CIGRE-405

2021 CIGRE Canada Conference & Expo
Montréal, Québec, October 25-28, 2021

Innovative Resilient Transformers for Maximum Operating Flexibility

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SUMMARY

Regular scheduled replacement of area substation transformers is part of a standard fleet asset management practice. It can be applied to service-aged transformers whose insulation systems and accessories are already affected by long years of service and where further operation might put the assets at risk of failure or is no longer economical. In other cases, the replacement may be more urgent and driven by malfunctioning of the unit. The replacement of transformers provides an opportunity to install more efficient units with reduced losses. It may also be an opportunity to upgrade the power rating of a substation in response to a growing load demand in the network. Upgrading of transformers and substations may also aim to improve the resilience of the grid. In the latter case, the transformers can be designed for overload capabilities higher than typical in order to be ready for unexpected events. Installing transformers with a higher nameplate capacity typically requires modification of the substation to accommodate the installation of larger equipment. This modification is typically time consuming, costly and reduces the availability of power from the given area substation while the modification is in progress.

The concept of upgraded and more flexible area station power transformers has been developed and designed to minimize the work required during deployment at the substation. These transformers allow higher continuous loading and an emergency overload while maintaining the size similar to the original units installed at the locations. The flexible substation transformers may combine conventional insulation materials with high temperature solid insulation for better thermal management of the designs. The use of ester liquids allows a further increase of the operating temperature of a transformer. This enables further optimization of the designs, either for reduced size and weight, or for increased overload capability. Current developments of transformers with high temperature solid insulation and ester liquids require development of new insulation parts and their application in the production, which is discussed in this article.

Examples are shown as case studies. In the first described case, area substation transformer (AST) Type 1, the utility was looking to find a replacement transformer for three different MVA ratings and two different impedances. The innovative use of high temperature winding

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insulation and spacers together with a sophisticated winding arrangement allowed all of the requirements to be met. In the second case - AST Type 2, the utility was looking for a design that uses synthetic ester to minimize the risk of fire and long-term effects to the environment while increasing the life of the transformer. The third evolution was the production of the first AST Type 1 transformer, combined with synthetic ester as the insulating liquid. The development of additional aramid insulation components allowed this synthetic ester filled transformer to become a reality.

Such technologies with continuous enhancements and innovations allow the design of transformers for fast deployment in the field of grid resilience. This article describes the development of the new transformer concept for a resilient unit for maximum operating flexibility. The unit would cover multiple power ratings and voltage levels allowing for installation in various substations at the power utility company.

KEYWORDS

Plug & Play Transformer, Resilience, Rapid Response, Mobile, Fast Deployable, High Temperature Insulation System, Aramid, Synthetic Ester, Asset Management

1. Introduction

Regular scheduled replacement of area substation transformers is part of a normal fleet management practice. It can be applied to naturally service-aged transformers whose insulation systems and accessories are already affected by long years of service and further operation might put assets at risk of failure or is no longer economical. In other cases, the replacement may be more urgent and driven by malfunctioning of the unit. The replacement of transformers gives an opportunity to install more efficient units with reduced losses. This efficiency improvement is related to the use of more advanced materials or advanced design techniques. Often, the replacement of transformers is an occasion for upgrading the power rating of a substation. This uprating may compensate for growing load demand in the network or planned future network expansion. One example of such growing future demand is the development of electric vehicles and the associated charging infrastructure. Upgrading of transformers and substations may also aim to improve the resilience of the grid. In this latter case, the transformers can be designed with overload capabilities higher than typical to be ready for unexpected events and contingencies.

Without new materials and production methods a higher name plate rating would come with a larger footprint of the transformer which need to be considered in the substation layout. This modification is costly, time consuming and reduces the availability of power from the given area substation during construction.

This article describes the development and implementation of the concept for upgraded and highly flexible power transformers that have been designed to minimize the work required during installation and placing into service at the substation. Examples of the flexible design include multiple voltage ratings or impedance selections within the same transformer. These transformers allow both higher continuous loading and emergency overload while maintaining a similar size to the original units installed at the location. Technical solutions used in these replacement transformers will be described in the article. One solution is to implement an advanced insulation system with aramid insulation components to better support the higher winding temperatures. An economical solution to provide the desired operational flexibility was achieved by optimizing the limited use of aramid insulation. Further efforts to develop and test new solutions that would lead to even more size compactness and installation and operational flexibility are underway. As utilities renew their existing, aging transformer fleet, this approach provides an innovative solution that helps to improve efficiency, increase loading capability and operational flexibility, and improve resilience within existing space constraints.

2. Materials enabling innovative transformer solutions

The use of high temperature insulation systems is one key tool among design methods that can be used to not only reduce the size and weight of power transformers, 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 optimized. However, the use of high temperature materials and insulation systems 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. Industry standards, both IEC 60076-14 [1] and IEEE Std. C57.154 [2], define high temperature insulation systems available for use in power transformers. The standards define typical constructions and provide guidance on how the high temperature transformers shall be designed.

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 allows using them at higher temperatures. Then, transformer designs can shift from hybrid systems towards more advanced high temperature insulation systems. These systems require more extensive use of high temperature materials in the transformer construction.

The combination of aramid insulation, like Nomex®, 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. Recently, compatibility studies have been performed for commonly used aramid insulation papers and representative ester liquids (synthetic and natural). There were no compatibility issues identified in the results of these studies. Some details can be found in CIGRE publication by Szewczyk et al. [3].

Plans for more extensive use of aramid insulation in power transformer high voltage insulation systems drives new developments for adequate insulation parts. One example is the development of wet formable aramid board for making 3-dimensional end insulation parts, such as angle rings, lead exit snouts, and edge protectors. A second phase of new insulation part development involves laminated aramid board for producing thick insulation blocks, e.g. for clamping rings and associated structures. Steps have already been made for producing larger sheets of high density aramid board.

3. Development of highly flexible transformer solutions demonstrated by case studies

Highly efficient transformers with low noise performance (Table I - New York City octave band requirements) and high flexibility with regard to voltage and impedance variation and easy handling for transport and installation are an important measure for utilities and grid operators to cover growing energy needs. The application of new technologies and materials in transformers must be intensively tested upfront to ensure that the compatibility of a new material within the transformer can be guaranteed (e.g. mineral oil and ester insulation liquids and Nomex®). The power transformer is a critical and expensive asset in a substation; thus, transformer reliability plays a major role in the electrical network. The industry usually follows a stepwise approach for implementing new materials or processes. First, the new developed materials will be tested in smaller size prototypes and later the material will be applied in mid-size or large power transformers. In the case of Nomex® based high temperature class materials, the paper has been used over decades and now the industry is using more parts made from the high temperature class material. The formed parts described in section 2 allow new opportunities to optimize transformer designs. The following three case studies describe the development of solutions which followed the availability of advanced materials.

Table I - Maximum permissible sound pressure level (source: Consolidated Edison Co. of NY)

Octave band [Hz]	Limit [dB]
63	77
125	71
250	64
500	57
1000	51
2000	45
4000	40
8000	39

3.1. Area station transformer (AST) Type 1 with mineral oil

The area station transformer (AST) is the typical application of a medium power transformer with the aim to transform the transmission line voltage (e.g. 132 kV) to a local area distribution network voltage (e.g. 11 to 33 kV), with a power rating in the range of 10 to 90 MVA. These special transformers are exposed to a varying load, starting with very low energy demand up to very high overloads. In addition, space constraints are a dominating factor for the design of transformers and substations. The necessity of highest flexibility and exchangeability of transformers was the major driver to create a solution based on the concept of using new and advanced high temperature class materials in the active part of the transformer. The need for highly flexible transformers, where one transformer fits several ratings or sites, drives the size, weight and costs. However for utilities and grid operators, an efficient, effective, reliable and cost optimized solution is key. The aim was to combine three different transformer designs with different MVA ratings and impedances to one tank which should fit in the smallest vault.

The lowest rating is 41 MVA and the highest 58 MVA, which give a relative deviation in MVA of 41%. Additionally, a relative deviation of 100% in impedance was given as clear requirement to fit in the existing network without changing substation equipment, like circuit breakers. It was not possible to find a solution within the industry standard of transformers. Standard materials and technologies result in too large and too heavy transformers. The only way to fulfil the customer requirement was the application of high temperature insulation material, which lead to a feasible transformer design solution. The usage of high temperature winding insulation was the key element of this solution, together with a high sophisticated winding arrangement. The solution was based on mineral oil as the insulation liquid and an intelligent mix of cellulose paper and high temperature aramid wire insulation and spacers (Fig. 1).

The compact design of the transformer allows the opportunity to fit within the space requirement in the substation. Fig. 2 clearly demonstrates the necessity of this compact design approach.

Figure 1 – Winding with a combination of high temperature Nomex® aramid wire insulation and thermally upgraded cellulose paper (photo: Siemens)

Figure 2 – Lifting a transformer into a substation in a dense urban area (photo: Consolidated Edison Co. of NY)

3.2. Area station transformer (AST) Type 2 with synthetic ester Midel® 7131 insulation liquid

The application of synthetic ester-based insulation liquid, Midel® 7131 was the target of the next step of transformer development. The target was to gain full advantage of the synthetic ester insulation liquid without compromising the size and noise constraints in the substations. The rating of the Type 2 transformer is more than 10% higher compared to Type 1, but the complexity of impedance change could be avoided. The design with mineral oil was very compact (see Fig. 3a), thus a tough baseline for further improvements. Due to the usage of ester insulation liquid and the requirement to use the same space for radiators (ON-cooling), higher temperature limits and the application of high temperature insulation materials, both solid and liquid, were necessary.

Even the very demanding overload requirement, up to 200% in some cases, could be handled by this state of the art area station Type 2 transformer. The different substations where this transformer could be installed, are not 100% identical, therefore the application of the radiator has to be flexible as well. Fig. 3b shows the final ultra-compact design with synthetic ester insulation liquid and optimized usage of solid high temperature Nomex® insulation components (e.g. wire insulation, spacers).

a) b)

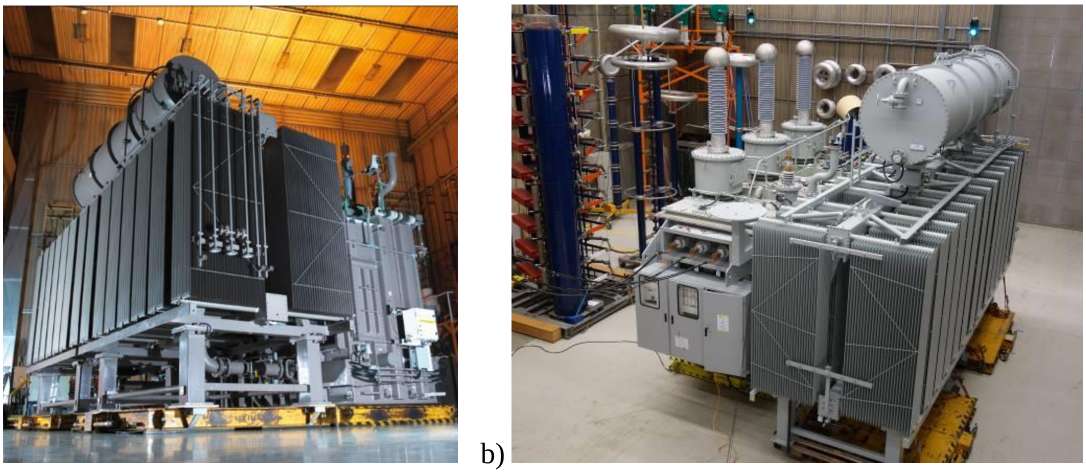

Figure 3 – Compact area station transformers Type 2:
a) with mineral oil, b) with synthetic ester liquid Midel® 7131 (photo: Siemens)

3.3. Area station transformer Type 1 with synthetic ester Midel® 7131 insulation liquid and intensive usage of high temperature insulation materials

The application of synthetic ester-based insulation liquid, Midel® 7131 was the target of the next step of transformer development. The aim was to create an environmentally friendly transformer design which substantially reduces the fire risk in the substation together with high oxidation stability of the insulation liquid and better ageing performance. The additional application of ester liquid, which effects the thermal behavior and the dielectric behavior of transformers, was the main driver for a more intensive usage of high temperature insulation material in the transformer windings. The materials described in section 2 are necessary to further decrease the size of transformer or support the change of insulation liquid in a way to maintain the transformer dimension at the same value or even smaller. The overall target is to optimize the transformer solution for every application by applying the perfect materials mix based on the need, like low noise and high flexibility or only a size reduction or increased MVA rating.

4. Applications for fast deployments applying state of the art design and materials

Technologies introduced above open new opportunities for enhanced solutions especially in the field of resiliency. The combination of different modules leads to solutions that enable designing transformers which can significantly reduce the impact of failures and increase the reliability and availability of the power grid. In addition to the mentioned technology on the electrical design of a transformer, the following features support a more resilient grid:

- Multi-ratio voltage design enables the usage at different locations and cover different type of transformers
- Single-phase design enables a much easier and faster transportation
- A design which allows oil filled transportation enables the reduction of the installation dramatically
- Plug-in RIP (resin impregnated paper) / RIS (resin impregnated synthetic) bushings reduce the installation time even further since no oil processing is needed after installation
- Cable connection contribute to shorten the installation time
- Incorporation in the world of IoT enables automatic indication of abnormalities and optimizing the operation (e.g. in the field of use of life)

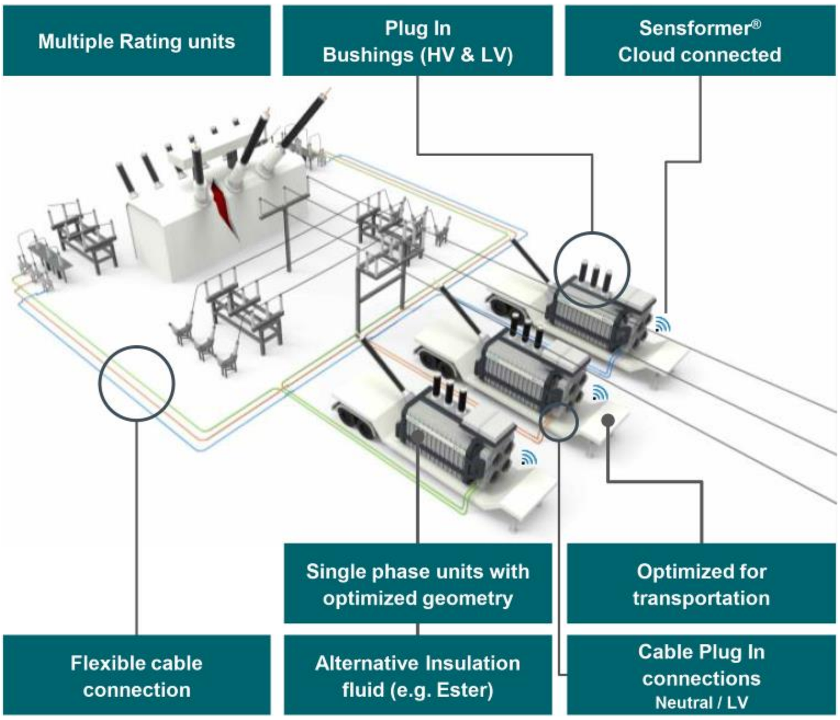

Figure 4 - Schematic arrangement of Siemens' resilience concept [4]

Fig. 4 shows some enablers to react quickly, as easy transport, flexible voltages and fast installation. Several projects applying this single-phase concept have been manufactured by using these enablers, like synthetic ester, changing the voltages via OLTC, DETC, switching links, and power up to 400 MVA while keeping the transportation weight below 100 tons and for high voltages up to 400 kV, which enables to cover up to 80 types of transformers (Fig. 5, 6).

Figure 5 - Rapid recovery resilience transformers on site (Case I and II) (photo: Siemens)

Figure 6 - Assembled single phase resilience GSU transformers (Case III) (photo: Siemens)

Although some of the requirements differ, the main purpose of the resilience transformer is the common goal: to be able to energize the transformers within the shortest possible time, even under difficult and unpredictable conditions:

- Installation time: within the shortest possible time
  (e.g. Case I: 30 working hours within three days working period) [6]
- Dimensions and weight to meet transportation limits
- Accessories delivered and stored in containers
- Cost efficient solutions for planned and forced outages for bypass solutions
- Applicable to all grid structures

Some other considerations to strengthen the resilience of a grid and considering the prevention and protection are:

- GIC (Geomagnetically Induced Currents)

  During the early stage of a project to consider the incorporate the withstand ability of GIC in the electrically design of the transformer to consider effects, like, additional noise, tank vibration, eddy losses heating metal parts.
- Tank rupture prevention to be considered in the mechanical design of the tank. Applying state of the art design tools to consider the energy created by an internal arc, which can be caused by external impacts as well. This leads to minimize the impacts on environment, health and safety.
- Physical protection of assets might be as well of importance of some critical substations. Such a protection can be designed by applying panels to withstand up to VPAM Class 13 / UL752 Level 10 (the highest likely ballistic threat). (Fig. 7)

Figure 7 – Bullet resistant transformers – new and retrofit solution (photo: Siemens)

5. Experience and usage at Con Edison

As utilities renew their aging transformer fleet, they are challenged to find innovative designs that provide improved efficiency, increased loading capability, safer and more flexible operation, and improved resilience within the space constraints of existing substations. In the first AST Type 1 case, the utility was looking to find a replacement transformer for three different MVA ratings and two different impedances. This provision allowed for the simplified standardization of the transformer fleet. It also allowed the reduction of the different number of spare transformers that would need to be held in inventory, for emergency replacement, in the event of a failure. One challenging constraint included the limited space available in the existing transformer vaults. The new design needed to fit within the smallest footprint, as major modification within each of the substations would not be performed to accommodate the transformer installation. In addition, the transformer needed to match the impedances of the existing installations since the transformer would be operated in parallel with other existing transformers. There could also be no exceedances of the zoned sound level octave band requirements. In addition, the transformer needed to be capable of meeting the utility's overload requirements to ensure operating reliability in the event of a contingency, or loss of another source within the station. The innovative use of high temperature winding insulation and spacers together with a sophisticated winding arrangement allowed all of the requirements to be met. Nine of these transformers have already been installed and satisfactorily operating, with the oldest operating since 2014.

Utilities and operators of transformers are looking for safer and less environmentally harmful designs. In the second AST Type 2 case, the utility was looking for a design that uses synthetic ester, Midel® 7131 to minimize the risk of fire and harm to the environment. The improved fire safety characteristics and reduced environmental impact of esters reduces operational risks. Because the utility is located within a dense urban area, reducing operational risk is one of its objectives. The utility selected a transformer rating that has a large installed population within its fleet. The new ester filled transformer would need to fit within the existing footprint and with two different radiator configurations to meet the requirement for a standardized design. In addition, the transformer needed to meet low noise, high overload, tight impedance, shipping dimension and weight design criteria. In order to meet the utility's design requirements within the constraints, the use of high temperature limits and high temperature insulating materials were required. Fifteen of these transformers have already been installed and satisfactorily operating, with the oldest operating since 2018. Additional units are being installed as part of the utility's fleet renewal program.

The third evolution was to produce the first AST Type 1 transformer, but with Midel® 7131 as the insulating liquid. Developing an ester filled transformer of this rating would allow further risk mitigation at additional substations in a densely populated portion of the system. The mineral oil design for this transformer was especially challenging with its operating requirements. The implementation of synthetic ester required an even more extensive use of high temperature insulation materials. The development of additional high temperature Nomex® insulation parts allowed this ester filled transformer to become a reality. Three of these units have been delivered, two of them in 2020.

In January 2017, the design of Case I fast deployment mobile resiliency transformer was successfully proven at a trial run where it took only 30 hours within 3 working days, as opposed to the usual several week timeframe, to install and successfully place into operation the 300 MVA transformer bank [5, 6]. The single-phase design allowed the units to be as compact and lightweight as possible. This size minimization was also facilitated by the hybrid insulation system that utilized high temperature materials: synthetic ester liquid (Midel® 7131) and aramid (Nomex®) conductor insulation. This insulation system design facilitates the reduction of the winding dimension. To support a quick installation, the transformers are transported liquid filled and equipped with plug-and-play bushings and cable connections. Operating flexibility was achieved through carefully thought out specifications. The transformers were designed for dual ratings and impedances for operating versatility to match the majority of the installed transmission fleet. A de-energized tap changer is used to easily change the operating mode from 300 MVA, 345-138 kV to 150 MVA, 138–69 kV without having to drain and enter the transformer to change internal electrical connections. With its three single-phase transformers, the associated secondary cable connections and portable pothead stands, this transformer provides flexibility in positioning the replacement transformer for interconnection within the substation. This innovative transformer solution helps to ensure grid resiliency by facilitating a quick replacement and restoration.

The latest development in transformers for fast deployment in the field of grid resilience at Con Edison is a transformer concept that would cover multiple power ratings and voltage levels allowing for installation in various substations.
Key technical parameters:

- Nameplate rating : 58 / 65 /93 MVA, 3-phase
- High voltage : 132 / 69 kV
- Low voltage: 35 / 28 / 13.8 kV

- Weight limit (filled with liquid): 91,000 kg (200,000 lbs)
- Dimensional limits: 3,660 / 3,250 / 8,890 mm (144" / 128 " / 350")
- Liquid: synthetic ester (for fire and environmental safety)

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