# Editorial

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The transformer is one of the most vital and expensive apparatus in an electric power system, and its reliability is of highest importance. The transformer's performance depends heavily on its electrical insulation system, as insulation failure almost always renders a transformer failure. Therefore, the electrical insulation is perhaps the most critical transformer internal part. In transformer failure surveys, the windings, tap changer, and bushing-related failures were the major contributors, followed by lead exit-related failures, irrespective of application or manufacturing period [1], [2].

The physical foundations for electromagnetism were laid through the experimental work by H. C. Oersted (1820), A. M. Ampere (1822), and M. Faraday (1831), which were later expanded theoretically by J. C. Maxwell (1861). The first practical transformer employing the principles of electromagnetism was invented in 1884 and patented in 1885 by the team of K. Zipernowsky, M. Déri, and O. Bláthy, from Ganz Companies in Budapest (then Austro-Hungarian Empire). Practically at the same time, similar development of transformers took place in the USA by W. Stanley, working with G. Westinghouse (1886), and by S. de Ferranti in England. In 1889 M. Dolivo-Dobrovolsky developed the first three-phase transformer at AEG in Germany [3]–[5]. Since then, during more than a 130-year-long history, the transformer fundamentals remained the same; however, this apparatus underwent dramatic changes as far as basic parameters and new applications are concerned. The rated operating voltage increased from several kilovolts to 1,200 kV (AC) and 1,100 kV (HVDC). The rated power increased from several kilowatts to more than 1,000 MW [6], [7]. In order to achieve such high values of rated parameters, the marked progress in transformer engineering, insulating materials, magnetic materials, conductors (oxygen-free copper and large continuously transposed cables), high voltage technology, thermal-hydraulic theory, cooling technology, etc. was required.

Although the small power transformers represent the largest part of the power transformer market, primarily due to their use in various applications, the large power transformers—as a result of recent advancements in their power ratings—represent the fastest growing segment. With emphasis on reducing the transmission losses, the implementation of high voltage transmission technologies such as EHV, UHV, and UHVDC has also significantly increased, especially in China and India. To see an example of the largest transformers, one may take a closer look at a recently built and tested 1,1000-kV HVDC, single-phase, 587-MVA unit with dimensions of 37.5 m in length, 14.4 m in height, 12 m in width, and close to 900,000 kg in weight. This unit passed dielectric tests at the following levels: AC applied voltage at 1,292 kV, switching impulse at 2,100 kVp, lightning impulse 2,300/2,530 kVp (FW/CW), DC applied 1,786 kVdc, and polarity reversal +/− 1,384 kVdc (see a photograph of this transformer on the front cover of this magazine) [8], [9].

In general, the dielectric strength of a liquid-cellulose insulation system depends on the duration of voltage application, polarity of voltage, field enhancement factor, area and shape of electrodes, kind and degree of contamination of the oil, its temperature and pressure, and type of insulating liquid (mineral oil, natural or synthetic ester). The transformer insulation design should be prepared with careful consideration for all these aspects. Ongoing development of insulating structures using the molded or formed pressboard parts allows for operation at higher electric stresses and results in a reduction of size, weight, and cost of the transformer. The transformer designers optimize the pressboard barrier structures using the two- and three-dimensional electric field calculations. Materials commonly used in power transformer insulation systems are (1) insulating fluid: mineral oil, synthetic or vegetable esters; (2) conductor insulation: paper (cellulose-based Kraft, synthetic aramid—Nomex®, mixed aramid and cellulose) or enamel coating; and (3) "solid" insulation, dividing and supporting the winding sections and spaces between the windings (i.e., barriers, blocks, spacers), made of pressboard for high voltage units or transformer wood (densified laminated wood) or pure wood (maple or beech wood) for lower voltage applications (e.g., [10]–[12]).

The magnetic material commonly used in large power transformer design is cold-rolled grain-oriented steel (CRGO), characterized by high permeability, low loss, and low magnetostriction. The losses generated in the CRGO steel can be divided into (1) a hysteresis loss, dependent on grain size and orientation, and (2) an eddy loss, dependent on the sheet thickness and silicon content. The classical eddy loss—as described by theoretical dependence on the squared values of frequency, thickness, and magnetic induction—is, in reality, higher than calculated by a theoretical equation, and this additional loss, generated by domain wall motion, is called an anomalous or excess eddy current loss and may be as high as 50% of total core loss [13], [14]. Therefore, the CRGO steel manufacturing processes are focusing on reduction of the anomalous eddy loss through surface modifications reducing the size of magnetic domains. This may be achieved by mechanical or chemical means, but the best results are obtained by laser irradiation (scribing) [15], [16]. The modern CRGO steel sheet thickness used in low loss, large power transformers was for several decades 0.23 or 0.27 mm and recently was reduced to 0.20 mm, allowing for further loss reduction [15]. Very important is the interlaminar

**Figure 1.** Hydro One Networks Inc. deployed two 230 × 115 kV, 30-MVA mobile transformers designed and built by PTI Transformers LP (Winnipeg, Canada) in an emergency situation at Minden substation, Toronto area, in August 2018. Published with permission of Hydro One Network Inc.

sheet insulation created by the surface coating, typically based on an inorganic substance with ceramic fillers. Critical to core performance is proper cutting of the sheets, without excessive burrs, achieved with computer-controlled shearing machines. The air gaps between laminations should be as small as practically possible, which is achieved by experienced personnel during the core stacking process or—more and more often, especially for lower power units—by automatic core stackers. All these core features are extremely important, as any problem with insulation, burrs, or large air gaps can result in conditions allowing for the core current circulations leading to overheating and gassing of the core during the factory test or in service.

The use of high temperature materials, such as aramid papers and boards, as well as ester fluids, resulted in the design and manufacture of large emergency units, or mobile substations. Recently, Con Edison, New York City's energy utility, requested a spare power transformer that was mobile, versatile in its applicability, and at the same time quick to install and environmentally friendly, allowing restoration of the electric power within a few days instead of weeks. A solution was a bank of three single-phase units, enabling reconnection to the 335/136 kV system (300 MVA) or the 132/68 kV system (150 MVA), with compact dimensions and relatively low weight of 95,000 kg [17], [18]. More conventional mobile transformers and substations using high-temperature insulation and compact design, allowing reconnection to different service voltages on both HV and LV sides, are more and more commonly used (Figure 1).

The concept of a mobile solution was taken to the extreme through the Saudi National Grid's request to design and build a 400-kV substation [19]. This enormous mobile substation consists of seven large trailers, carrying the three single-phase power transformers, the 400-kV and 132-kV circuit breakers, the SCADA and telecommunication equipment, and the connection tools and gantries (Figure 2). These mobile substations allow fast and reliable deployment, either for temporary or standby emergency electrical power transmission as well as in new and fast track projects. In some circumstances the mobile substation may be used as a permanent transmission solution (e.g., in remote and challenging areas).

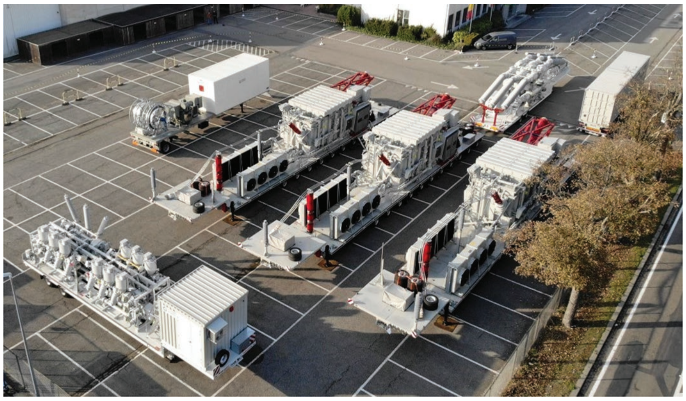

**Figure 2.** CG Belgium designed and built a 400-kV mobile substation on seven trailers (with permission of CG Holdings Belgium NV).

For small power units, the solution that saves land; reduces overhead grids; eliminates fencing; reduces maintenance and outages associated with wildlife, weather, and trespassers, utilizing the most recently available quick connection and monitoring methods, was introduced [20]. The skid mounted concept and solution, a portable outdoor distribution substation (PODS), was designed, assembled, completely tested, and commissioned in the factory and delivered in one or two pieces, reducing on-site assembly to a few days. PODS are of a dead front design, often integrated with a vacuum type on-load tap changer, fluid containment, primary or feeder protection using reclosers or circuit breakers with controls configured with IEC 61850 communication protocols and DC batteries and backup. Another similar concept is a high voltage pad-mount transformer (HVPT) [21], which employs a modular dead front transformer connected underground to other apparatus or components, each located on their own pad. This concept accommodates using standard and approved apparatus and components arranged as preferred by each user, with high voltages up to 230 kV, with secondaries 48 kV and less (Figure 3).

The transformer manufacturing processes are under continuous development. Physical phenomena influencing the status of the insulation during assembly, during drying, and during and after oil impregnation are carefully considered to ensure the designed dimensions of the windings and active parts and required clamping forces [22].

The transformer in operation is subjected to numerous phenomena affecting its insulation. Aging processes—pyrolysis, hydrolysis, and oxidation—as well as partial discharges gradually weaken the solid insulation. Precise assessment of the status of the insulation, especially in operation under overload conditions, is still a challenge to power utilities, since available methods (DGA, furan analysis, methanol analysis, partial discharge detection and location, etc.) are not perfect. Nonetheless, they are in constant development, bringing new methods (e.g., Duval pentagon) or improved monitoring systems (PD location using electrical, acoustic, and UHF methods), comparing the test results to the performance in service, etc. (e.g., [23]–[30]).

**Figure 3.** 115-kV and 69-kV, 10-MVA HVPT and 138-kV and 72-kV, 12.5-MVA PODS manufactured by PTI Transformers LP (Regina, Canada) for utilities in central Canada.

One may summarize that in the second century of transformer technology existence, the progress is still happening and very much is needed in the future.

## References

[1] WG A2.37, "Transformer reliability survey," Cigre Technical Brochure 642, 2015.

[2] W. Ziomek, "Editorial," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 19, no. 6, Dec. 2012.

[3] D. J. Allan, "Power transformers—The second century," *IEE Power Eng. J.*, vol. 5, pp. 5–14, Jan. 1991.

[4] A. A. Halacsy and G. H. Von Fuchs, "Transformer invented 75 years ago," *Trans. Am. Inst. Electr. Eng., Part III: Power Apparat. Syst.*, vol. 80, pp. 121–125, Jun. 1961.

[5] S. Jeszenszky, "History of transformers," *IEEE Power Eng. Rev.*, pp. 9–12, Dec. 1996.

[6] WG B4.60, "Designing HVDC grids for optimal reliability and availability performance," Cigre Technical Brochure 713, 2017.

[7] L. Zehong, G. Liying, W. Zuli, Y. Jun, Z. Jin, and L. Licheng, "R&D progress of ±1100kV UHVDC technology," Cigre Session 2012, B4-201_2012.

[8] World's First 1,100 kV HVDC Transformer. [Online]. Available: https://www.siemens.com/press/en/feature/2018/energymanagement/2018-01-1100kv.php

[9] R. Wimmer, R. Fritsche, T. Hammer, W. Kutzleb, K. Loppach, L. Zheong, and Z. Jin, "Introduction of a new level of HVDC to UHVAC linked systems with respect to main component transformer technology and design," Cigre Session 2018, B4-126, 2018.

[10] H. P. Moser, *Transformerboard*. Scientia Electrica, 1979.

[11] D. J. Tschudi, "AC insulation design," presented at the WICOR Insulation Conf., Rapperswil, Switzerland, Sep. 1996.

[12] W. Ziomek, K. Vijayan, D. Boyd, K. Kuby, and M. Franchek, "High voltage power transformer insulation design," presented at the IEEE Electrical Insulation Conf., Annapolis, MD, 2011.

[13] G. Bertotti, *Hysteresis in Magnetism*. Academic Press, 1998.

[14] Y. Gao, Y. Matsuo, and K. Muramatsu, "Investigation on simple numeric modeling of anomalous eddy current loss in steel plate using modified conductivity," *IEEE Trans. Magnet.*, vol. 48, no. 2, Feb. 2012.

[15] Nippon Steel, "Electrical sheets," Tokyo, Japan, 2018. [Online]. Available: http://www.nssmc.com/product/catalog_download/pdf/D003jec.pdf

[16] JFE Steel Corp., "Electrical steel sheets." [Online]. Available: http://www.jfe-steel.co.jp/en/products/electrical/catalog/f1e-001.pdf

[17] "Resilience power transformer installed in NY in record time," *Transform. Mag.*, Feb. 2017. [Online]. Available: https://www.transformers-magazine.com/tm-news/4014-siemens-installs-resilience-power-transformer-in-ny-in-a-record-time.html

[18] "Enabling resilience: Mobile resilience transformers," Siemens, 2016. [Online]. Available: https://www.energy.siemens.com/us/pool/hq/power-transmission/Transformers/grid-resilience/downloads/react/Case-Mobile-resilience-transformers.pdf

[19] "CG inaugurates world's first fully integrated 400 kV mobile substation." [Online]. Available: https://www.powertransformer-news.com/2018/11/09/cg-inaugurates-worlds-first-fully-integrated-400-kv-mobile-substation/

[20] "Portable outdoor distribution substation, PODS," PTI Transformers LP, Regina, Canada. [Online]. Available: https://www.partnertechnologies.net/wp-content/uploads/2016/04/PODS.pdf

[21] "High voltage padmount transformers," PTI Transformers LP, Regina, Canada. [Online]. Available: https://www.partnertechnologies.net/products/hv-padmount/

[22] Bengtsson et al., "CIGRE Reference Paper: Insulation condition during transformer manufacturing," Cigre, 2018 .

[23] A. J. Kachler and I. Hohlein, "Aging of cellulose at transformer service temperatures. Part 1: Influence of type of oil and air on the degree of polymerization of pressboard, dissolved gases, and furanic compounds in oil," *IEEE Electr. Insul. Mag.*, vol. 21, no. 2, pp. 15–21, 2005.

[24] T. V. Oomen and T. Prevost, "Cellulose insulation in oil-filled power transformers: Part II—Maintaining insulation integrity and life," *IEEE Electr. Insul. Mag.*, vol. 22, no. 2, pp. 5–14, Mar.-Apr. 2006.

[25] P. Boss, "Presentation of Cigre SC A2 'Transformers'; Technical developments and inputs from present activities," *Electra*, No. 242, 2009.

[26] A. Schaut and S. Eeckhoudt, "Identification of early-stage paper degradation by methanol," CIGRE, Paper A2-107, 2012.

[27] M. Duval and L. Lamarre, "The Duval pentagon—A new complementary tool for the interpretation of dissolved gas analysis in transformers," *IEEE Electr. Insul. Mag.*, vol. 30, no. 6, pp. 9–12, 2015.

[28] C. Rajotte, "Experience with transformer loading tests and direct temperature measurements in laboratory and in service," PaperA2-110, Cigre 2018 Session.

[29] B. W. Min, et al "Development of power transformer defect location detection technology using UHF partial discharge monitoring system," Paper A2-201, Cigre 2018 Session .

[30] J. Fuhr, et al "Localization of PD sources in transformers by analysis of signals in time and frequency domain," Paper A2-205, Cigre 2018 Session.

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