DRY-TYPE TRANSFORMERS FOR THE SUB-TRANSMISSION VOLTAGE LEVEL

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ABSTRACT

Manufacturers of electrical equipment undertake permanent efforts to develop better and safer products. A recent innovation are dry-type power transformers for the 72.5 kV subtransmission voltage class. The complete absence of inflammable transformer oil makes the transformers suitable for installation at any location, including simple installations in buildings or underground. In case of earthquakes there is no risk for tank rupture and related consequential damage. A number of technical hurdles had to be overcome during the development of the 72.5 kV dry transformer technology.

INTRODUCTION

The use of dry-type transformers in the distribution grid is strongly expanding. Improved technologies, proof of long lifetime, and extended product portfolios are supporting this trend. The installation and application of dry-type transformers is simple and fast. The transformers have high strength against short-circuit or other mechanical loads and don't require maintenance.

Dry-type transformers use air as main insulation medium. The dielectric strength of air is considerably less than the dielectric strength of transformer oil and dry-type transformers require therefore larger insulation distances. This results in an active part which is larger and therefore also more costly. On the other hand, thanks to the lack of inflammable and ecologically harmful liquids, dry-type transformers of fire class F1 are unrivalled with respect to safety for people, for installations and for the environment. No risk for oil spillage and contamination of soil or water and no risk of failure due to leaking transformers exists.

Dry-type transformers are usually only available for distribution applications for voltages up to 36 kV. Dry-type transformers for the 52 kV voltage class were introduced about 10 years ago. They have meanwhile been used in a number of utility and industrial installations and proved their high reliability also at that voltage class. Another step in voltage has recently been done by introducing dry-type transformers for the 72.5 kV subtransmission level.

For 72.5 kV dry-type transformers the rated voltage and test voltages are double compared to the usual voltage range of dry-type transformers. Very careful R&D work and intensive testing was necessary to guarantee safe performance, to optimize the design and to minimize the size of the transformers.

Using air instead of an insulation liquid or of a pressurized insulation gas (e.g. SF6) is on one hand a disadvantage due to the lower dielectric performance, but it offers on the other hand also an

important benefit, since air is always available with only little pressure variation. Air-insulated transformers can therefore guarantee high reliability in operation.

While in the distribution grid on-load tap changing is so far very rarely required, for transmission and subtransmission voltages this is a must for the majority of installations. The availability of an On-Load Tap Changer (OLTC) is therefore an important prerequisite for subtransmission applications. In order to guarantee its safety features, it also needs to be of dry-type technology.

72.5 kV DRY-TYPE TRANSFORMER AND ON-LOAD TAP CHANGER

The dry-type transformers for the 72.5kV voltage class offer the same full functionality as liquid-immersed transformers and comply with their dielectric test requirements according to the relevant IEC or ANSI/IEEE standards. They have the usual characteristics of premium dry-type transformers (Table 1). No IEC or ANSI/IEEE standard exists currently for dry-type transformers of voltage class 72.5kV. Therefore the respective standards for dry-type transformers up to 36 kV or for oil-immersed power transformers are applied, whenever relevant.

Rated power	up to 63 MVA	Partial discharge	<10 pC
Primary voltage	up to 72.5 kV	Insulation class	F (155°C) or H (180°C)
Lightning impulse voltage	325 kV for IEC 350 kV for ANSI/IEEE	Environmental class	E2
Short duration AC withstand voltage	140 kV for IEC 140 kV for ANSI/IEEE	Climatic class	C2
Secondary voltage	up to 36 kV	Fire class	F1
Connection group	Y or D	Cooling	AN, ANAF, AFAF, AFWF
Tapings	17 positions, $\pm$ 8 x 1.25%	Enclosure	IP00 (none) IP21 (indoor) to IP54 or IPX4D (outdoor)

Table 1: Characteristics of 72.5 kV dry-type power 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 filament. Due to this reinforcement they offer superior mechanical strength, making them most suitable in the event of extraordinary loading cycles, short-circuit current, or other mechanical strain. RESIBLOC transformers offer excellent performance in very cold climates and can be operated at temperatures as low as -60°C.

The on-load tap changer is based on dry-type, oil-free technology, of linear switching type. The linear configuration is used for dry-type OLTCs at lower voltages since many years and is well proven. Vacuum interrupters are used as diverter switches.

The OLTC consists of a separate unit for each phase, mounted in front of the respective transformer coil. The phases are commonly operated from a single drive via a common shaft (Figure 1).

The actual solution offers 17 positions, and a tapping range of $\pm$10%, with a maximum voltage step of 900 V. The maximum current is 500 A. The actual number of electrical operations are 100’000. Very little maintenance is required with a dry-type OLTC and the product allows

atmospheres of pollution level II. Further improvements with respect to ratings and number of operations are ongoing.

The connection between the taps of the dry-type transformer and the OLTC contacts is done using insulated cables. The windings, the OLTC and the insulation between individual cables and between cables and ground has to be properly dimensioned for withstanding the operational and lightning impulse voltage levels at all possible tap positions. An exact knowledge of the voltage distribution in the winding is therefore of high importance.

Figure 1: Dry-type on-load tap changer and connection between transformer and OLTC

In case of substation installations in buildings, it is most straightforward to do an IP00 installation for the dry-type transformer, i.e. without any enclosure and use a fence for avoiding that people or larger animals could touch the energized transformer. Alternatively, the use of IP21 or IP23 enclosures is possible. The 72.5 kV transformers can also be installed outdoor by using an appropriate enclosure (Figure 2).

There are different possibilities for connecting the transformers. In case of open busbars coming from breakers, the HV coils can be directly connected to the busbars (Figure 2). If a cable is coming to the transformer, the cable termination can be mounted in front of the transformer coil. If an overhead line is coming to a building or to an enclosure, a wall bushing is used for entering.

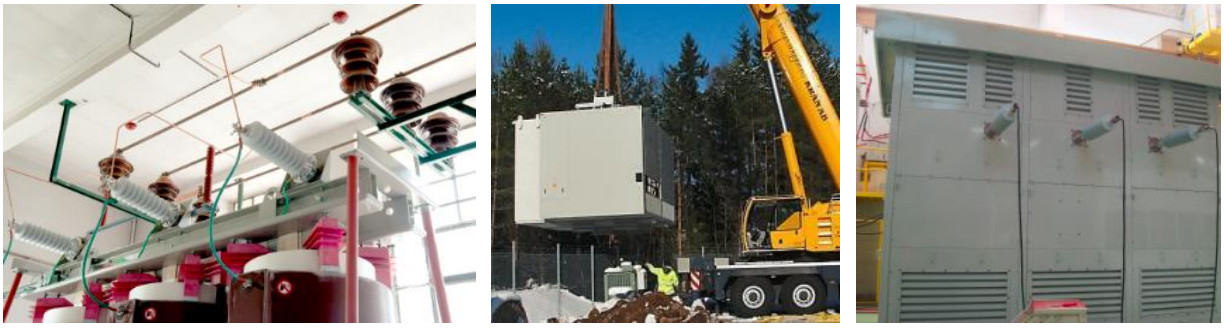

Figure 2: Transformer installations without (IP00, left picture) and with enclosure (IPX4D outdoor installation). Connection of transformer via open busbar (left), via cable entering into enclosure (center) or from overhead line via wall bushings.

INDOOR 69 kV TRANSFORMER SUBSTATION AT FONTE NOVA ARENA, BRAZIL

The 72.5 kV dry-type transformers allow innovative and compact substation installations. Such an installation has been realized in the newly constructed soccer stadium in Salvador de Bahía in

Brazil (Figure 3). It is one of the stadiums hosting the 2014 FIFA Soccer World Cup and provides 55'000 seats. The 69 kV substation, containing two 25 MVA vacuum cast coil transformers went into operation in spring 2013.

The stadium is supplied by a 69 kV cable line. The HV/MV substation is integrated in the basement of the stadium, below the access to the arena and grandstand seats. Safety and reliability are key factors since any incident could have terrible consequences. By using the dry-type transformers, the local utility Coelba, part of Neoenergia Group, was not only able to realize a safe installation, but achieved also cost savings compared to alternative solutions, thanks to reduced need for civil works and for other additional installations [1, 2].

The incoming 69 kV feeder connects to a 72.5 kV hybrid gas-insulated switchgear (PASS) and further to the dry transformer (Figure 3). The transformer secondary side provides two voltage levels: 11.95 kV or 13.8 kV, and further connects to the MV switchgear. The transformer is cooled by natural convection (AN). Thanks to the E2 environmental class it is suitable to be installed in the hot and humid Brazilian climate, not far from the sea. It is designed and tested for a lightning impulse voltage of 350 kV. The OLTC offers a regulation range of +4/-12 x 1.25%.

Figure 3: Fonte Nova Arena, Salvador de Bahía, Brazil, with 69 kV/25 MVA dry transformer with OLTC and hybrid gas-insulated HV switchgear installation in the basement

Figure 4 shows a general outline for a very compact indoor substation with power ratings of 10-40 MVA. The required footprint is about 10x10 m^2, and the room height is 6-7 m [3].

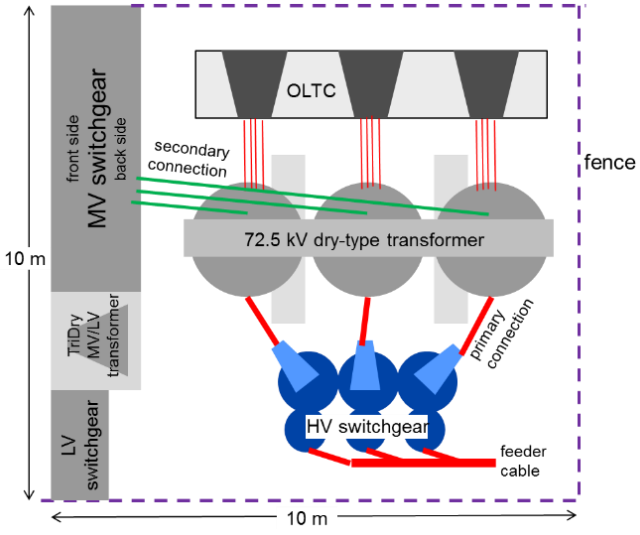

Figure 4: Compact 72.5 kV indoor substation installation with dry-type transformer connected to on-load tap changer and to MV and HV gas-insulated switchgear

THE TECHNICAL CHALLENGE FOR 72.5 kV DRY-TYPE TRANSFORMERS

Compared to distribution transformers, the transformers for subtransmission voltage levels are much more demanding. Besides the higher voltage, the higher rated power and an increased range for voltage regulation leads to several technical challenges. A number of dielectric, thermal and mechanical problems had to be solved. The development tasks were carried out by intensively using FEM based simulations in combination with experimental testing. The use of numerical simulations allowed to investigate a wide set of new technical solutions. Validation testing on various model windings allowed to verify the breakdown voltages for impulse and AC tests. Testing of the models also allowed to increase the test voltage beyond the required test levels in order to determine the safety margin. Finally, full type testing was performed on a 2 MVA RESIBLOC and a 10 MVA VCC transformer. [4-6]

DIELECTRIC DESIGN

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. The dielectric strength of air is therefore the limiting factor and defines maximum electric fields and minimum insulation distances. Parameters like varying air pressure, altitude, temperature and humidity, as well as dielectric surfaces will additionally have an influence on the withstand voltage.

Gas ionization physics has to be applied in order to investigate the details of the breakdown. For engineering purpose, the concepts of streamer inception, streamer propagation and leader transition and propagation can be applied [7]. Depending on the specific regime, a different maximum field applies for the transformer design (Figure 5).

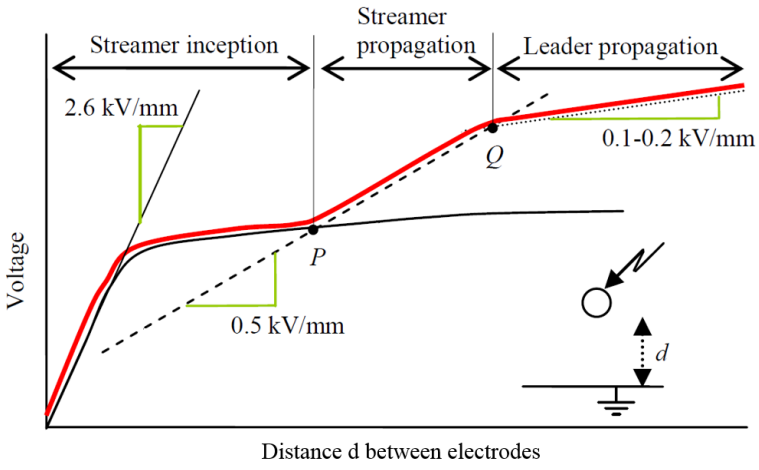

Figure 5: Sketch illustrating regimes of inception and propagation mechanisms for dielectric breakdown of air (Fig. 1 from [7])

The electric fields in a transformer are local and depend on the exact geometry. A careful 3D FEM-based calculation of the electric fields has therefore to be performed and a field analysis needs to be executed (Figure 6). The most critical discharge paths can be identified and the transformer design adjusted in order to exclude such discharges. The simulated results were validated by preparing a number of model coils and model set-ups and performing experimental investigations.

Electric fields present under operational and test conditions (350 kV lightning impulse voltage) have to be considered (Figure 7).

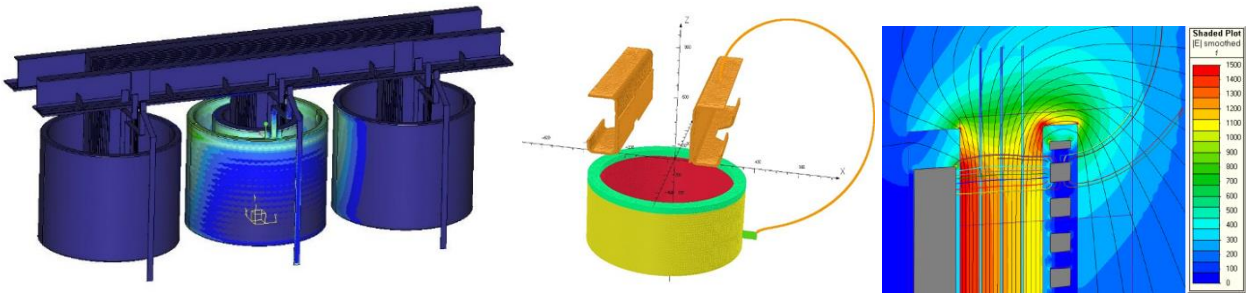

Figure 6: 3D simulation of the electric field intensity in a 10 MVA 72.5 kV dry-type transformer (left side), evaluation of a prospective discharge path between high voltage terminal and core clamp (center) [5], and electric field distribution, equipotential lines, and streamlines around the end of a winding [6]

Figure 7: 72.5 kV dry-type transformer prototype testing beyond the limits [4]

We have optimized the dielectric design and clearance distances are reduced by introducing a number of new concepts for dry-type transformers: shielding rings in the windings, shielding of core parts, and the application of multiple barrier concepts and barrier arrangements. The use of such means allows to influence the local electric field distribution and to "design" prospective discharge paths.

DESIGN OF WINDINGS AND TAPPINGS

Design rules for dielectric stress in solid materials of dry-type transformer coils are well established and proven for the standard transformers up to 36 kV. The maximum allowable values depend on the specific winding design, e.g. foil-disk windings or wire-layer windings and the materials used. Applying the same rules for the 72.5 kV coils results in same internal dielectric stresses and minimizes the risk for a turn-to-turn or a disk-to-disk breakdown in a coil.

The IEC 60076-11 standard for dry-type transformers requests partial discharge (PD) measurement as a routine test and defines a PD level of maximum 10 pC at 1.3 U_r as acceptance criterion. In case of presence of voids in the solid insulation, partial discharge may occur in the voids. If PD occurs at operational voltage, the insulation may degrade over time, treeing may start and finally result in a dielectric breakdown. There is no real physical reason for demanding this very low PD level, but it is generally recognized that in case the PD test is passed, any potential PD process

developing in a void will not have sufficient energy to damage the insulation over the lifetime of the transformer. Although IEC 60076-11 is applicable only up to 36 kV, we also apply this PD criterion for the 72.5 kV transformers. In fact, the measured PD values were considerably below the 10 pC limit value.

While distribution transformers typically offer a regulation range of +/-5% for off-load voltage adjustment, for power transformers on-load voltage regulation of +/-10% to +/-20% is required. In case of liquid-immersed power transformers the tapings are normally realized by using a separate regulation winding. The use of separate regulation windings is more difficult in case of dry-type transformers and the tapings are therefore integrated into the main winding. A large regulation range of up to 40% and the high BIL voltage of 325 kV resp. 350 kV can make the design quite a challenge and it is necessary that the voltage distribution within the windings can be precisely calculated.

A 1.2/50 ms BIL impulse covers frequencies into the MHz range. At such high frequencies, a transformer behaves capacitive. The series capacitances in the winding and its capacitances to ground therefore define the initial voltage distribution in the winding. The distribution may be strongly nonlinear. With growing time, the inductances of the winding also start to play a role and change the voltage distribution. Resonances may develop. Additionally, depending on the specific tap connection, there can be quite long open winding parts causing reflections at their end and causing high voltage transients.

Existing tools for the calculation or simulation of the voltage distribution in transformer windings were not able to reproduce experimental results with the required accuracy. We had therefore to develop a novel method for accurate high-frequency modeling of dry-type transformer windings [8]. A detailed equivalent circuit, considering the winding system in its full complexity by taking into account each single turn is used and the relevant parameters for the C, L and R values are determined with the help of magnetic and electric field simulations. In this approach all inductive and capacitive couplings are taken into account and the resulting large matrix system of ordinary differential equations is solved. The results of a simulation of the voltage at different positions in a model coil are shown in Figure 8.

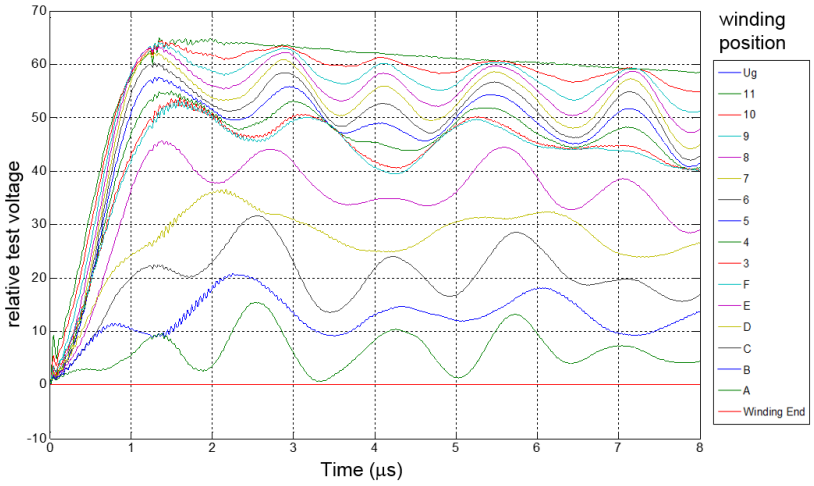

Figure 8: Simulation of voltages at different locations inside a dry-type transformer coil during the application of a lightning impulse [8]

The voltages appearing at the transformer taps are of course also determining the dielectric requirements for the on-load tap changer. Note that capacitive or inductive components of the OLTC can interact with the transformer winding and cause a further modification of the voltage distribution.

THERMAL DESIGN

The rating of power transformers and therefore also the load loss in the windings is much higher compared to typical distribution transformers. Magnetic stray fields can cause eddy currents in the windings, which can become very significant with growing cross section of the conductor, and create additional eddy losses and hot spots at unexpected locations. These eddy losses strongly depend on the winding design. When the OLTC is connected at its minimum position and part of the winding turns are "deactivated", the magnetic stray fields (Figure 9) and eddy currents can be especially strong and the local heat generation considerably higher [6].

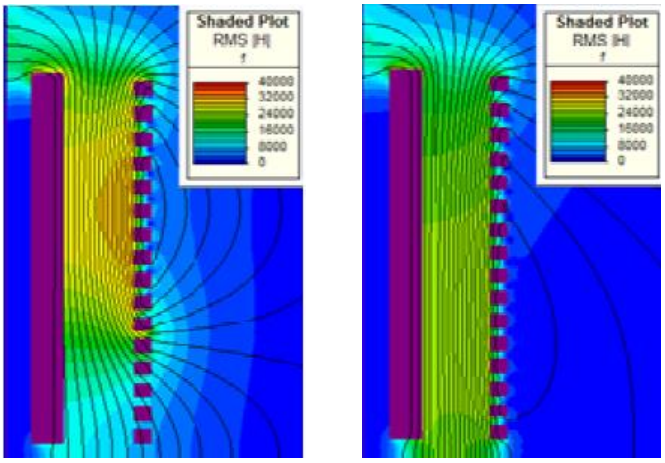

Figure 9: Simulation of magnetic flux distribution in transformer coils. The left side graph represents a situation where the OLTC is connected to the minimum position (-18%), the right side graph to one where all turns are active (+18%)

By using combinations of different winding types and conductors in the same winding, the size of the regulation winding part can be minimized and eddy losses and hot spot temperatures are reduced.

Dry-type transformers have the advantage of using insulation materials of thermal class F or H, allowing an average winding temperature of 140°C resp. 165°C. This is much more than in case of transformers containing mineral oil (105°C). The higher temperature gradient to the ambient and the direct cooling of the coils by air without the need to pass via a heat transferring liquid and radiators, makes cooling of the dry-type subtransmission transformers quite efficient.

MECHANICAL DESIGN

The windings of cast coil transformers are embedded in a solid and robust matrix of epoxy. They are therefore very rigid and the conductor cannot move and has a high short-circuit strength. Correctly designed and manufactured coils offer also in case of large physical dimensions high mechanical strength. The C2 thermal shock qualification, where the coils are heated starting from

-25°C with twice the nominal current, guarantees that they are not prone to thermo-mechanical stress and cracking.

An important advantage of the dry-type transformer technology is that it does not need a tank containing liquids, which might break under application of vibrations or strong acceleration. In case of special requirements, e.g. for regions with high seismic risk or for wind turbine applications, the mechanical structure can be additionally reinforced as shown Figure 10.

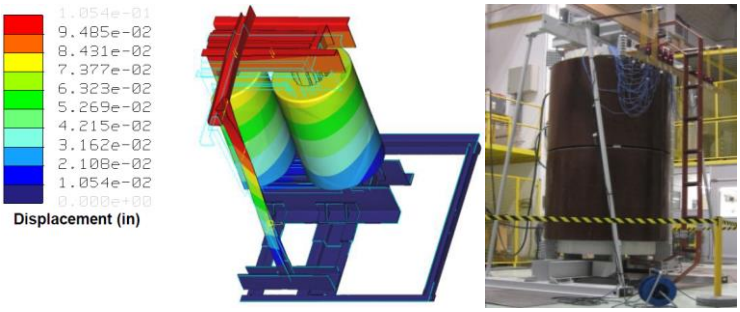

Figure 10: Examples of bracings for mechanical reinforcement of the transformer and simulation the displacement in case of a seismic event

CONCLUSIONS

The development of dry-type transformers for subtransmission applications is a major step forward with respect to providing equipment with increased safety for people, property and environment. These transformers allow to use new concepts for compact indoor substations and their fast and simple installation.

It was necessary to solve a bunch of technical challenges since rated and test voltages have doubled compared to usual dry-type transformers. Additional requirements like on-load tap changing with large regulation range further complicated the development. A good understanding of gas discharge physics and of transformer electromagnetics was a prerequisite for the success. Broad use of 3D FEM-based simulations in combination with experimental testing allowed to expand the safe and reliable dry transformer technology into a new voltage range. We expect that the technology will be further improved in the coming years and dimensions and weight of these dry transformers further reduce.

Meanwhile, a number of 72.5 kV HiDry transformers are in operation in different applications. They are performing according to expectations without any problems.

REFERENCES

[1] M. Berrogain, M. Carlen: “Dry-type transformers for subtransmission”, paper and presentation 1140, CIRED, Stockholm, June 2013

[2] M. Carlen, M. Berrogain, “Dry-type subtransmission transformer installations and potential grid interactions”, CIGRE SC A2 & C4 Joint Colloquium 2013, Zürich, Sep. 2013

[3] M. Carlen, M. Berrogain, R. Cameroni, M. Spiranelli, “Dry-type subtransmission transformer: compact and safe indoor substations”, CIGRE A2-304, Paris, 2014

[4] M. Carlen, R. Murillo, M. Berrogain, J. Tepper, "Transformer Innovation: Dry-type Transformers for the 72.5 kV Voltage Class - Safe and Ecological", ARWtr 2010, Santiago de Compostela, Spain, Oct. 2010

[5] R. Murillo, J. Tepper, C. Roy, J. Smajic, A. Nogués, "Dry-type transformers for the sub-transmission voltage level", CIGRE SC A2 & D1 Joint Colloquium, Kyoto, Japan, 2011

[6] R. Murillo, J. Smajic, J. Tepper, A. Nogués, T. Steinmetz, "Electromagnetic simulations supporting the development of dry-type transformers for subtransmission voltage levels ", CIGRE A2-208, Paris, 2012

[7] A. Pedersen, T. Christen, A. Blaszczyk, H. Boehme, Streamer inception and propagation models for designing air insulated power devices, Proceedings IEEE Conf. on Electrical Insulation and Dielectric Phenomena, Virginia Beach, USA, 19 – 21 Oct 2009

[8] J. Smajic, Th. Steinmetz, M. Rueegg, Z. Tanasic, R. Obrist, J. Tepper, B. Weber, M. Carlen, "Simulation and Measurement of Lightning-Impulse Voltage Distribution Over Transformer Windings", IEEE Transactions on Magnetics, vol. 50, no, 2, 2014