10864 Session 2022
A2 Power transformers & reactors
PS2 Beyond the mineral oil-immersed transformer and reactors

Dry-type 145 kV transformers: safe indoor substations with improved environmental performance

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SUMMARY

Historically dry-type transformers had been limited up to a voltage level of 36 kV and only in the later years this limit has been increased up to 72.5 kV. Recently the 145 kV voltage level has been reached, allowing the use of dry-type transformers as a safe alternative to oil-immersed units in some applications.

After an extensive research and development process, we managed to manufacture cast-coil dry-type transformers with a nominal voltage as high as 138,000 V and with 145 kV insulation level (e.g. 230 kV applied voltage and 550 kV lightning impulse). The Design of Experiments (DOE) method was used to investigate how the change of various insulation parameters affected the withstand voltage. This campaign of dielectric tests was done using reduced models as well as a real scale transformer. This process finished with the successful testing of a 5 MVA demonstrator.

Two years later, when the engineering and operations staff of an American utility decided to replace a 50 year-old transformer at Jocassee Hydroelectric Power Station, they believed a dry-type unit would be the best option. The power station is a 780 MW pumped storage plant in Salem, South Carolina (USA). The reason why a dry-type transformer was preferred is its good environmental performance, as it was going to be placed near the shore of Keowee lake, the lower reservoir of the power station. The old unit was the auxiliary power supply transformer, a 3 MVA oil-immersed bank formed by three 1 MVA single-phase transformers plus one spare.

This old transformer was replaced by a 3 MVA three-phase dry-type unit, with nominal voltage 100,000 V and insulation voltage 145 kV. The new transformer successfully passed all routine and special tests in presence of the customer, including a partial discharge level below 10 pC, 230 kV applied voltage and 550 kV lightning impulse.

This new transformer was installed at the old outdoor substation, which was converted into an inner substation reusing part of the firewalls and adding metallic walls and a roof. The operational experience is demonstrated, as the unit has been in service since middle of 2020.

By reaching these high voltages with the vacuum cast coil technology, users now have access to the safest and the best environmentally friendly solutions for power systems at substations in buildings, underground locations and outdoors. This includes, among others, shopping malls, sport stadiums, airports, metro, data centres, manufacturing centres and power plants.

KEYWORDS

Dry-type transformer - Safety - Indoor substation - Sub-transmission - 123 kV - 145 kV

INTRODUCTION

Although dry-type transformers have been used from the very beginning of the development of electrical systems, they historically had been limited to relatively low voltages, typically up to 36 kV insulation level. It only has been in the last years when the dry-type technology has reached the 52 and 72.5 kV insulation level (Fig. 1). The main challenges for the dry-type insulation are both the short time but high level over-voltages as well as the long term behavior of the solid insulation during the whole life under nominal voltage. The suitability for the first ones is proved with applied voltage (AC) and lightning impulse (LI) tests, while the second one is checked with partial discharges (PD) measurement.

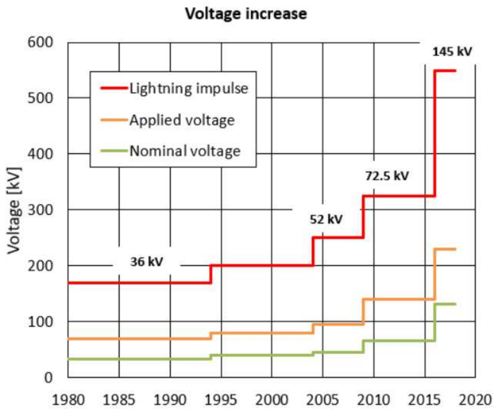

Fig. 1 – Insulation levels reached for dry-type transformers

This paper describes the research and development process followed to reach the 145 kV insulation level for dry-type transformers. It also explains the design, manufacturing, testing and commissioning of the first 145 kV transformer built in the world, a 3 MVA auxiliary transformer placed in a power station.

RESEARCH AND DEVELOPMENT PROCESS

The development of the 145 kV insulation level did not start from zero, because we already had a wide experience manufacturing 72.5 kV dry-type transformers. It includes, among others, four 31.5 MVA 66,000/22,000 V with OLTC for an urban substation in Spain (Fig. 2, left) and two 25 MVA 69,000/13,800 V with OLTC installed in a soccer stadium in Brazil (Fig. 2, right).

Fig. 2 – Examples of installed 72.5 kV dry-type transformer: four 31.5 MVA units in an urban substation in Spain (left); two 25 MVA in a soccer stadium in Brazil (right)

Given the relatively fast process and the good results obtained, we decided to follow the same development course for 145 kV which was used for 72.5 kV [1]. This process was split into two main steps: the first one was a series of Design of Experiments (DoE), where subparts of the transformer were tested, and the second one was the testing of a whole transformer.

The Design of Experiments consisted in the manufacturing and testing of real scale parts of the transformer, e.g. models, where only a part of the whole insulation system was tested. Using a series of similar models where only a single item is changed each time, the effect of each change could be investigated. The models were used to test the following insulation clearances:

- Between HV and LV windings, including the low voltage bars
- Between HV and magnetic core, including the clamps
- Between HV windings of adjacent phases
- Between terminals along the same HV winding

The tests were used to refine both the required air clearance as well as the solid insulation. Note that the solid insulation does not only refer to the arrangement of the laminated papers and reinforcement fiber-glass nets inside the windings. It also includes the number, thickness and arrangement of the insulating barriers outside them.

Fig. 3 – Models being tested up to dielectric failure: LI between terminals along the HV winding (left); AC between high voltage and the clamps (right)

Each model was tested under AC and LI, increasing the voltage step by step until a dielectric failure happened. Although usually the failure was not destructive, meaning it happened between not insulated electrodes or the solid insulation withstand without permanent damage, sometimes the failure involved the breakdown of the epoxy resin or the damage of some other insulating material. These last cases were particularly useful for finding weak points, although they demanded an extra effort repairing the models and planning the tests.

Although after a comprehensive series of experiments with models we had a good approximation of the required design, the insulation system in any electrical machine works as a whole and thus, with models alone we did not have the required security in the design. Apart from that, with the models it was only possible to do LI tests against ground, while a whole transformer allows the testing of the LI stress with the real voltage distribution along the windings. A whole transformer was also necessary to have partial discharge measurements done. So, it was a must to manufacture a whole transformer, e.g. a demonstrator. The demonstrator transformer had the main technical shown below (Fig. 4, left). The rated power was chosen to have realistic dimensions and included a wide tap-changer range to test the effect of LI on it.

Rated power	5 MVA
Nominal voltage	110,000 / 10,500 V
Off-circuit tap-changer	±8 x 2.25%
Insulation level	145 kV
Aplied voltage	230 kV
Lightning impulse	550 kV
Connection group	YNyn0
HV winding technology	Foil disk

Fig. 4 – 5 MVA demonstrator: main technical data (left); demonstrator being tested (right)

The demonstrator passed all routine tests successfully, including a partial discharge level below 10 pC (note the measurement voltage is 1.3 times the nominal voltage, e.g. 143,000 V). Regarding the dielectric test, the applied voltage test (AC 230 kV) was withstood and only the lightning impulse (LI 550 kV) was not reached in all cases. To improve the LI insulation, the following elements had to be redesigned in the demonstrator:

- Insulation between HV and magnetic core and clamps
- HV supporting blocks
- HV line terminals

As stated before, the design of the insulation system must be treated as a whole, and this had never been more true than when we tried to reach the required lightning impulse level. Indeed, we realized that a reinforcement of the insulation in the weak point ended in a new mode of failure in a different insulating element. A new improvement in the new weak point created a different mode of failure in a new place. Given the fact that a failure involving the breakdown of a winding required the disassembly and assembly of the top yoke of the magnetic core, we tried to minimize the number of tests needed to refine the insulation. In that sense, we used Finite Element Method (FEM) analysis to find a more robust solutions with a reasonable manufacturing effort [2].

A comprehensive electrical simulation requires a good knowledge of the physics involved, a reliable model. As this was out of the scope, the FEM analysis only was used in a qualitative way and supposing a static electric field (Fig. 5). As an example, slightly different insulation arrangements were simulated with FEM and the most promising, meaning the one with the lower electric stress, was chosen to be manufactured and tested. Following that process, and with minor changes in the demonstrator, the required LI withstand voltage was reached with enough safety margin and repeatability.

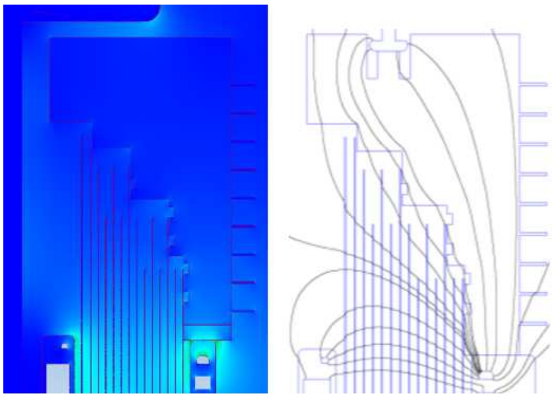

Fig. 5 – FEM simulation of the HV windings: electric field (left); discharge paths (right)

OIL SUBSTATION TO BE UPDATED

The chance to install the first 145 kV transformer on a real site appeared when the engineering department of an important North American utility decided to replace a fifty-year-old oil filled transformer located in a hydroelectric power station (Fig. 6, left). The power station is a 780 MW pumped storage plant, and the transformer to be renovated was its auxiliary unit. The old transformer was a three-phase bank consisting of three 1 MVA units plus one spare (Fig. 6, right).

The transformers form part of an outdoor substation located on the shore of the lower reservoir. One of the reasons to change from oil-filled to dry-type was to eliminate the risk of water contamination. A second reason was to develop experience with 145 kV dry-type transformers, with the aspiration of one day replacing old generator step-up (GSU) units in hydro power stations with dry-type transformers. The utility is also looking to replace other oil insulated devices in this outdoor substation, such as its three death-tank circuit breakers with new SF_6 units.

Fig. 6 – Hydroelectric power station where the first 145 kV dry-type transformer was installed: overall view (left); fifty years old three-phase bank to be replaced (right)

It was decided a single 3 MVA three-phase transformer would replace the 3x1 MVA single-phase bank. But this change in the electrical network raised additional technical questions. One of them was, knowing the transformer is star-star connected, if a compensation delta winding would be necessary or not. To be on the safe side, it was decided to add a delta connected tertiary winding rated one third of the power of the transformer. Another question was the insulation level required for the star of the HV windings. In the single-phase bank the star of the HV winding was solidly grounded and its insulation level was lower than the insulation level of the line terminals. So, it was decided to keep a reduced insulation level for the star of the new transformer, which allows the use of graded insulation in the HV winding (Table I).

Table I – Main technical data of the 145 kV transformer

Rated power	3 MVA (1 MVA unloaded tertiary)
Nominal voltage	100,000 / 600 / (990) V
Off-circuit tap-changer	+3-1 x 2.5%
Insulation level	145 / 72.5 kV, HV line / HV star
Aplied voltage	230 / 140 kV, HV line / HV star
Lightning impulse	550 / 325 kV, HV line / HV star
Connection group	YNyn0(d5)
HV winding technology	Foil disk

The mechanical arrangement of the transformer was done in parallel with the design of the civil work of the new substation and in close collaboration with the customer. It had to take overall dimensions into account, the position of the HV terminals and how they are going to be connected (cables or overhead line), how to ensure the safety distance from the live parts, etc. In that sense, technicians from the factory visited the power station to get a first-hand knowledge of the available room and transportation restrictions.

DESIGN AND MANUFACTURING OF THE DRY-TYPE TRANSFORMER

The specification and the design were reviewed with the customer. As it is typical for the lower insulation levels, a 145 kV dry-type transformer has higher no-load losses and lower load losses compared with the equivalent oil-filled. The capability to withstand short-circuit mechanical efforts, a determining factor in the design of oil-filled transformers, is very favorable for dry-type transformers. The reason for this good behavior under short circuit is the fact that all windings are casted with epoxy resin and reinforced with fiber-glass net, which makes them work as a single mechanical element [3]. As the power rating of the transformer (3 MVA) is well below the maximum manufacturable (some tens of MVA), the cooling was not a design problem at all. Specifically, the minimum height required for the electrical insulation ends in a wide cooling surface that makes unnecessary the use of other common cooling techniques, like cooling ducts or fans. In that sense, a transformer with a higher power rating will not have much bigger dimensions.

It was agreed with the customer to manufacture and initially test just one phase to validate the design. The idea being if the tests were passed, the full transformer will be manufactured with almost full certainty. Although the freedom to modify the electrical design is quite limited once the magnetic core is manufactured, it is always possible to increase slightly the insulation in one zone bearing the cost of a small reduction in a different zone.

Fig. 7 – The first 145 kV dry-type transformer: testing one phase to validate the design (left); finished transformer after factory acceptance tests with the customers (right)

This single phase passed successfully all the tests, remarking partial discharges measurement below 10 pC, applied voltage 230 kV and lightning impulse 550 kV (Fig. 7, left). At this point, it was agreed with the customer to increase the voltage level of the lightning impulse in steps of 10 kV up to failure to know the safety margin of the design. The safety margin found was satisfactory, and the limiting factor that prevented us from increasing the voltage level was the line terminal and the clamp of the magnetic core acting as arcing horns. The transformer withstood the lightning impulse 550 kV after this external discharge. After these good results, it was decided to manufacture the three-phase transformer without changes in the design. However, to be on the safe side, the high voltage windings used in the previous tests were not assembled in the three-phase transformer.

For the manufacturing of the three-phase transformer a strict quality control was kept. This control was refined along the production of the single phase. The control consisted in the definition of stop points in key stages of the manufacturing. A stop point cannot be passed until one expert of each of the main departments involved (R&D, Engineering, Production and Quality) give a favorable opinion.

The transformer was tested in the presence of the customer (Fig. 7, right), and it passed all routine and type tests successfully. The transformer was partial discharge free (measurement below 10 pC), and it withstood applied voltage 230 kV and lightning impulse 550 kV without any incident.

TRANSPORT, COMMISSIONING AND OPERATION

Compared with an oil-filled transformer, the work needed to prepare the transformer for its transportation is minimal. A wood support saddle is placed outside the high voltage windings to avoid any movement during the transportation. To reduce the overall height, the three 145 kV support insulators for the line terminals are disassembled and sent separately. Compare this with the work needed for an oil filled 145 kV transformer, where multiple components must be disassembled (bushings, radiators, conservator tank, etc.) and the oil removed from the tank. One of the advantages of dry-type transformers is the possibility to inspect visually most of its components, as there is no tank. In that sense, the position of the windings is marked to check its centering before and after the transportation. Additionally, an accelerometer register is attached to check that the maximum allowed mechanical efforts are not exceeded.

The work to turn the outdoor substation into an indoor one had been done in parallel with the manufacturing of the transformer. Thanks to a reserve auxiliary transformer, it was possible to do it keeping the power station connected to the system. The work consisted of the removal of the oil-filled transformers and the three firewalls between them. The remaining firewalls were left to form three of the walls of the new substation, while the fourth wall and the roof was made in metallic structure (Fig. 8, left). The three old dead-tank oil circuit breakers were replaced with SF_6 units placed outdoors, while the low voltage circuit breakers were installed inside the new building. This way, most of the footprint of the old substation was freed for other uses.

Fig. 8 – The new 145 kV substation: turning the outdoor substation into an indoor one (left); the dry-type 145 kV transformer in service (right)

Like the preparations for the transportation of the transformer, its installation requires a reduced scope of work. Once the transformer is placed at the final position, the support saddle is removed, the high voltage bushings are assembled and the cabling from the sensors to the control box is done. In that sense, the transformer is equipped with one infrared thermometer per phase, so that the temperature of the windings can be measured with safety despite the high voltage involved. The only element that has been added, and that it is not always required for oil transformers, is a protective barrier to prevent any electrical hazard.

The last step of the commissioning is the repetition of part of the tests done in the factory. Some of them, like the measurement of the insulation resistance and the analysis of the excitation current, are done to ensure that the transformer has not been damaged during transportation and can be energized safely. Others, like Sweep Frequency Response Analysis (SFRA), are done to obtain a fingerprint of the unit that can be used in the future to facilitate the maintenance.

CHALLENGES

Looking at the development of the project from the very beginning, the main challenge was to reach the demanding lightning impulse level of 550 kV with enough safety margin and repeatability. Two points make it difficult: firstly, a lightning impulse failure ends quite often in a breakdown of the solid insulation that increases the time and resources needed for a test campaign; secondly, the lighting impulse test has some dispersion in the results, which requires a statistical approach and so a higher number of trials. This was problematic testing the models, but it was even worse testing the whole transformer as the assembly and disassembly is time-consuming.

Looking at the development of the 3 MVA transformer, the discussion until the technical specification was fixed and the design review accepted took a long time and some rework. Thanks to the comprehensive previous test campaign, including whole transformers, the success probability was high, but the manufacturing of the first 145 kV dry-type transformer in the world is always a challenge. In that sense, a strict quality process with predefined control points where the manufacturing is stopped until all the experts involved give their approval, has been fundamental for the success. Special consideration was given to cleanliness during the manufacturing process, as the exclusion of foreign material is critical to reach a low partial discharge level.

BIBLIOGRAPHY

[1] R. Murillo, J. Tepper, C. Roy et al. “Dry-type transformers for sub-transmission voltage level” (CIGRE A2 & D1, Kyoto, 2011)

[2] B. Cranganu-Cretu, R. Murillo, M. Berrogaín et al. “Dry-type subtransmission transformer: dry power transformers for the 123 kV and 145 kV voltage class” (CIGRE A2-307, Paris, 2016)

[3] R. Murillo, J. Smajic, J. Tepper et al. “Electromagnetic simulations supporting the development of dry-type transformers for subtransmission voltage levels” (CIGRE A2-208, Paris, 2012)