Abstract

Résumé:
The article discusses the use of aramid based insulation papers in distribution transformers filled with ester fluids. Ester fluids are typically used for improved fire safety or environmental aspects. The article analyses design solutions which can bring additional technical and economic benefits by proper combination of the available advanced insulation materials.

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Improved reliability and performance of transformers in solar installations by use of advanced insulation materials

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Paris, le 28 avril 2013

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Application of Ester Fluids with Aramid Insulation in Distribution Transformers Radosław Szewczyk Nomex® Electrical Infrastructure DuPont Łódź, Poland Radoslaw.Szewczyk@dupont.com Russell Martin MIDE® M&I Materials Manchester, UK RussellMartin@mimaterials.com Abstract—The article discusses the use of aramid based insulation papers in distribution transformers filled with ester fluids. Ester fluids are typically used for improved fire safety or environmental aspects. The article analyses design solutions which can bring additional technical and economic benefits by proper combination of the available advanced insulation materials. Keywords—ester fluids; synthetic esters; natural esters; aramid insulation; aramid enhanced cellulose paper; design optimization; material compatibility; laboratory testing; I. INTRODUCTION With continuous advancements in new material developments it is more and more common that distribution transformers use various types of ester fluids, synthetic or natural. They provide improved safety by mean of excellent fire performance characteristics. Also, they are biodegradable, which contributes to environmental safety and reduced environmental footprint of transformers. Insulation systems of transformers may combine the ester fluids with aramid insulation in the form of paper or pressboard. This gives additional benefits to the transformer designs. This article describes selected liquid and solid insulation combinations and their related benefits. For example, combination of esters with high temperature aramid insulation allows for compactness of transformer design, and reducing its dimensions and weight. The new cellulose paper enhanced with aramid offers different capabilities, as it is only suitable for operation at 140°C in esters, as compared to high temperature aramid papers suitable for 180°C operation. It does not allow for significant size reduction of transformer but gives extended life of insulation system, increased overloadability, lower
sensitivity to operation at high ambient temperatures (valuable feature in case of transformer installations in compact substations). Moreover, combination of ester fluids with the aramid enhanced cellulose paper allows for cost optimization of transformer filled with ester liquid. This article presents examples of optimization studies showing that transformers filled with esters and optimized with aramid enhanced cellulose paper can be cheaper than those designed with conventional Kraft cellulose paper. While the number of applications for transformers combining ester fluids and aramid papers increase, a number of material studies are on-going to better characterize this material combination with esters for the most optimal use. This article includes recent compatibility studies performed for various aramid papers immersed in various ester fluids. Paper and fluid properties were measured before and after aging materials in given conditions, and the results have proven no negative impact of fluids on paper properties, nor negative impact of papers on fluid characteristics. II. HIGH TEMPERATURE TRANSFORMERS A. Applications of High Temperature Transformers Use of high temperature transformers combining alternative fluids and aramid insulation are typically driven by the need for compact size and minimized weight of equipment. One common application is traction on-board transformers, another are step-up transformers for wind turbines. Other applications have been also investigated and developed for more specific cases. Examples can be track side transformers for supplying underground transport systems or compact pole type transformers for increased power capacity while maintaining the limited weight. More recent use of ester fluids in large distribution or small power transformers drives developments for use of aramid with esters in those larger pieces of equipment. B. Standard References Use of aramid insulation with ester liquids has been reflected in international standards. The standards for liquid-immersed transformers using high temperature insulation materials define construction of insulation systems with specific combination of materials and also provide temperature limits for winding and fluid in those systems (Table I). Both IEC and IEEE standards addressing the topic have been developed and used globally as references [1, 2]. C. Example of High Temperature Design Based on the new acceptable and defined temperature limits different from conventional (those for cellulose insulation in mineral oil) the high temperature transformer design may take advantage of materials used. Table II presents comparison of Table I. TEMPERATURE LIMITS FOR HIGH TEMPERATURE LIQUID-IMMERSED TRANSFORMERS WITH ESTERS (AS PER IEC/EN 60076-14 [1]) 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 TABLE II. COMPARISON OF 2.3 MVA / 20 KV WIND TURBINE TRANSFORMERS WITH ESTER FLUID AND DIFFERENT INSULATION [3] Cellulose Insulation Aramid Insulation (Nomex®) Core loss (W) 2 350 2 350 Load loss @ 75°C (W) 18 000 16 000 Load loss @ 120°C (W) - 18 000 Uk (%) 6 6 Length (mm) 2 085 2 160 Width (mm) 1 150 760 Height (mm) 2 150 2 125 Fluid weight (kg) 1 210 840 Total weight (kg) 6 000 5 040 Top oil rise (K) 50 70 Avg winding rise (K) 55 110 two transformers designs: one with ester fluid and conventional cellulose; another with ester fluid and high temperature aramid insulation (DuPont™ Nomex®). The example clearly shows capability of this technology for reducing transformer dimensions, weight and material needs. At the same time, the losses can be maintained at the same level [3]. III. MEDIUM TEMPERATURE ARAMID PAPER A. Material Description and Characteristics The cellulose paper enhanced with aramid is a unique insulating material comprised of high-quality electrical grade cellulose pulp and web-like binders made from aramid. Because the product is comprised of both cellulose and aramid ingredients, it exhibits properties that are between typical insulating papers made of cellulose and aramid [4]. The new solution of cellulose paper enhanced by an aramid component has been developed in order to improve the thermal performance of cellulose paper and still offer an economical and affordable solution for enhancement of transformer properties. Long-term laboratory studies have proven the thermal performance of the new insulating paper to be better than common Kraft cellulose paper and thermally upgraded paper. Fig. 1 shows life time characteristics of engineered cellulose paper Nomex® 910 (i.e. expected useful life vs. operating temperature). As seen in the chart, the tested paper could operate at the temperature 120°C in mineral oil (MO) or 140°C in representative natural ester and expected useful life would be equivalent to thermally upgraded Kraft paper (TUK) that can operate at 110°C or regular Kraft paper Fig. 1. Life time characteristics of engineered cellulose paper Nomex® 910 in various liquids vs. thermally upgraded Kraft paper (TUK) and Kraft paper in mineral oil operating at 98°C (approximately 20 years based on functional life of a transformer). B. Application of Aramid Enhanced Cellulose Paper in Overloadable Transformers Example of application of aramid enhanced cellulose paper for improved overloadability of distribution transformer has been demonstrated in development of de-rated distribution transformers for compact kiosk substations. Those substations may face a lock-in effect when Tier 2 of European Commission (EC) Regulation 548/2014 comes into force in 2021. Replacing of transformers may be very difficult in such compact substations because all new transformers will need to have reduced level of losses after 2021. Hence, they will likely be bigger. The concept developed by Cahors and described by Szewczyk et al. [5] showed that these transformers for compact substations and exposed to relatively low typical loads of approx. 25-30% could be specified for reduced nameplate rating. This would be of benefit for their size and Total Ownership Cost (TOC). If higher loading would be needed on these de-rated transformers, they would be capable of taking higher loads by utilizing properties of advanced insulation system based on ester liquid and aramid enhanced cellulose paper. Overall, the de-rated transformer with advanced insulation could have the same purchasing price as the Tier 2 mineral oil option, but would be cheaper in operation than typically sized TABLE III. COST COMPARISON FOR TRANSFORMER 160 KVA AND UNIT WITH ADVANCED INSULATION SYSTEM DE-RATED TO 125 KVA [5] 160 kVA EC Tier 1 A0/Ck 160 kVA EC Tier 2 A0-10%/Ak 125 kVA EC Tier 2 A0-10%/Ak Purchase price (with mineral oil) 100% 128% - Purchase price (with ester liquid) 109% 138% 128% TOC @ 40 kVA, 25% of 160 kVA (with ester liquid) TOC160 TOC160+10% TOC160+4% unit (Table III). However, the main huge benefit would be possibility of using it as direct quick transformer replacement in existing compact substation without the need for replacing the substation with a larger one. This could represent 60% saving based on typical cost of a complete new substation and installation works for 160 kVA kiosk. C. Application of Aramid Enhanced Cellulose Paper for Transformer Cost Optimization While
the previous example showed quite special case of a transformer installed in compact substation, there are also possibilities for cost optimization in transformers in not so specific installations. Another article by Szewczyk et al. [6] shows examples of transformer cost optimization independent on installation. Transformers filled with ester fluids are typically more expensive than those with mineral oil. That is due to the cost of the fluid itself, but also due to some design modifications that are normally considered for esters. These may relate to cooling performance of a liquid having higher viscosity than mineral oil, or to some dielectric considerations. To mitigate that increased cost of transformers filled with esters, they may be designed for operating at higher temperatures and better utilize performance characteristics of esters (higher allowed operating temperature). Fig. 2 only shows one example of the 20 MVA unit that has been optimized for operation at higher temperature and utilizing higher temperature limits for fluid and solid insulation (in this case aramid enhanced cellulose paper Nomex® 910). The optimized cost of transformer materials has been reduced by 11%. This makes the transformer filled with ester being more affordable as compared to the unit insulated with conventional cellulosic insulation. It must be noted that this optimized construction, although designed for higher temperatures, still meets efficiency requirements as per EC Regulation. It must be remembered that the example cost increase in Fig. 2 and the example cost saving is for illustration only, and is based on design simulation study. The numbers may be different depending on design assumptions, design rules and the type of transformer under evaluation. For example, larger distribution transformers allow more flexibility for Fig. 2. Transformer cost depending on insulation system selected (20 MVA, losses as per Tier 1 of EC Regulation 548/2014) optimization vs. small distribution transformers. Similarly, transformers with more flexibility on efficiency allow for better optimization. Authors encourage users to make their own cost evaluation for different design options and observe possible benefits in their specific cases. IV. MATERIAL COMPATIBILITY STUDY A. Test Program The compatibility study was based on procedures outlined in ASTM D3455-11 [7]. However, the test program was adjusted to be more adequate for the fluids and papers capable of handling higher temperatures than conventional mineral insulating oils and cellulosic papers. Various material combinations were aged for one week in temperatures: 120 – 140 – 170°C. Paper and fluid properties were tested before and after the aging to observe possible aging impacts. Paper properties: • Weight, • Dimensions, • Tensile strength. Fluid properties: • Neutralization value, • Dielectric strength, • Color and appearance, • Water content, • Flash point (PMCC), • Fire point (COC), • Viscosity at 40°C. The material combinations included the following papers and fluids: • Aramid paper (Nomex® 410), • Aramid enhanced cellulose paper (Nomex® 910), • Synthetic ester fluid (MIDEL® 7131), • Natural ester fluid 1 (MIDEL® eN 1215), • Natural ester fluid 2 (MIDEL® eN 1204). B. Impact of Ester Fluids on Aramid Papers Dimensional changes to the paper samples were observed to be negligible. No major changes were observable for width, length, or thickness of paper samples tested. Also for the weight of the samples, the accuracy of the test equipment did not allow for identifying any specific trend in sample weight change after the aging vs. the weight before. It is concluded that aging of the two different insulating papers containing aramid in three different ester fluids did not result in any significant change of their properties. Impact of aging in fluids on paper mechanical tensile strength is shown in Fig. 3. There is no significant difference or trend observed on aramid paper. The paper maintains constant strength independent on fluid used or temperature. This proves very good thermal and chemical stability of the aramid paper. The cellulose paper enhanced with aramid is less consistent in its properties. Again, there is no trend observed which could indicate specific impact of any fluid in combination with temperature. A wider spread of test results confirms that a) b) Fig. 3. Compatibility test results – mechanical strength of paper after aging in different fluids: a) aramid paper (Nomex® 410), b) aramid enhanced cellulose paper (Nomex® 910), a) b) Fig. 4. Compatibility test results – acid value of fluids after aging with and without papers: a) synthetic ester (MIDEL® 7131), b) natural ester (MIDEL® eN 1204). properties of cellulose based papers are less consistent when they are exposed to relatively high temperatures in the range 120-170°C. C. Impact of Aramid Papers on Ester Fluids More properties were tested for evaluation of fluids, Fig. 4 and 5 only show example properties to illustrate that properties of each tested fluid were not affected by presence of evaluated insulating papers (properties indifferent whether fluid aged with paper or without). a) b) Fig. 5. Compatibility test results – breakdown voltage of fluids after aging with and without papers: a) synthetic ester (MIDEL® 7131), b) natural ester (MIDEL® eN 1204). Similar results were obtained for other tested properties of fluids. The presence of different insulating papers based on aramid had no influence on measured properties of fluids. V. SUMMARY The selection of solutions presented in the article indicate the variety of possibilities on how aramid paper or cellulose paper enhanced with aramid can be used in transformers filled with ester fluids for both technical and economic benefits. These advanced materials, which are verified for material compatibility, are worth considering in design of modern distribution transformers for various applications. REFERENCES [1] IEC/EN 60076-14 “Power transformers – Part 14: Liquid-immersed power transformers using high-temperature insulation materials”, 2013. [2] IEEE Std C57.154 “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”, 2012. [3] “Bio-Slim® A New generation of environmentally safe transformers”, Pauwels International N.V., 2005. [4] DuPont™ Nomex® 910 Engineered Cellulose Paper, Preliminary Technical Data Sheet, 2018. [5] R. Szewczyk, J.-C. Duart, and P. Trifigny, “Mitigation of lock-in effect for compact substations with transformers meeting future EU efficiency regulations”, CIRED 2019, paper No. 2089, June 2019. [6] R. Szewczyk, R. Marek, R.C. Ballard, J.-C. Duart, and G. Vercesi, “Innovative insulation materials helping in cost reduction of modern transformers ”, CIRED 2019, paper No. 2108, June 2019. ASTM D3455-11 “Standard Test Methods for Compatibility of Construction Material with Electrical Insulating Oil of Petroleum Origin”, 2011. DuPont™ and Nomex® are registered trademarks of DuPont de Nemours, Inc. MIDEL® is a registered trademark of M&I Materials Ltd.

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