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Editorial

Problems during the Design and Testing of Instrument, Special and Power Transformers: The Outlook

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In 1831, Michael Faraday discovered the phenomenon of electromagnetic induction, which allowed for the construction of previously unknown electrical devices and significantly impacted economic and social development. Transformers work on the principle of Faraday's law and are used to transform electrical energy (changing voltage and current values). Ottó Bláthy, Miksa Déri, and Károly Zipernowsky from Austria-Hungary initiated the design and use of transformers for both experimental and commercial purposes and patented the single-phase transformer in 1885.

The pioneer of alternating current technology was Tesla, but it was Michał Doliwo-Dobrowolski who invented the 1891 squirrel cage motor and three-phase power transformer and energy transmission system. In Europe, the first experimental transmission of energy via a three-phase 15 kV high-voltage line took place in 1891 (from a hydroelectric power plant to Frankfurt am Main via a 178 km long line) under the leadership of Doliwo-Dobrowolski.

As the transmitted power and voltages of transmission lines increased, instrument transformers became an essential element of the measurement system, and the requirements for their accuracy also began to rise.

In 1895, transformers began to be used to measure voltage, and in 1899, Siemens patented the current transformer. Increasing powers and voltages increased the role of instrument transformers as measuring and protection devices, resulting in increased requirements for the accuracy of instrument transformers, especially when measuring the amount of energy produced. Instrument transformers are part of power systems [1]. They aim to transmit operating current and voltage values for measurement or protection applications. So, the design problems of instrument transformers differ from those of power transformers problems [2]. Power transformer standards IEC/EN 60076, IEC/EN 60726, IEC/EN 61558, and IEC/EN 60551 apply to both 1- and 3-phase transformers, voltage values, losses in transformers, and noise levels. However, although the principle of operation of instrument transformers is the same as that of a power transformer, the requirements placed on them concern the conversion of currents and voltages with high accuracy [3,4]. The standards vary depending on the type of instrument transformer; current, voltage, combined, measurement, insurance, for steady, and transient state but are also very restrictive ICE/EN 61896-1 and etc. For example, classes of 0.1, 0.2, and 0.5 are required for measuring current transformers, i.e., the amplitude error in percent and phase shift errors in minutes.

Currently, designs other than inductive instrument transformers have appeared, such as electronic and optoelectronic instrument transformers based on the Faraday magneto-optical phenomenon [5] and the Pockels effect using optical fibers [6], as well as transformers using microwaves and the so-called Bluetooth technology. However, induction instrument transformers are still most often used due to their reliability, and problems related to the design of more and more accurate structures still exist.

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Special transformers are often single phase and built for various particular purposes, e.g., short circuits, welding, testing, semiconductor, and safety transformers [7,8].

In this Special Issue of *Energies*, in addition to issues related to three-phase power transformers (contribution 1–4), problems of measurement transformers are addressed in articles (contribution 5,6) and a review article (contribution 7). However, the authors of (contribution 5,8–10) analyzed special transformers. In addition, there is also a review article (contribution 11), which presents exciting transformer models implemented using the SPICE program, considering the nonlinearity of magnetization characteristics and magnetic couplings, thermal compressions, and temperature differences [9].

The authors of (contribution 1) studied the physical phenomena occurring in a three-phase power transformer during the first period of its power supply. The problem of limiting inrush current surges in 3-phase power transformers is a current one and has also been the subject of other articles, e.g., [10]. The research used a nonlinear model based on classical modeling, which does not consider hysteresis. The model is described using a system of stiff, nonlinear ordinary differential equations. Computational methods that considered the influence of residual magnetism in various columns of the transformer core and the influence of the time moment determined in the voltage waveform at which the indicated voltage is applied to a given transformer winding were examined.

The authors of (contribution 2) compared 3D and 2D finite element models of a power transformer designed for reactive power compensation stations. The results of numerical 2D and 3D calculations of no-load current and losses in the transformer core were obtained and compared with data measured at the test station. Correctly estimating power losses is essential for the correct operating conditions of the transformer. Even moderate excesses of rated oil temperatures may release excessive amounts of dissolved gases [11]. The impact of considering the hysteresis loop phenomenon on the calculation of core losses was investigated using the Jiles–Atherton model [12]. The equivalence of two- and three-dimensional numerical models has been described in a previous publication [13]. The results presented in this paper also show that the numerical model should consider the area of core overlapping.

In turn, the authors of (contribution 3) considered the forces that can appear in conductors connecting the transformer windings and on-load tap changers during short-circuit conditions, which may lead to extremely dangerous electromechanical effects [14].

A mechanical transient simulation was analyzed in [15] to determine the deformation and mechanical stresses in the busbar system, which has a simple geometry and linear material properties.

Through repeated 3D numerical experiments, standard analytical formulas were extended to consider the presence of a ferromagnetic plate and proximity effects introduced by eddy currents inside the conductors. It makes it possible to overcome the limitations of the so-called multi-physics approach [16] and calculate the realistic structures of transformer leads.

The authors of (contribution 4) presented a step-by-step methodology for calculating the vibrations of the transformer tank caused by electromagnetic forces acting in the phase windings. In their approach, they use three-dimensional finite element models to calculate the distribution of forces and the acoustic pressure field in an oil-filled tank. A key factor in this analysis is the cross-domain data connection algorithm. The calculation results are verified by measuring the vibrations of the tank walls. The detailed model of the transformer, including the winding structure reduced to its orthotropic equivalent, was analyzed in [17] using the coupled magneto-mechanical approach. A similar treatment but extended to the real coil distribution in space may be found in [18]. In both of these works, a two-stage 2D-3D transformer model was used with considering construction details.

Instrument transformers are an element of the power measurement system; these devices process signals but add their transformation errors to the measured values. International Electro-technical Commission (IEC) standards require designers to identify and limit these errors. Moreover, by coupling the primary and secondary circuits, instrument transformers enable the propagation of electromagnetic disturbances generated in their primary circuit [19]. Problems with measurement accuracy are becoming more important due to the use of non-linear receivers and distributed generation units with uneven electricity production depending on external factors that cause deformation of the voltage shape in the power system. Also, due to their magnetic characteristic, instrument transformers operating in an overcurrent state may be an element introducing higher harmonics into measurement systems.

The authors of (contribution 6,7) studied the influence of higher harmonics of supply (up to the 100th harmonic) on the accuracy of measuring inductive instrument transformers. The authors of (contribution 7) present a review article that discusses advanced work devoted to characterizing the accuracy of the transformation of currents and voltages distorted by inductive voltage and current transformers.

Special current transformers deserve special attention.

Electronic instrument transformers using low signals from a Rogowski coil are known [20]. However, they have not found widespread use. Nevertheless, the authors of (contribution 10) developed an electronic DC transformer, where it is impossible to apply Faraday's law to change the voltage and current values. The work is innovative and interesting, mainly because electricity is sometimes transmitted via direct current lines. HVDC direct current transmission technology has been developed and improved since the first half of the 20th century, and now—especially in the face of energy transformation—is gaining importance [21]. A limitation of HVDC is also the complexity of the electrical energy conversion process and operation of HVDC stations—(this also applies to electronic DC current transformers). Lem's DC current transformers are known, but in (contribution 10), a different method of measuring current was proposed; this method involves using Hall sensors without iron cores, significantly reducing environmental interference during measurement. The authors focused on the accuracy of this method, i.e., the precise measurement and calibration of the delay time of an electronic DC current transformer under operating conditions.

In turn, the authors of (contribution 5) studied the known through-line primary conductor current transformer with a unique application and a particular design. Due to its application, it can be said to belong to both measuring current transformers and special transformers. Compared to classic through-line current transformers, the difference is that instead of the primary wire with a current of approximately several to several dozen kiloamps, a beam of particles passes through the center of the core.

This creates other measurement conditions, and it turns out that the non-uniform magnetic permeability of the ferromagnetic sheets around the core circumference influences the measurement accuracy. Therefore, what is new here is the design used by the authors to compensate for inaccuracies in the distribution of the core material. In this way, they obtained an amplitude error of 0.1%, i.e., a current transformer with very high accuracy. It enables precise measurements of the number of particles contained in the beams of the Large Hadron Collider at CERN [22]. The technology described and tested in the laboratory constitutes a significant advance in the state of knowledge in the instrumentation of super-accurate current transformers.

The authors of (contribution 8,9) special single-phase transformers, which have opposing design assumptions due to their operation. These are special high-power transformers that operate practically in the state of short circuits. The no-load condition for these types of transformers is an emergency, not an operating condition. Therefore, they are tested in the short-circuit condition, and the parameters of the transverse branch of the transformer equivalent circuit are irrelevant. The leakage inductance of these transformers is a critical design parameter.

The authors of (contribution 9) studied a semiconductor transformer operating in a system with electronic elements. For the proper operation of the entire system, obtaining the lowest possible transformer leakage inductance is necessary because the power that the transformer can transfer depends on it. The dissipation flow is unfavorable because it partially passes through the core, causes additional heat release, and thus limits the power transferred to the secondary circuit. This article considers the problem of selecting the type of transformer windings that will provide the lowest leakage inductance. Interleaved windings of the Litz type [23] and windings made of thin aluminum foil [24,25] were considered. The developed 3D model of a transformer with a GOES steel core considers the phenomena of current displacement and proximity in the windings. The results were compared with measurements made on the prototype.

In turn, the authors of (contribution 8) described the problems of designing a dissipation transformer with increased leakage reactance, powering systems operating in a near-short-circuit state, where there is a need to limit the short-circuit current. Such a device must ensure the continuity of the electric arc and prevent the flow of high current in the event of a short-circuit of the electrodes. These include car starting transformers, welding machines, soldering irons, and welding transformers [7]. The authors analyzed the magnetic field dissipation in a transformer with beveled edges and a magnetic shunt. The reactance of the fault transformer was calculated as a parameter for the selected position of the magnetic shunt. Point measurements of magnetic flux density vectors and winding reactance were carried out to verify the calculation results.

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