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Design of innovative resilient transformers for maximum operating flexibility

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SUMMARY

During the CIGRE Session 2020, the authors presented a study about the development of area substation transformers (AST) with reduced footprint, reduced weight and increased overload capability. The study described the evolution of AST specifications at Consolidated Edison Company of New York (Con Edison) and provided examples of user experience. The presenters covered evolution and technological development of transformers that rely on hybrid insulation systems with cellulose and aramid materials immersed in synthetic ester liquid.

This paper describes the next step of transformer design to meet even more stringent requirements from Con Edison. The emergency response transformers will use the high-temperature insulation system with synthetic ester. The development of these transformers – which has begun – will take into account the industry's goal of increasing the resilience and reliability of power grids. Utilities aim to reduce outage risks related to:

- Operational issues, such as network failures, an aging equipment fleet;
- Extreme weather;
- Other external events, such as a malicious attack.

Con Edison needs transformers it can deploy quickly and that provide maximum operating flexibility. The units would cover two voltage levels on the high-voltage side and three voltage levels on the low-voltage side, allowing for installation in various substations. The power rating, which is 93 MVA, would match the highest capacity transformers in the fleet for this high-voltage level. The specifications also include ambitious requirements on dimensions and weight, as the unit would already be filled with liquid while crews transport it to the site. Filling the liquid in the unit in advance will save time on installation.

Meeting the dimension and weight requirements while including complex winding configurations for all the voltage systems is a challenge. Therefore, the liquid operating temperature and the hottest spot temperature rise have to be higher than the conventional levels, as defined for mineral oil or cellulose insulation. Consequently, the transformers will need aramid insulation not only for insulation parts that are typically used in hybrid insulation systems (like conductor insulation, key spacers, and vertical strips). This will also extend to components of high-voltage end-insulation structures (like stress rings, molded caps, collars, snouts, spacer blocks, clamping plates and winding cylinders). Extensive research and development resources helped produce these parts in aramid, ensuring they are available on the market. This paper presents studies and laboratory test programs for component evaluation.

The innovative resilient transformer design will demonstrate maximum operating flexibility through advanced construction with upgraded materials. That flexibility is a key to helping energy grids evolve and support improved stability of transmission and distribution systems throughout the world.

KEYWORDS

High Temperature Insulation System, Nomex®, Aramid Paper, Aramid Board, Ester Liquid, Plug & Play Transformer, Grid Resilience, Mobile Transformer, Rapid Response, Interchangeability, Reconnectable Transformer, Overload Capability

1. Introduction

As utilities renew aging transformer fleets, they are seeking innovative designs with better efficiency, higher loading capability, safer and more flexible operation, and improved resilience within the space constraints of existing substations. The design challenge for the transformer this paper presents was to achieve maximum operating flexibility with a fast-deployable, lighter-weight unit (200 000 lbs., 91 000 kg) that would fit in a tight substation space. The design is the logical next step in the development of more standardized area station transformers up to 90 MVA and 132 kV.

During the 2017 CIGRE A2 Colloquium in Cracow, one of the preferential subjects was "Innovative Solutions for Transport and Installation". The presented design options included the solutions for mobile transformers with insulation systems that allowed operation at high temperatures. Participants also saw examples of ester liquids being used in power transformers to increase fire safety and reduce the environmental impact of failures or leaks.

The discussion at the CIGRE 2020 Session covered the development of upgraded and more flexible area station transformers [1]. The area station transformer (AST) is the typical application of a medium-power transformer with the aim to transform transmission voltage (e.g. 132 kV) to a local area distribution network voltage (e.g. 11 to 33 kV), with a power rating of 10 to 90 MVA. These special transformers handle loads ranging from low up to overload levels. The design must also take space constraints into account. These transformers allow higher continuous loading and an emergency overload, though they are similar in size to the original units at the locations. The described AST solutions were based on the combination of conventional insulation materials and high-temperature insulation, such as ester or aramid-based materials.

The next development step was ensuring a flexible transformer that utilities could quickly install at a substation. Contribution to the CIGRE Canada 2021 Colloquium discussed examples [2].

Con Edison serves the densely populated region of New York City and Westchester County, N.Y. World-class reliability is essential in the company's service territory, which includes important government institutions like the United Nations, a transit system that runs 24-7, the world's financial capital, and important hospitals and labs. Space is limited in this intensely urban environment, making for challenging transformer size restrictions. In addition, the existing infrastructure places constraints on transport weights. The company's emphasis on protecting its service and customers from the impact of climate change makes a forward-looking approach, integrated planning, and robust investment more critical than ever. Con Edison's equipment must remain reliable during all kinds of extreme weather, including punishing winter storms and intense summer heat waves.

Con Edison must maintain its high level of reliability while continuing to lead the transition to a clean energy future. The company's commitment to a low-carbon system is evident in its robust energy efficiency offerings, support for distributed generation and electric vehicles, and investments in energy storage and transmission lines to maximize the benefits of renewables. The evolving requirements for the grid pose even greater constraints and demands on transformer design and operation. Innovative solutions are a must.

As previously highlighted, a study about the development of a family of AST with reduced footprint, reduced weight and increased overload capability began a few years ago. The technological development led to an evolution where transformers combined cellulose and aramid materials - a hybrid solid-insulation system, immersed in synthetic ester liquid. Utilities already had transformers they could deploy quickly in large transmission substations. But utilities now recognize the need for fast-deployable transformers with superb operating flexibility that can work in area substations. To allow operating flexibility, the unit would cover multiple voltage levels. The high-voltage side can operate at either of two voltage levels and the low-voltage side can operate at three voltage levels. The power rating would match the highest-capacity transformers in this fleet, which is 93 MVA. These operating options maximize the interchangeability and allow one transformer to be installed throughout various substations, maximizing the equipment investment. These ambitious requirements further challenge the transformer dimensions and total weight, as the unit would be filled with liquid while crews transport it to the site, saving installation time.

2. Transformer design challenges

Utilities and grid operators need highly efficient, quiet transformers (New York City octave band requirements [1]) with high flexibility regarding voltage and impedance variation to meet growing energy needs. The units must be easy for crews to transport and install.

Fast deployment can mean shorter customer outages and contingencies. Shortening outages reduces customers' risk of loss and damage. The utility needs to be able to transport the transformer anywhere in its service area without a long permitting process. That makes the dimensions and weight critical. This is particularly true in large cities where substations in tight spaces can be difficult to access. The design needs to incorporate plug-and-play features to make the installation and commissioning time as short as possible. Most importantly, the transformer must be safe for workers and members of the public.

Technical requirements for the presented design:

- Fast deployment (less than a week) for emergencies;
- Two high-voltage levels (132 and 65 kV), three low-voltage levels (13.8, 28 and 35 kV) in combination with low-voltage LTC and a narrow impedance band;
- Power rating up to 93 MVA and high overload capacity of up to 200%;
- Quiet operation;
- Maximum transport weight of 200 000 lbs. (91 000 kg).

These specifications led to a complex winding configuration, which is required to meet all the voltage levels but stay within a very narrow impedance band. This is essential for the system stability and eases the process of integrating this unit into the existing substation protection system.

Increasing the operating temperature requires new materials, such as aramid materials and ester liquids, in the manufacturing process. For the combination of increased temperatures and new materials, the thermal hydraulic model of the design tool must be highly precise to avoid local overheating. This thermal model must be verified through calculation, low-scale lab testing and testing on actual transformers. The update of the design tools with the transformer testing results needs to be handled in a constant feedback loop.

This also refers to manufacturers of transformer insulation parts. Developers need to consider aspects of the high-temperature materials and insulation components made of them in every step of the value chain. New developments are essential to make the power transformer insulation kit available in aramid with all the components. The section below highlights some of these developments toward optimization of materials and their properties for optimal performance of the newly developed resilient transformers.

3. Development of advanced insulation system

3.1 Need for aramid-based insulation components

As indicated previously, high-temperature insulation systems are a key tool that can help reduce the size and weight of power transformers and improve their flexibility. Industry standards, both IEC and IEEE, define high-temperature insulation systems available for use in power transformers [4, 5, 6]. The standards define typical construction and provide guidance on possible designs. This includes guidance on acceptable temperature limits for various insulation systems with ester liquids. See Table 1. Similar guidance can be found in IEEE Std. C57.154.

Table 1 – Thermal limits for windings with high-temperature insulation systems and ester liquids as per IEC 60076-14

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

The higher temperatures allowed with ester liquids may require extensive use of aramid material for insulation components. Aramid papers and boards are ideal for typical insulation parts in hybrid insulation systems, such as conductor insulation, key spacers, vertical strips and clack band. They can also extend to include winding cylinders and components of high voltage end-insulation structures, like stress rings, molded caps, collars, snouts, spacer blocks or clamping plates. Those newer types of insulation systems create categories called "hybrid plus" or "full high temperature." Extensive research helped develop these parts in aramid and get them on the market.

The publication [7] presented selected results of chemical compatibility studies proving no negative material interactions between aramid and representative synthetic or natural esters. The following sections of this publication present selected studies on new aramid-based insulation components, including winding cylinders or wet formed three-dimensional end-insulation structures.

3.2 Winding cylinders

In hybrid insulation systems used historically for mobile transformers with mineral oil, the cellulose-based winding cylinders were used. They were separated from hot winding conductors with sufficient space of cooling oil. In hybrid-plus or high-temperature designs with ester liquids, higher temperatures are acceptable for both winding and liquid. Therefore, aramid insulation may be necessary for winding cylinders. The challenge in construction was shaping the relatively rigid sheets of aramid high-density board into a cylinder that could maintain its shape and diameter. This, together with a limited available size of high-density aramid board, resulted in first trials made with medium-density product. The shaping was possible, but shrinkage was a problem. Investigation for optimal aramid grade had to be performed.

3.2.1 Shrinkage evaluation

During the manufacturing of winding cylinders and transformer coils, those components undergo pre-drying, liquid impregnation and cooling. Each of these processes results in shrinkage and expansion of pressboard sheets due to water evacuation and absorption. Laboratory experiments tested the impacts of typical drying processes on various grades of aramid pressboard. Those processes can be modeled by adjusting the drying temperature and the duration of the different stages of the process. The experiments tested different materials, including: a medium-density pressboard in 2-mm and 3-mm thickness and a high-density pressboard, also in 2-mm and 3-mm thickness. The samples were 100x100 mm.

The example test results in Fig. 1 are from the following process:

Step A: Conditioning in controlled lab environment (50% RH, 23°C) for at least 24 h;
Measure all dimensions: length, width, thickness
Step B: Drying #1 at 105°C for 24 h;
Measure all dimensions
Step C: Conditioning in controlled lab environment for at least 24 h;
Measure all dimensions
Step D: Drying #2 at 105°C during 24 h;
Measure all dimensions
Step E: Conditioning in controlled lab environment for at least 24 h;
Measure all dimensions

The results indicate that medium-density board can absorb more water (above 5% water by weight) during exposure to the normal atmospheric conditions, while the high-density board absorbs less water (up to 3.4% water by weight). This effect can be seen through weight measurements as shown in Fig. 1. Consequently, the effect of the absorbed water on the shrinkage and expansion is in the figure where sample length measurements in machine direction are presented. The shrinkage of the medium-density board reached 1.1% vs. maximum shrinkage for the high-density board not exceeding 0.5%. This difference confirmed that high-density board should be the material of choice for the winding cylinder construction where size stability is important for precise manufacturing of transformer coils. Developers selected the 2-mm thick Nomex® 994 board for future use in winding cylinders.

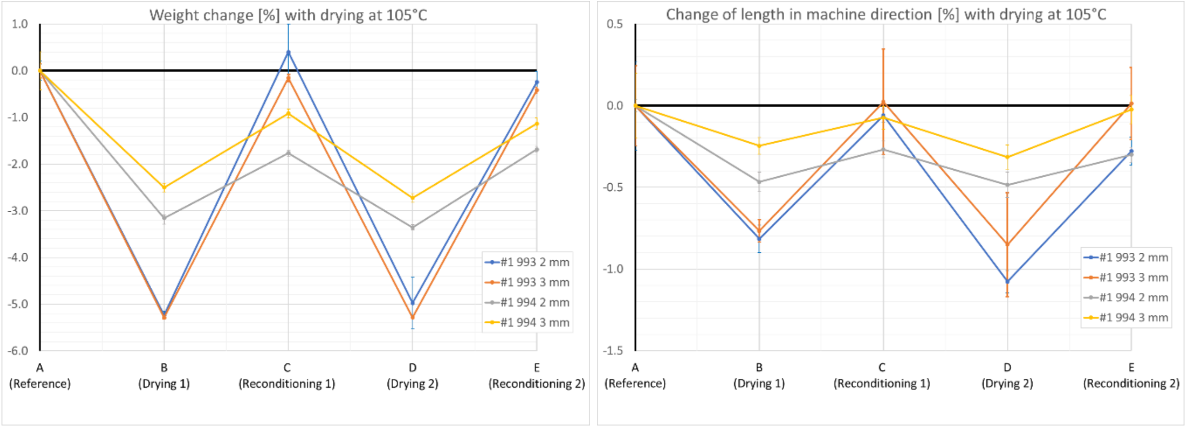

Figure 1 – Left: percent weight change of aramid pressboard - representing water evacuation or absorption during drying/conditioning cycles; Right: percent length change of aramid pressboard - representing shrinkage or expansion of material (tested materials: medium density board Nomex® 993 and high-density board Nomex® 994)

3.2.2 Bonding evaluation

The original choice for medium-density aramid board for the construction of winding cylinders was partly due to the availability of larger board sheets vs. those available in high-density products. The latest developments for large sheets of high-density aramid board mitigated this concern, although, scarfing and gluing of cylinders are still necessary during cylinder manufacturing. Testing evaluated the strength of scarfed and glued pressboard joints for high-density aramid board in comparison to medium-density board.

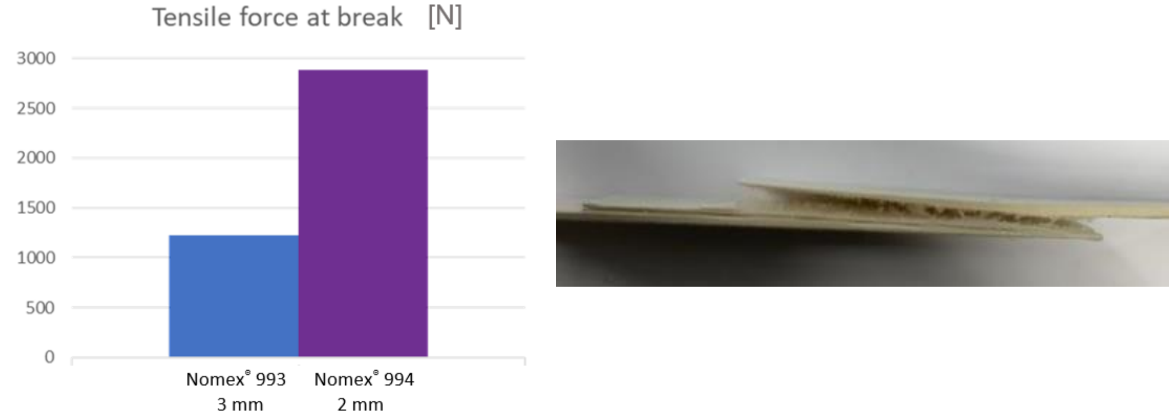

Figure 2 – Comparison of tensile force at break for scarfed joints for medium- and high-density aramid board (tensile force applied along the axis of the sheets); Failure phenomena shown.

Fig. 2 illustrates the failure phenomena in the joints. The testing proved the glued surfaces were stronger than the internal strength of the material. This shows it is critical to select the right adhesive for the application with aramid board. In such case, the strength of the bonded area depends on the internal ply strength of the board. Then, the high-density material has an advantage over the medium density board. Tensile strength measurements on the scarfed joints confirmed this. The figure shows significantly higher strength of the glued joint in high-density board.

3.2.3 Shaping evaluation

The selection of high-density board required adjusting the shaping process for the cylinders. The aramid material is more difficult to form and requires different pressures and processing temperatures than the cellulose-based pressboards. As a result of thorough process optimization, the component manufacturer was able to shape the cylinders in diameter as small as 280 mm (Fig. 3). Bending the board to such a small diameter results in significant stress on the glued joints. The manufacturer verified the integrity of the component through thermal cycling (drying and cooling down).

The presented small diameter of the cylinder is not typical for power transformers. A larger diameter offers easier shaping into the cylinder. The small diameters would be more typical for booster transformers or reactors that are part of the power transformer. Or, they could be used in transformers with lower power ratings. In any case, the development made confirms the solution availability.

Fig. 3 - Example of tall winding cylinder with small diameter
(280 mm) made of high-density aramid board
(Photo courtesy of Schweizer and Isotek.)

3.3 Wet formed insulation parts

Molded caps and collars, snouts, and lead exit structures are examples of insulation components that require a wet forming process. While those parts are available in cellulose and the forming process is well developed, similar parts in aramid were not available until recently. One reason was that the wet aramid board was not available to the component manufacturers. Therefore, the first step in development was identifying a right grade of wet board material for making the formed components. Researchers sought to determine the best set of properties for the wet aramid board. They evaluated how water content, material density and the “wet thickness” would affect the performance of the formed components.

3.3.1 Shelf life evaluation and initial forming trials

One special aspect of the wet board is the shelf life of the material. Cellulose-based wet boards are suitable for component manufacturing for only several months. After that, the wet cellulose material degrades and develops fungus, even if it is stored in cold rooms and inside sealed packaging. The evaluation of wet aramid board included more than two years of storage in various conditions. After specific storage periods, the researchers inspected the samples for fungus. They also evaluated the forming capability with mechanical and dielectric testing of sample components.

The scouting tests showed satisfactory moldability and performance of the material even after extended periods of storage. Due to the synthetic nature of the aramid wet board in comparison to natural cellulose material, it did not develop as much fungus or bacteria. Consequently, the shelf life could be longer, perhaps up to two years. This could simplify logistics in supplies of the product and allow longer storage of the base material for formed insulation components compared to traditional cellulose wet pressboard. Further trials with bacteria growth counting may yield more answers.

3.3.2 Component prototyping and technical characterization

The next step was to use the material that was pre-qualified for industrial application in the trial manufacturing of prototype insulation components typical for large, high-voltage transformers. The wet board was 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, like winding exit snouts or wall bushings.

Thorough evaluation of mechanical performance was conducted. Fig. 4 shows a prototype wet formed angle ring prepared for mechanical testing of sections cut from different areas of the component. Fig. 5 shows example test results of the flexural strength of a 3-mm thick angle ring, as measured on its flat sections (Specimens A and B). The tested flexural strength of wet-formed aramid did not precisely match the strength of the cellulose. However, the values obtained, and the practical inspection of the components showed the performance after the forming process optimization matched the quality of conventional cellulose-based angle rings.

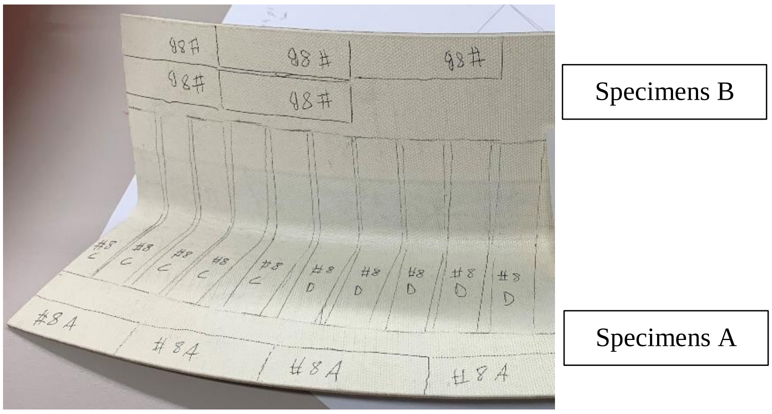

Figure 4 – Wet-formed angle ring with marking of sections for mechanical testing (Photo DuPont)

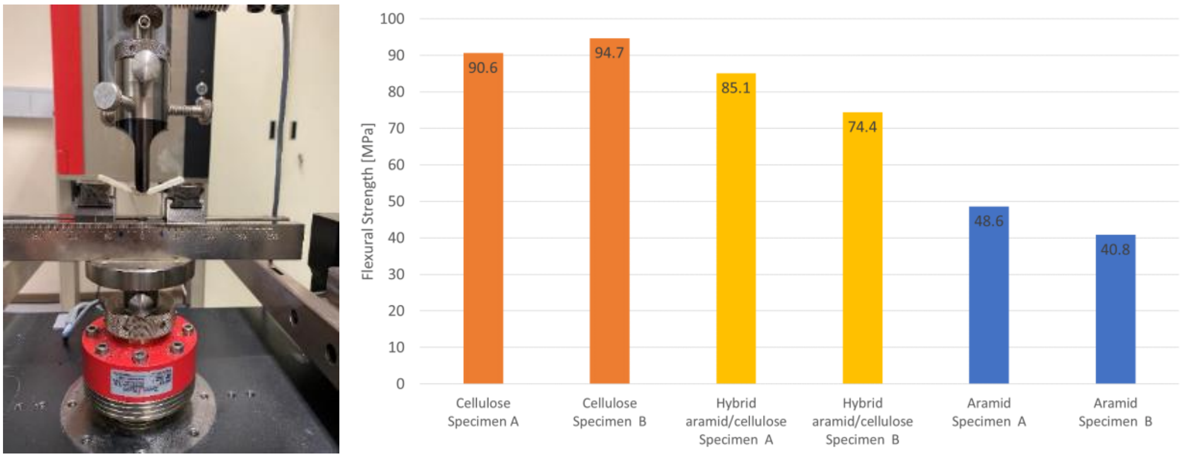

Figure 5 – Example test results of flexural strength of a 3-mm thick angle ring made of different wet formed materials (hybrid aramid/cellulose material combines layers of wet Nomex® board and wet cellulose board)

As Fig. 5 shows, one tested material solution was the “hybrid aramid/cellulose.” This solution could combine layers of wet aramid and cellulose formed together in a ratio of 50%. This could lower the cost of the components and improve some performance characteristics, like flexural strength. It would, however, be limited to areas that do not require the thermal capabilities of a 100% aramid insulation component.

The evaluations allow for considering the new components for innovative transformer designs. Fig. 6 shows an industrial-quality aramid-based angle ring and lead exit snout ready for implementation in a commercial transformer project. Additionally, the recent development led to a new type of sophisticated formed component, which is a wall bushing insulation structure. Such manually formed insulation tube with integrated electrodes for bushing connections must withstand the pressure test and show adequate drip proof performance.

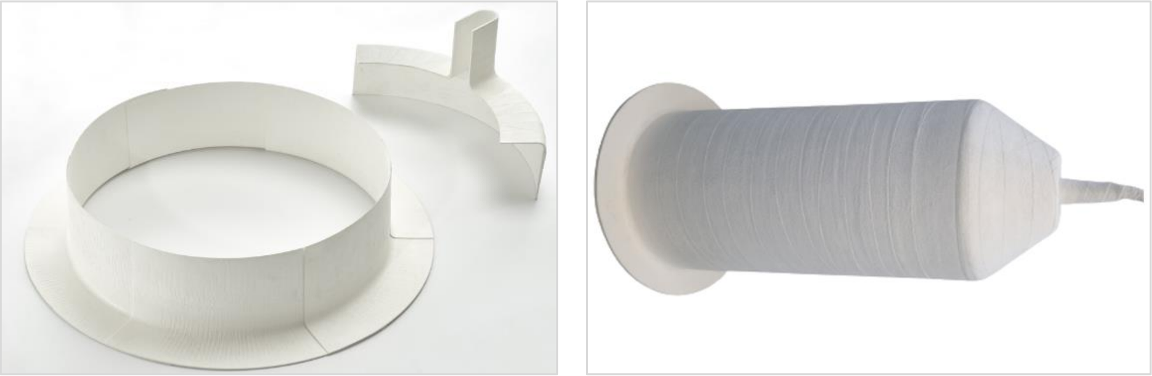

Figure 6 – Insulation parts made of wet formed aramid board: commercially available angle ring and lead exit snout (left); prototype wall bushing (right); (Photos courtesy of Schweizer and Isotek.)

3.4 Other insulation parts with high temperature performance

A range of other insulation parts have been developed for supporting transformers that may have windings that could operate at higher temperatures during regular operation or during extended overload periods resulting from emergency situations. These parts include:

- Clack band – an innovative solution that allows connection of aramid pressboard blocks with carrier aramid paper strip without gluing. That eliminates the need to verify glue compatibility with liquids and a risk of partial discharge inside the glue;
- Pill carpet – a solution for core cooling ducts based on ceramic pills glued on aramid carrier paper;
- Stress rings and slope end-rings – based on a laminated aramid board and used for reducing dielectric stress at winding ends or providing mechanical support for the spiral windings.

4. Selection of final design of transformer and solutions

The requirements led to a combination of newly developed materials and solutions. The application of new technologies and materials must undergo intense upfront testing to ensure that the new materials are compatible in the transformer. The design tools also need updating and verification via tests of transformers of various sizes. The sophisticated electrical and mechanical tool landscape was capable of optimizing the transformer design within the given constraints. The innovative and highly experienced designers created a breakthrough transformer design. The design is based on the latest material developments shown in section 3.

Due to the extreme compact design, the liquid operating temperatures - as well as the hottest spot temperature rise - must be increased above the conventional levels, as defined for mineral oil and cellulose insulation. Due to the wide range of liquid operating temperatures, a conservator design is the most efficient liquid preservation system. This conservator will be mounted on the tank during transportation and operation and shall not interfere with the transport restrictions. Accommodating the new boundaries required a stepwise approach to testing new materials and defining new engineering tools and calculations. The design features and solutions below are in two categories: active part design and external design.

1. Active part design:
    - The stringent noise requirements and the complex winding geometry will require a massive core of low-noise, grain-oriented magnetic steel grade, with cooling ducts of a high-thermal class material.
    - The various voltage levels on the high-voltage and the low-voltage sides, and the necessity of low-voltage regulation will lead to a complex winding design within a small footprint.
    - The multitude of narrow impedance bands and voltage levels will require up to eight individual windings per phase.
    - De-energized tap changers (DETC) will accommodate the changeover of voltage levels and avoid the handling of liquid during deployment. The design will include four DETCs and one on-load tap changer (OLTC).
    - A highly efficient routing of the lead structure will be essential to accommodate the heating effects from stray flux.

2. External design (see Fig. 7). The plug-and-play features are also crucial for the successful deployment of grid resilience units. These features include, but are not limited to:
    - To avoid the handling of insulating liquid, the high-voltage side will have dry-type plug-in bushings. These bushings are a light in weight for easy handling.
    - The low-voltage substation connections will be made by direct cable connections to increase the flexibility when positioning the unit in the substation.
    - The low-profile conservator will be designed so that it can remain mounted on the transformer for transportation and operation without interfering with the required high-voltage clearances.
    - The cooling equipment will be readily transportable.
    - Liquid-filled connection pipes between components that cannot be transported together will be connected via quick-connect piping to reduce the assembly time.
    - Connections to auxiliary equipment will be realized by heavy-duty plug connectors.

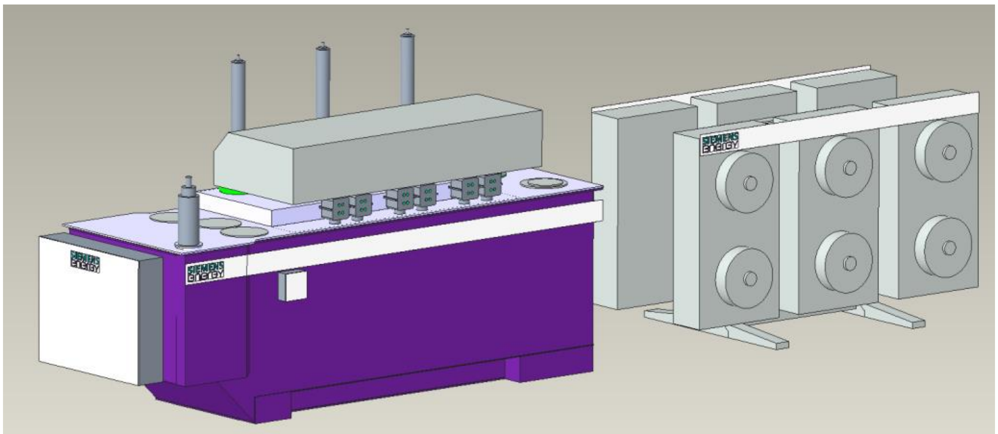

Figure 7 – Preliminary design of the 93 MVA emergency response area station transformer (Graphic by Siemens Energy)

5. Conclusions

Operating flexibility is a key feature for the energy grid transition that will support and improve the stability of transmission and distribution systems. The innovative resilient transformer design solution will demonstrate maximum operating flexibility by advanced construction with upgraded materials. The described design proves the feasibility of combining fast deployment with highest operational flexibility. The application of upgraded materials, highly sophisticated design tools and experienced professional designers offers a new level of transformer design for high-end applications. Breakthrough innovations could also be used in standard transformer types at the power utility to create new optimized and standardized solutions with either reduced size or higher load capability, or both.

The studies described in section 3 give evidence for the application of aramid-based insulation materials for most of the parts in state-of-the-art power transformers. The manufacturing aspects of the newly developed materials and insulation parts have been tested for the application at Siemens Energy and further tests are in progress or in preparation.

Furthermore, a new commissioning procedure lets utilities bring transformer banks online quickly. Such a procedure has already enabled the installation and commissioning of a 300 MVA bank in less than 30 hours [8].

The presented concept of a resilience multi-ratio transformer can be applied to extra high-voltage (EHV) large generator step-up transformers (GSU), too [9].

BIBLIOGRAPHY

[1] R. Szewczyk, J.-C. Duart, A. O'Malley, K. Kaineder, E. Schweiger, "Replacement of area substation transformers with flexible units with reduced footprint and increased overload capability" (CIGRE Session 48, 2020, Paris, France, paper D1-302)

[2] R. Szewczyk, J.-C. Duart, A. O'Malley, K. Kaineder, R. Mayer, E. Schweiger, "Innovative Resilient Transformers for Maximum Operating Flexibility" (CIGRE Canada Colloquium 2021, Toronto, Canada, paper 405)

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

[5] IEEE Std C57.154^{TM}-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

[6] IEEE Std 1276-2020, IEEE Guide for the Application of High-Temperature Insulation Materials in Liquid-Immersed Distribution, Power, and Regulating Transformers

[7] R. Szewczyk, R. Martin, "Application of Ester Fluids with Aramid Insulation in Distribution Transformers" (Matpost 2019, Lyon, France, paper 46)

[8] S. Bose, C. Ettl, S. Riegler, E. Schweiger, M. Stoessl, "Recommendation of site commissioning tests for rapid recovery transformers with an installation time less than 30 hours" (CIGRE Session 2018, Paris, France, A2-204)

[9] E. Gomez Hennig, K. Kaineder, R. Mayer, E. Schweiger, "Bypassing GSU transformers in case of emergencies or maintenance" (CIGRE Colloquium 2019, Montreal, Canada, paper 157)

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