NEW OPTIONS FOR INSULATION SYSTEMS IN POWER TRANSFORMERS

by **Radoslaw Szewczyk**
and **Jean-Claude Duart**

Radoslaw Szewczyk received his master's degree in Electrical Engineering at Lodz University of Technology, Poland, in 1998. He works for DuPont™ Nomex® Electrical Infrastructure business as a Technical Service & Development Expert for EMEA region. With his background of transformer design engineer, he supports transformer developments with application of Nomex® insulation materials. He is a member of IEC, IEEE and CIGRE working groups.

Dr. **Jean-Claude Duart** has been employed at DuPont de Nemours in Switzerland since 1995. He currently works as Business Development Leader for the Nomex® Electrical Infrastructure segment, in charge of technical development in the area of power and distribution transformers. Dr. Duart received his PhD in Electrical Engineering from the University of Toulouse in France while working as R&D Engineer for Jeumont Schneider Transformers from 1990 until 1994. Dr Duart has published several international papers in both electrical insulation field as well as electrical arc ash protection. He is part of IEC TC112 and TC10.

Introduction

The development of new insulation materials has been critical in the evolution of the design of power transformers. **Insulation systems for liquid filled power transformers are a combination of materials that are aimed to provide the required electrical, mechanical, thermal properties together with a full chemical compatibility for successful operation of the transformer for several decades under defined operation conditions.**

Materials enabling innovative power transformer solutions

The offering of solid materials like papers or pressboards as well as dielectric fluids has been in constant evolution in the 20th century as the use of transformers was expanding through the development of electrical networks around the world. As the timeline in Figure 1 shows, several materials have played important role in the design of the transformers over the past century.

Insulation systems for liquid filled power transformers are a combination of materials that are aimed to provide the required electrical, mechanical, thermal properties together with a full chemical compatibility for successful operation of the transformer for several decades under defined operation conditions.

Photo: Shutterstock

While the first half of the 20th century has seen the development and combination of cellulose based materials for the solid insulation [1] and mineral oil for the fluid, the second half of the century has seen the arrival of new materials based on synthetic polymers.

Figure 1.
Timeline of main insulation materials for liquid filled power transformers

1920	1930	1940	1960	1970	1980	1990	2010
Kraft paper	Pressed board	PCB fluid	TUK paper	Silicone fluid	Synthetic ester fluid	Natural ester fluid	TUK paper with Nomex®
Mineral oil			Nomex® paper		Nomex® pressboard		

The options offered by the combination of various insulation materials allow more flexibility for the designers to develop transformers that will be able to operate in environments where new constraints have been evolving, whether they are related to space and weight restriction, loading profiles or ambient temperatures.

With the introduction of high-quality cellulose pulp, the production of cellulose paper with improved performance has seen tremendous progress initiated in the late 1920s making it the main choice of insulation combined with mineral oil. Another step was the introduction of thermally upgraded Kraft (TUK) papers in the 1960s. Already at that time the aim was to improve the thermal stability of the paper insulation, a limiting element when transformers have to overcome challenging load profiles or need to meet more stringent size and weight constraints.

About the same time, and in line with the interest of the chemical industry for developing products that featured advance characteristics, a 100% synthetic paper was developed based on the known polyamide polymer, most known under the name of nylon. Here again, in order to overcome the thermal limitation of the nylon, the polymer was modified to integrate aromatic rings that would provide improved thermal performance (Figure 2). The DuPont™ Nomex® paper, an aromatic polyamide, also called aramid, was born. With its thermal class of 220 in the air it was initially used in insulation systems for dry type transformers and rotating machines. It took less than 10 years for the electrical industry producing oil filled transformers to consider it as an insulation for the conductors. An advantage was taken of its significant thermal capabilities combined with excellent electrical and mechanical characteristics, although applicable temperatures had to be reduced due to limited thermal capability of dielectric liquids.

Photo: Shutterstock

In the area of insulating papers, no other comparable technical steps were achieved in the 20th century and it was only in the beginning of the 21st century when another paper combining the benefits of thermally upgraded cellulose ingredients and aramid was developed. A new generation of thermally upgraded paper was introduced, taking advantage of DuPont™ Nomex® to reach an improved thermal stability compared to regular thermally upgraded Kraft paper (Figure 3).

Figure 2.
DuPont™ Nomex® meta-aramid, poly(meta-phenyleneisophthalamide)

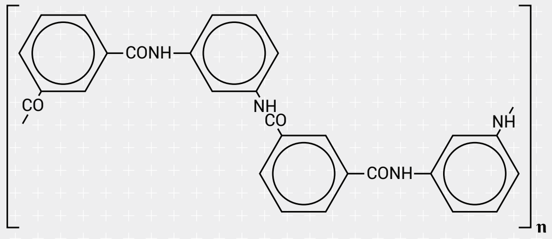
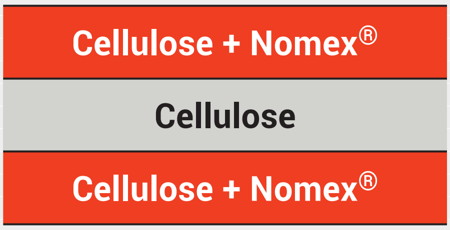


Figure 3.
DuPont™ Nomex® 910 structure



In parallel to the paper evolution the insulating fluids have also seen major developments in the 20th century. First, fluids like PolyChlorinated Biphenyl's (known as PCB) introduced in the 1940s as dielectric coolant and then replaced by silicon oil in the 1970s as they were found harmful to people's health. Then, the upraise of ester fluids, synthetic in the 1980s and then natural in the mid-1990s. It has been a constant search for solutions that could provide additional benefits like fire resistance or, more recently, biodegradability. However, still today mineral oils remain the main insulating fluid for liquid immersed power transformers.

It is also important to indicate that another major material was critical to the development of advanced insulation systems, particularly with the increase of operating voltages that power grids have seen. Almost 100 years ago Kraft pressboard was invented allowing for development of insulating components that would become critical in high and extra high voltage transformers. About 50 years later another pressboard type important for the development of advanced insulation system for power transformer was invented: the aramid pressboard. The DuPont™ Nomex® pressboard followed a similar principle as Kraft pressboard, i.e. combining specific known ingredients dedicated to electrical applications and a manufacturing process involving press capabilities that still remain unique today. This aramid pressboard also offers improved thermal capabilities as compared to the Kraft pressboard.

While these materials development may not describe the only changes than occurred over the last 100 years in insulation materials for liquid filled transformers, they indicate important categories that are used in transformers today to meet the evolving constraints to which transformers are exposed.

Developments in insulation systems

In recent years it could be seen that transformer designs have evolved to not only reduce the size and weight of units, but also improve their operating flexibility. Many modern design techniques or available state-of-the-art technical solutions drive designs to be smaller and more optimal. However, the use of aramid-based materials allows a step change in the ability to make designs significantly more compact, when compared to "conventional" designs that are based on cellulose insulation and mineral oil. These transformers may also benefit from longer lifetime as the new insulation systems are more thermally robust. They also offer more resistance to overload conditions that may result from planned maintenance periods or unplanned demands due to summer heat waves or other operational circumstances.

Industry standards, both IEC and IEEE, define such insulation systems available for use in power transformers. The standards define typical constructions and provide guidance on how the "high temperature insulation materials" shall be used. For example, Tables 1 and 2 present the temperature limits according to IEC 60076-14 [2]. Similar guidance can be found in IEEE Std. C57.154 [3].

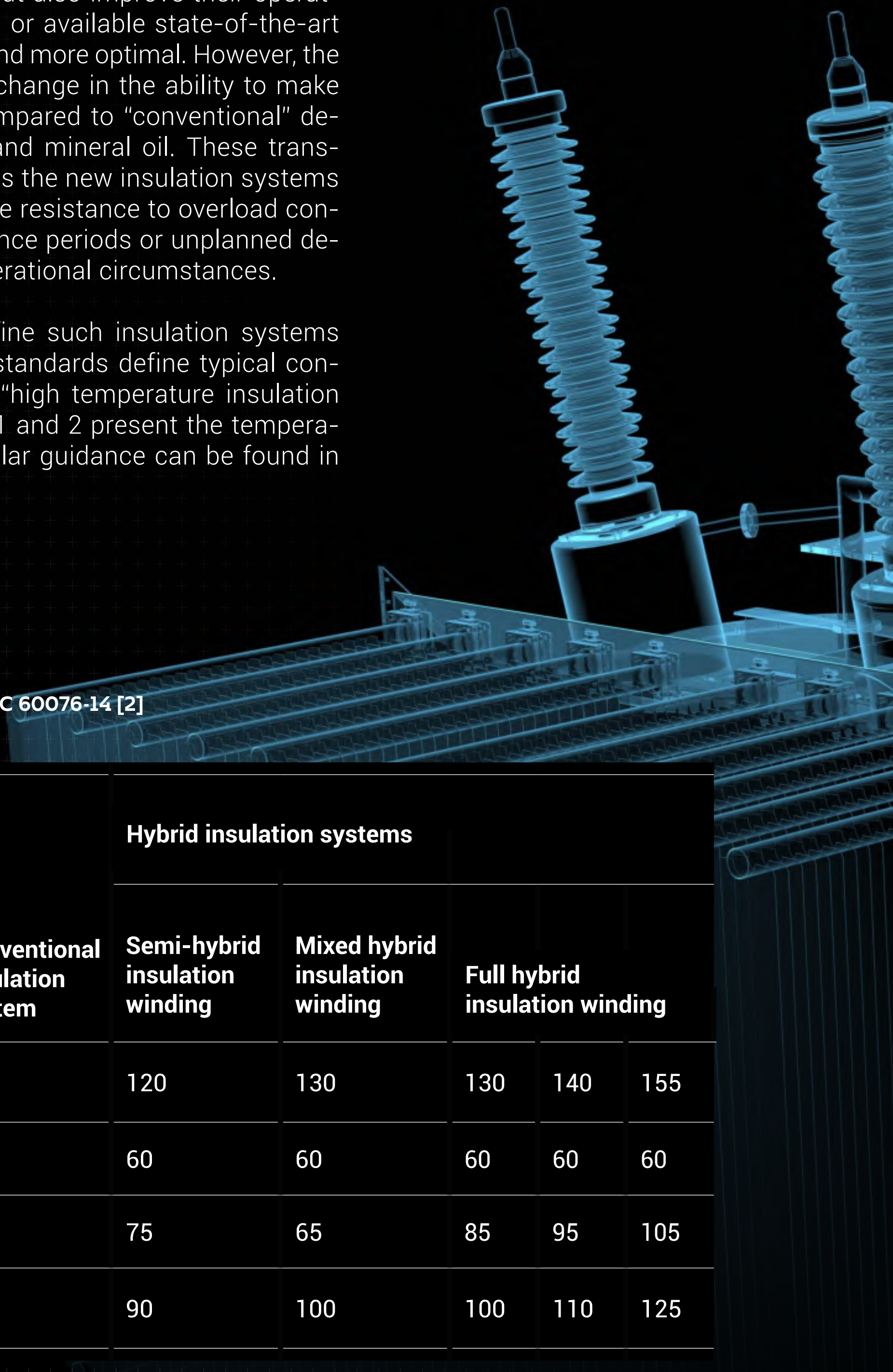


Table 1.
Hybrid insulation windings - thermal limits as per IEC 60076-14 [2]

		Hybrid insulation systems				
	Conventional insulation system	**Semi-hybrid insulation winding**	**Mixed hybrid insulation winding**	**Full hybrid insulation winding**		
Minimum required solid high-temperature insulation thermal class	105	120	130	130	140	155
Top liquid temperature rise (K)	60	60	60	60	60	60
Average winding temperature rise (K)	65	75	65	85	95	105
Hot-spot temperature rise for solid insulation (K)	78	90	100	100	110	125

Table 2.
High-temperature insulation windings with ester liquids - thermal limits as per IEC 60076-14 [2]

Minimum required high-temperature solid insulation thermal class	**130**	**140**	**155**	**180**
Top liquid temperature rise (K)	90	90	90	90
Average winding temperature rise (K)	85	95	105	125
Hot-spot temperature rise (K)	100	110	125	150

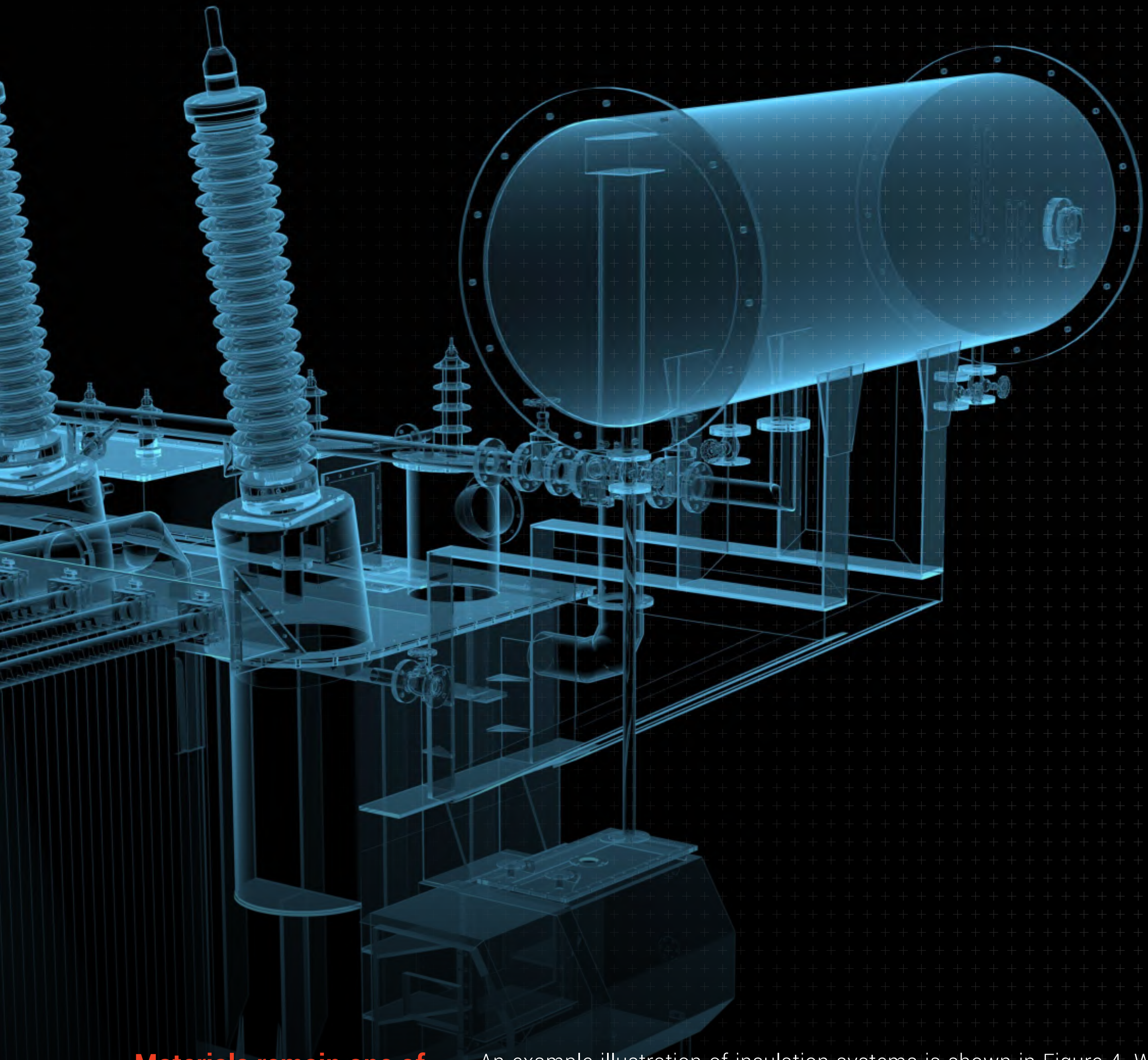


Photo: Shutterstock

Materials remain one of the critical elements to allow for the transformer designs to continue their evolution to meet end-user requirements.

An example illustration of insulation systems is shown in Figure 4. While few decades ago the Kraft insulation in mineral oil system was vastly used in liquid immersed power transformers (Figure 4a), we have seen over the last five decades the arrival of different insulation systems. One recently developed system consists of the thermally upgraded Kraft paper enhanced with Nomex® on the conductors (referred to as Nomex® 910 paper) combined with cellulose pressboard components and mineral oil (Figure 4b). This system gives the benefit of longer insulation system lifetime when used at conventional operating temperature but also help mitigating a load increase that can be due to planned demand or due to climatic events, generally unplanned.

Another system that has recently emerged is a hybrid system where aramid materials are used for conductor insulation, spacers and strips, while other materials remain in cellulose pressboard. Recently, these systems are combined with ester fluids (Figure 4c). This system is a response to increasing fire and environmental constraints that power utilities can see, e.g. in large cities [4]. Historically the solid materials of this system have been associated to mineral oil since the 1980s in applications for mobile transformers.

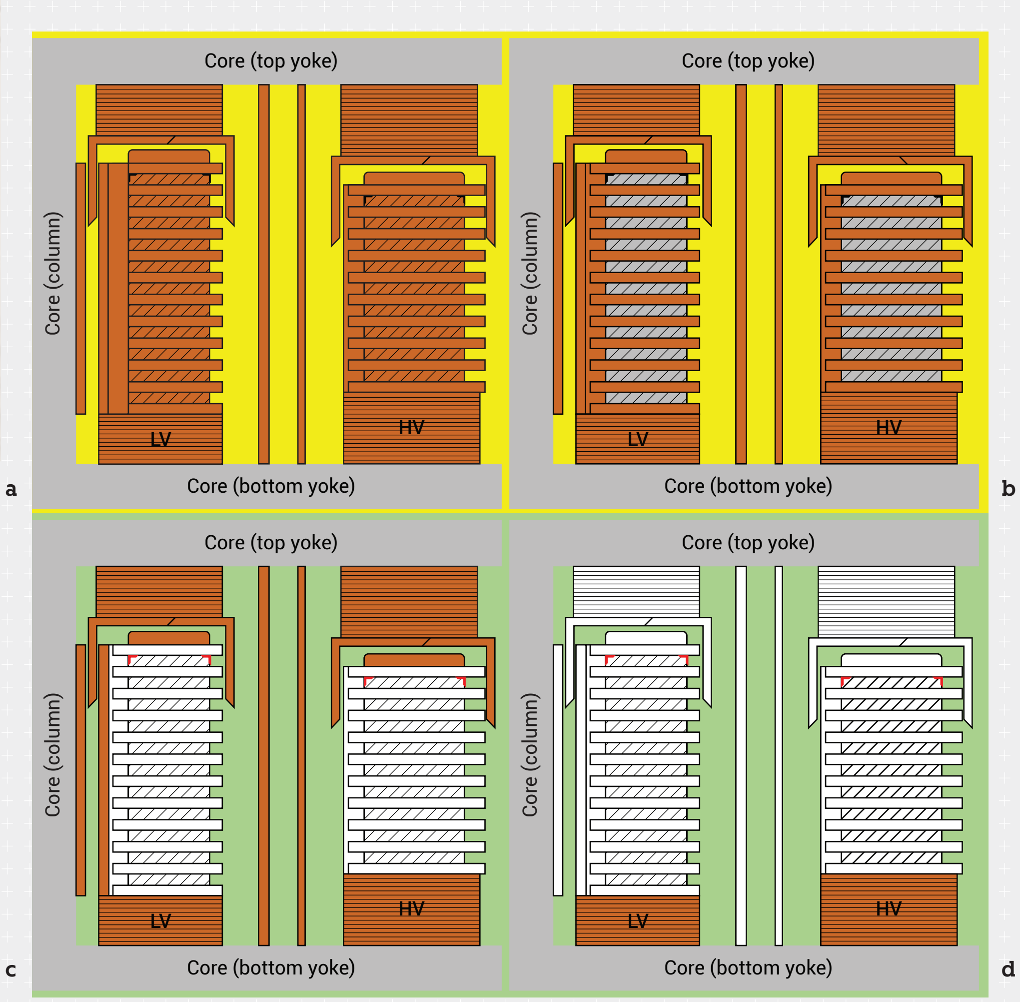


Figure 4.
Example illustration of various insulation systems for power transformers:
a - Kraft with mineral oil (conventional)
b - semi-hybrid with Nomex® 910 conductor insulation
c - hybrid system with ester fluid
d - high temperature system with ester fluid

Recently, an increasing number of developments focus on the use of ester liquids, due to their fire safety and environmental advantages. The thermal capability of ester liquids would allow using them at higher temperatures (although the test methods for more precise evaluation of thermal capabilities of ester liquids are only under development). Then, transformer designs can shift from hybrid systems (Table 1) towards more advanced high temperature insulation systems (Table 2). These systems will require more extensive use of high temperature materials in the transformer construction as illustrated in Figure 4d. The combination of aramid insulation and ester liquids has already been used for many years in smaller transformers, e.g. on-board traction units for rolling stock and compact wind turbine step-up transformers. Nevertheless, the research is continuing for better characterization of these systems and proving their high performance.

New aramid-based insulation parts

Plans for more extensive use of aramid insulation in power transformer high voltage insulation systems drives new developments for innovative insulation parts. One example is the development of formed 3-dimensional end insulation components, such as angle rings, lead exit snouts, and edge protectors. For some of these components there is a need to use a wet formable aramid board.

Photo: Shutterstock

The development focused first on identifying the grade of wet aramid material most suitable for forming the required 3D shapes of typical insulation parts. Then, the materials were evaluated for the two typical processes of forming:

- machine forming for more regular angle ring sectors (caps and collars),
- hand molding for more complex combined shapes, e.g. winding exit snouts.

Process optimization led to development of parts that matched the benchmark mechanical and dielectric performance of conventional cellulose based components.

The development of new insulation components also included laminated aramid board for producing thick insulation blocks, e.g. for clamping rings and associated structures. Steps have been made for producing larger sheets of high-density aramid pressboard. Comprehensive studies were performed for adequate glue selection and the process for laminating such boards, and proper characterization of critical properties. The testing included mechanical, dielectric and thermal properties. The dielectric test confirmed the partial discharge inception in the laminated board not happening below the required threshold of 9 kV/mm (Figure 5). This included tests on the laminated board samples aged in synthetic ester at the temperatures up to 155°C. Another test program analyzed dielectric strength and the partial discharge behavior of the laminated board when dielectrically tested at elevated temperatures up to 120°C.

Figure 5.
Test arrangement for partial discharge measurement on laminated aramid board after aging in synthetic ester (photo: DuPont/Siemens Energy)

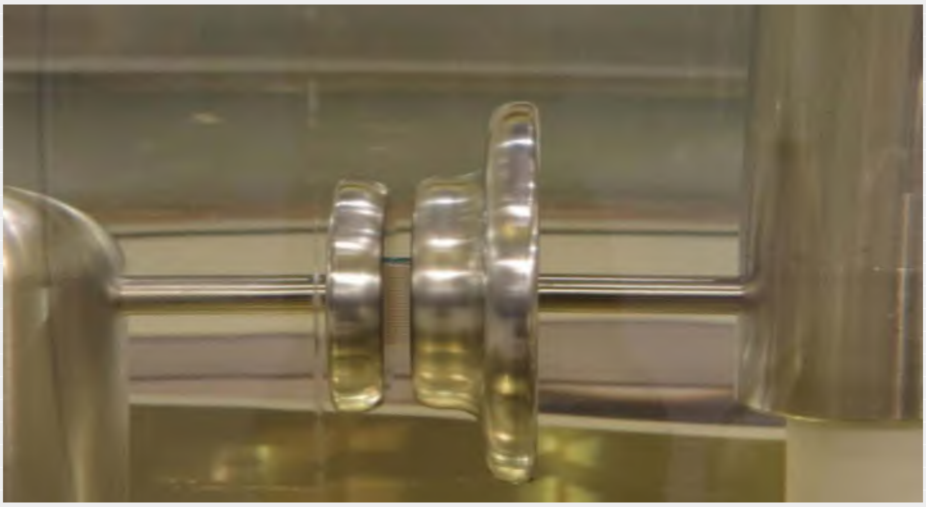


Figure 6.
Example of insulation kit with winding cylinder shaped from high-density aramid pressboard Nomex® 994 PSB (Photo: DuPont™)

Aging in hot synthetic ester liquid was part of the research to ensure the appropriate long-term performance of the laminated material in service. Compatibility with the selected synthetic ester liquid was confirmed.

Additionally, the development was made for large winding cylinders. For producing them, two aramid pressboard options have been evaluated:

- high-density aramid pressboard - in large sheets like those used for the laminated board, or
- lower density aramid pressboard - available in even larger sheets and more flexible but requiring more attention in the processing due to the air humidity impact on dimensional stability.

Figure 6 shows assembly of various insulation components mentioned previously in an innovative insulation kit for advanced power transformers.

Photo: Shutterstock

Summary

The options offered by the combination of various insulation materials allow more flexibility for the designers to develop transformers that will be able to operate in environments where new constraints have been evolving, whether they are related to space and weight restriction, loading profiles or ambient temperatures. Materials remain one of the critical elements to allow for the transformer designs to continue their evolution to meet end-user requirements.

References

[1] Prevost, T. A., Oommen, T. V. "Cellulose insulation in oil-filled power transformers: Part I - history and development," IEEE Electrical Insulation Magazine, Vol. 22(No 1), Jan/Feb 2006, pp. 28–35

[2] IEC 60076-14:2013, Power transformers – Part 14: Liquid-immersed power transformers using high-temperature insulation materials

[3] IEEE Std C57.154™-2012, IEEE Standard for the Design, Testing, and Application of Liquid-Immersed Distribution, Power, and Regulating Transformers Using High-Temperature Insulation Systems and Operating at Elevated Temperatures

[4] Szewczyk, R., et al., "Replacement of area substation transformers with flexible units of reduced footprint and increased overloadability," e-CIGRE session 2020