

DRY-TYPE TRANSFORMERS FOR THE 72.5 KV VOLTAGE CLASS

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ABSTRACT

Typical voltage classes for dry-type transformers are up to 36 kV and their application is mainly in the distribution grid. After intensive R&D activities, dry-type transformers have recently been introduced for the 72.5 kV voltage class, making them now also available for the subtransmission voltage level.

A fast development was reached thanks to a combination of experimental investigation and extensive use of computer simulations. A special interest for the application of dry-type transformer is in inner-city substations, power plants, substations in or close to buildings or caverns, in water protection areas and for industrial applications, such as the chemicals, oil & gas industry. This is due to their intrinsic feature of providing high levels of safety by not containing any flammable, explosive, or leaking liquids.

INTRODUCTION

The good dielectric properties of mineral oil, together with its ability for cooling very close to the heat source, resulted in a compact transformer design, which makes mineral oil-filled transformers nowadays the dominating transformer technology. However, due to the flammable nature of mineral oil, the risk of oil spillage with the related contamination of the ground and the risk of failure due to leaking transformers, the development of dry-type transformers was initiated, as far back as several decades ago. Since then, dry-type transformer technologies have well evolved and are now widely used in applications where safety is of major importance, for example in buildings or in industrial applications, or for ecologically sensitive areas, such as water protection areas.

While dry-type transformers are typically used up to 36 kV, ABB introduced in the 1990ies dry-type transformers for the 52 kV voltage class. Since then, they have proved their high reliability in a number of utility and industrial installations. Several world-wide trends and customer demands, like urbanization and increased environmental awareness, motivated ABB to take the dry-type transformer technology one step further and to introduce a product for the 72.5 kV voltage class.

Of special interest for such a sub-transmission dry-type transformer application are inner-city substations, power plants, substations in or close to buildings or caverns, in

water protection areas and for industrial applications, such as the chemicals, oil & gas industry.

A major challenge was to develop an insulating configuration made of a combination of air and solid materials which is able to fulfil the 72.5 kV voltage class requirements without using an insulating liquid, in a competitive way, that is to say, with small enough clearances in the active part.

Although a failure in any piece of electrical equipment can never be excluded, the consequence of such a failure may heavily depend on the technology used. With a dry-type transformer it is possible to minimize occurrences like burning transformer in an urban area producing smoke and fumes, widely visible to the public.

72.5 KV DRY TRANSFORMER

Dry-type transformers for the 72.5 kV voltage class are now available with the following characteristic:

Rated power	up to 63 MVA
Primary voltage	up to 72.5 kV
Lightning impulse voltage	325 kV for IEC 350 kV for ANSI/IEEE
Short duration AC withstand voltage	140 kV
Connection group	Y or D
Secondary voltage	up to 36 kV
Partial discharge	<10 pC
Insulation class	F (155°C) or H (180°C)
Environmental class	E2
Climate class	C2
Fire class	F1
Cooling	AN or AF

Table 1: Characteristics of 72.5 kV voltage class dry-type transformers

No IEC or ANSI/IEEE standard exists for dry-type transformers with voltage classes above 36 kV. Therefore the respective standards for dry-type and oil-immersed transformers were applied, whenever relevant [1].

The dielectric stress within a dry-type transformer is taken up by solid and air insulation. Due to the higher permittivity of the solid insulation, the electric field in the solid material is reduced and the main insulation comes from the air. Partial discharge measurements at transformers of the 72.5 kV voltage class yielded very small values, much

below the limit of 10 pC for dry-type transformers. The transformer is quasi partial discharge free, which guaranties a quasi void free insulation. The latter is necessary to obtain insulation lifetimes of several 10 years.

Oil-filled transformers are mostly built in accordance to an A-class temperature rise of 65°C. For the present dry transformer solution F-class or H-class insulation material are used, which allows an average winding temperature rise of 100°C and 125°C, respectively. In case of applying a forced air cooling the rated power of the dry-type transformer can be increased by several 10%, depending on its rating.

These transformers can be provided with common number of tap positions and regulation range.

The E2 environmental class allows for heavy pollution and frequent condensation on the transformer. Operation and storage for temperature down to -25°C is possible for C2 climatic class transformers. F1 class transformers offer restricted flammability and the emission of toxic substances and opaque smoke is minimized. In fact, ABB dry-type transformers are self-extinguishing.



Fig. 1. New 66 kV/10 MVA dry-type transformer

72.5 kV dry-type transformers are available with vacuum cast coil (VCC) or Resibloc® coil technology. The VCC technology uses foil disk windings together with a well-proven and high quality epoxy resin and silica filler casting technology. The ABB unique Resibloc® transformers are cast resin transformers reinforced by glass fiber filaments. Due to this reinforcement they offer superior mechanical strength, making them most suitable in cases of extraordinary loading cycles or short-circuit currents. Resibloc® transformers also have excellent performance in very cold climates and can be operated at temperatures down to -60°C.

Figure 1 shows a 10 MVA VCC transformer for the 72.5 kV voltage class.

APPLICATION ASPECTS

72.5 kV dry-type transformers require a similar footprint as oil transformers. Cooling equipment and radiators of oil transformers are quite spacious, especially for larger ratings. In contrast to this, dry-type transformer coils are directly cooled by air and heat does not need to be transmitted first to the radiators by the oil. Further, the higher temperature rise of the dry-type transformer makes the cooling more efficient due to a higher temperature gradient between cooling air and coil surfaces and the corresponding increased heat transfer. In addition the radiative cooling is also increased at higher temperature.

However, since the dry technology requires larger dielectric clearance distances, the core and therefore also the mass of the transformer is slightly larger. This also results in a somewhat increased no-load loss. The load loss is comparable to the load loss of an oil transformer, so that total losses are only slightly larger with a dry transformer.

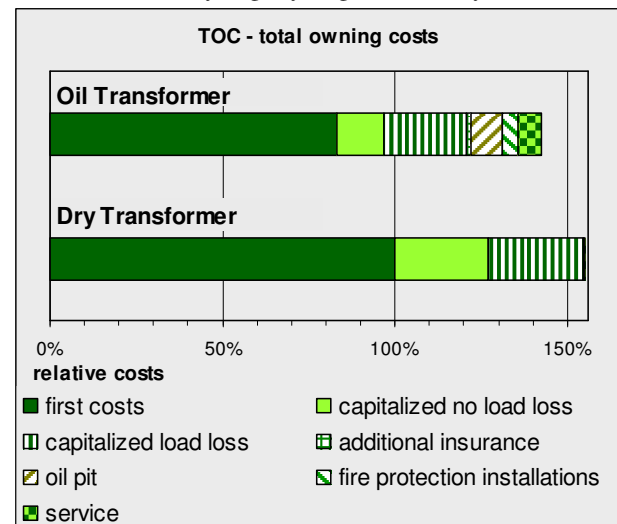


Fig. 2.: Comparison of total ownership costs for a 66 kV / 16 MVA Oil and Dry Transformer with OLTC

Figure 2 shows a comparison of the total ownership cost of a dry transformer compared with an oil transformer of the 72.5 kV voltage class (66 kV/11 kV 16 MVA) with On Load Tap Changer (OLTC), considering also the evaluated costs of the no load losses and load losses. It is a typical approach for utilities to account the losses over the lifetime of the transformer with a corresponding cost of e.g. 1 €/W for load losses and 5 €/W for the no-load losses [2]. It shows that the costs, purely based on the transformer costs and the loss evaluation, are approximately 30% larger for a 72.5 kV dry transformer compared to an oil transformer. This is a drawback for the sake of achieving increased safety and is also typically the case in the conventional voltage range of dry transformer.

If costs related to the use of oil are also taken into account the following cost evaluation has to be considered. Avoiding the oil allows to avoid an expensive oil pit, oil related fire extinguisher installations and more expensive

insurances. Furthermore, the fact that dry transformers have much less need for service, accounts to the result. As a conclusion it can be seen that the total cost difference of a 72.5 kV dry transformer to an oil transformer is rather small.

If system considerations are taken into account, the application of dry technology may also allow the achievement of substantial energy savings. Taking the example with power supplied from a subtransmission line (see Fig. 3), it is now possible to connect customers using a 69 kV cable and to transform the power directly at the customer site or in its building to the required voltage. Traditionally the power is transformed to a medium voltage level in a substation close to the transmission line. Due to the lower current, the cable losses are substantially reduced. For a 5 km long cable this results in annual energy savings of 280 MWh, which corresponds to a reduction of 140 t/yr of CO₂ emissions (for EU electricity mix).

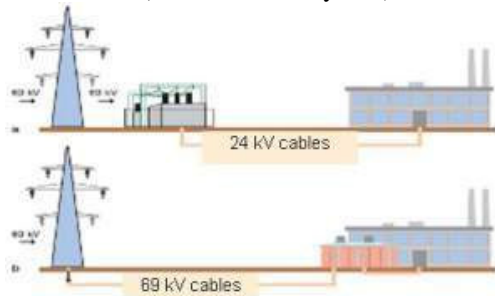


Fig. 3. Substantial energy savings due to reduced cable losses can be achieved by transforming directly at the customer site

The 72.5 kV dry-type transformer is also suitable for substation retrofit. Paralleling with existing oil transformers is possible. Since the two coil technologies VCC and Resibloc® are available, choosing the technology which best matches the behaviour of existing transformers is possible.

TECHNICAL CHALLENGE

The major technical challenges for the 72.5 kV dry-type transformer can be separated into the control of the external dielectric clearances, the control of the surge voltage distribution in the winding and the corresponding inner winding clearances, and the control of the thermal behaviour of the transformer, i.e. avoiding hot spots in the windings, bus bars and metal pieces.

External dielectric clearance

The challenge was to develop an insulating configuration made of a combination of air and solid materials which is able to fulfil the 72.5 kV voltage class requirements without using an insulating liquid, in a competitive way, that is to say, with small enough clearances in the active part.

In order to reduce the clearances of the active part a new set of concepts for dry-type transformers were taken into account: shielding rings in the windings, conductive

shielding pieces for the clamps and magnetic yokes, rounded corners in windings and shields, and an optimized number of barriers and barrier arrangement criteria to control the electric field in the insulating air.

At the beginning very simple test setups with few variables were investigated, and adding complexity step by step until a full dry-type transformer has been built. This systematic approach has enabled to separate and evaluate the effect of each design parameter independently. Each step of complexity has included both the theoretical approach by electric field simulation of the configuration (Fig. 4), and validation testing on real models (Fig. 5) to verify the breakdown voltages for both impulse and AC tests.

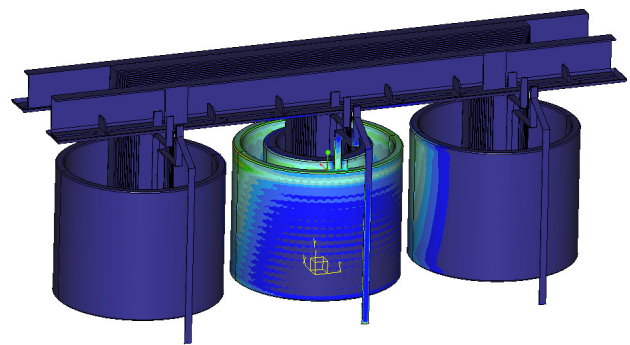


Fig. 4: 3D simulation of the electric field intensity in a 10 MVA 72.5 kV dry-type transformer

The theoretical evaluation of the breakdown voltage was done by an initial calculation of the streamer-inception voltage by means of a 3-D electric field analysis [4]. In order to reach a robust dielectric design, the discharge propagation was further taken into account. This was reached by an evaluation of the 3-D electric field analysis, the prospective discharge path and the background electric field, which has to be above a “stability field” to enable streamer propagation [3,4].

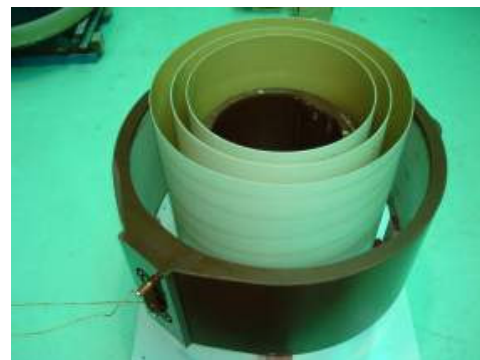


Fig. 5.: Simple configuration for real model test with high voltage and low voltage winding

The discharge lengths in air for dry transformers for the 72.5 kV voltage class are typically below the meter range, so that from that perspective a leader transition should not occur [3]. Anyhow, due to the presence of dielectric barriers and insulation material, respectively, a leader transition could occur even at smaller discharge length. This has to be

avoided, since the voltage drop along a leader becomes significantly small and an immediate breakdown is then expected [3].

The initial testing model consisted of a high voltage winding, a low voltage winding, and some insulating barriers. The tested parameters were the clearance between the high (HV)- and low-voltage (LV) coils, the number of barriers, and the criteria for barrier arrangement. Then the influence of the barrier height was evaluated. In a later step, the impact of adding insulating blocks for fixing the coils in the transformer assembly was checked.

The next test setup consisted of several winding designs, including shielding rings and rounded corners with the theoretically found optimum radii. Once the HV to LV insulation was optimized, the magnetic yoke was added to the model. First, the impact of the clearance between HV to yoke was evaluated. Then the effect of shielding and insulating the yoke was checked. Finally, the metallic clamps were added to the model and the influence of insulating and shielding the clamps with various covers was evaluated. In a similar way the phase-to-phase distance was minimized.

INNER WINDING CLEARANCES

Apart from the control of the dielectric stress in the air, it is necessary to design the internal solid insulation in the high voltage winding in accordance to induced voltage and surge voltage stresses. This has to be done with a reasonable safety margin, not only in order to pass the lab test, but specifically to ensure a reliable long-term operation and long lifetime.

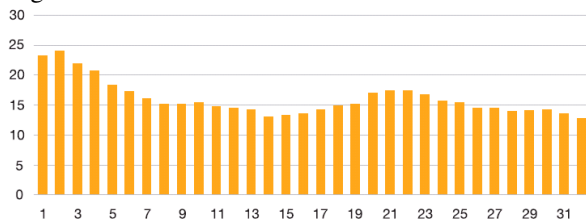


Fig. 6: Voltage between discs (maximum values, in kV) along the high voltage winding during 325 kV impulse testing.

The allowed dielectric stress in solid materials is well known for several dielectric conditions, that is to say, for impulse tests, one minute tests, and long term operational voltage. These dielectric stresses have been successfully used for the internal design of the high voltage coils of dry-type transformers for tens of years for the voltage range up to 36 kV. For the new 72.5 kV voltage class, the same dielectric stresses are used internally in the high voltage coils, so no additional risk is introduced when compared to the current 36 kV dry-type transformers. This condition has easily been met by internally splitting the coil in a suitable number of sections, either as discs or in layers (Fig. 6).

EDDY CURRENT LOSSES and HOT SPOTS

Increased clearance distances and increased power ratings also influence the magnetic stray fields [5]. Especially for

transformers with ratings of some 10 MVA, care needs to be taken to minimize eddy-currents in windings and structural components, otherwise load losses substantially increase and create intolerable thermal hot-spots. Based on simulations, several designs were evaluated with the aim to reduce additional eddy current losses. The found measures, i.e. shieldings, special winding designs and special busbar and structural designs were realized.

FULL PROTOTYPING

After all these simulations and experimental tests were performed, the optimum insulating configuration was defined and ready for full transformer prototyping.

Finally, two prototypes were simulated, manufactured and tested: a 10 MVA unit in vacuum cast technology and a 2 MVA unit with Resibloc[®] coils. Both passed all routine and type tests, (325 kV impulse and 140 kV applied voltage for 1 minute). Both prototypes were tested to the limits by increasing the test voltage beyond the values required by the standards, until a flashover occurred (Fig. 7). The results validated the forecasted theoretical breakdown voltage and confirmed that adequate safety margins exist.



Fig. 7: 72.5 kV dry-type transformer prototype being tested to the limit.

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