, L. Ren, and K. Ren, “Design of spun high-birefringent fiber for fiber optic current sensor,” Hongwai yu Jiguang Gongcheng/Infrared Laser Eng., vol. 44, no. 1, 2015.
[29] S. Tao, F. Yue, L. Yipu, Z. Mengxue, D. Hailong, and W. Xinlao, “Simulation of polarization errors for all-fiber optic current sensors,” in Proceedings - 8th International Conference on Future Generation Communication and Networking, FGCN 2014, 2014.
[31] P. Liu, K. Chen, S. Chen, and Z. Liu, “Study on polarization errors of re-entrant fiber-optic current sensor,” Bandaoti Guangdian/Semiconductor Optoelectron., vol. 35, no. 2, 2014.
[31] M. G. Grigoriev and N. V. Turushev, Development of fiber optic current sensor, vol. 1040. 2014.
[32] K. Bohnert, R. Thomas, and M. Mendik, “Light measures current: A fiber-optic current sensor integrated into a high-voltage circuit breaker | Strom messen mit Licht: Faseroptischer Stromsensor in einem Hochspannungs-Leistungsschalter,” ABB Rev., no. 1, 2014.
[33] C. Li, C. Zhang, H. Sun, and H. Cui, “Effect of polarization crosstalk of polarization-maintaining delay optical fiber coil on the fiber-optic current sensor,” Zhongguo Jiguang/Chinese J. Lasers, vol. 41, no. 11, 2014.
[34] Y. Wang, M. Kang, L. Ren, K. Ren, J. Xu, and N. Shi, “A novel compensation fiber coil for eliminating Sagnac Effect in fiber optic current sensor,” in Chinese Control Conference, CCC, 2013.
[35] C.-Y. Zhang, C.-X. Zhang, X.-X. Wang, Z.-F. Ma, and Q.-Q. Liu, “Signal processing system for digital closed-loop fiber optic current sensor,” Zhongguo Dianji Gongcheng Xuebao/Proceedings Chinese Soc. Electr. Eng., vol. 29, no. 30, 2009.
[36] L. Jing, H.-E. Olovsson, J. Fan, and R. Thomas, “Small footprint high performance,” ABB Rev., no. SPEC. REP., 2008.
[37] K. Bohnert, P. Gabus, J. Nehring, S. Wiesendanger, A. Frank, and H. Brändle, “Nonlinearities in the high-current response of interferometric fiberoptic current sensors,” in Proceedings of SPIE - The International Society for Optical Engineering, 2008, vol. 7004.
[38] M. Kang, Y. Wang, J. Xu, K. Ren, and S. Liu, “Vibration immunity fiber optic current sensor employing a spun or twisted highly linear birefringence fiber,” in Chinese Control Conference, CCC, 2013.
[39] B. Jiao, Z. Wang, F. Liu, and W. Bi, “Interferometric fiber-optic current sensor with phase conjugate reflector,” in Proceedings of IEEE ICIA 2006 - 2006 IEEE International Conference on Information Acquisition, 2006.
[40] K. Bohnert and P. Guggenbach, “Innovation in high DC current measurement,” Elektron, vol. 22, no. 7, 2005.
[41] K. Bohnert and P. Guggenbach, “A revolution in high dc current measurement,” ABB Rev., no. 1, 2005.
[42] S. Torbus, “Frequency analysis of work of polarimetric current sensor with measurement coil made with the single mode optical fiber not resistant to bending,” in Przegląd Elektrotechniczny, vol. 2017, no. 6, 2017.