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A2 POWER TRANSFORMERS AND REACTORS

PS2 – Beyond the Mineral Oil-Immersed Transformer and Reactors

420 kV Shunt Reactors for Reactive Power Compensation Explaining the Trends Favoring Air-Core Dry-Type Technology

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SUMMARY

The extended range of applications for air-core dry-type reactors over the last few decades may be attributed to such factors as the economic advantages of air-core reactor technology when compared to that of iron-core oil-insulated reactors, the benefits of the linear characteristics of air-core dry-type reactors as opposed to iron-core reactors, and the development of new high-performance insulation materials and advanced manufacturing technologies which enable the use of air-core dry-type reactors for not only higher power levels, but also much higher voltage levels.

As a consequence, air-core dry-type shunt reactors can now be directly connected to transmission lines rated at system voltages of over 500 kV. The high continuous voltage across the reactor winding is handled by employing a cascaded concept consisting of series connected winding modules. The number of modules is essentially determined by the transmission system voltage level.

The paper addresses important aspects of the air-core dry-type reactor design including special considerations of the high voltage application. These aspects include the demand for high-performance insulation materials and advanced manufacturing technologies, transient voltage issues, the need for protective coatings or covers, loss evaluation and audible sound requirements. High-voltage reactor testing will be addressed as well. Furthermore, the paper highlights comparisons between liquid-type and dry-type reactor technology. This includes such topics as economic and environmental considerations, the physical dimensions and footprint for the station layout and the philosophy behind reactor spares philosophy and resulting savings.

Finally, the paper presents an example of a project with 420 kV air-core dry-type shunt reactors installed on the transmission network of a well-known German transmission system operator.

KEYWORDS

Circular Economy – High Voltage Air-core Dry-type Reactor – Installation – Losses – Sound – Transient Voltage

1) Introduction

Reactive power compensation, especially in high voltage transmission systems is one of the major reactor applications. These reactors are connected to the power system in a "shunt"- configuration to compensate for capacitive reactive power of the transmission systems, which may be particularly critical during light load conditions and for maintaining system stability. The grid integration of renewable energy sources, such as wind and solar parks, is one of the driving factors for increasing demand for shunt compensation.

Air-core dry-type reactor technology has been employed for over 100 years. With continuous improvements in insulation materials, in particular turn-to-turn insulation films, the synthetic resins used for the winding impregnation, the surface coating materials as well as the winding production technology the application of air-core dry-type reactor technology has been significantly extended.

Shunt reactors can either be connected directly to the high voltage line, or to the tertiary winding of high voltage transformers. In the past, liquid-immersed iron-core technology was employed for shunt reactors directly connected to the high voltage line. Air-core dry-type shunt reactor applications were limited to lower system voltage levels. Consequently, they were mainly applied at distribution class voltages for shunt compensation on the tertiary side of a high voltage transformer.

More recently, resulting from already mentioned industry advances in there has been a significant shift towards favoring the use of air-core dry-type reactor technology in high voltage shunt applications. The above may explain an obvious trend preferring the use of air-core dry-type reactor technology for HV Shunt Reactors (HVSR). The paper will present some of the reasons for this trend.

2) Basic Design and Construction of Air-Core HV Shunt Reactors

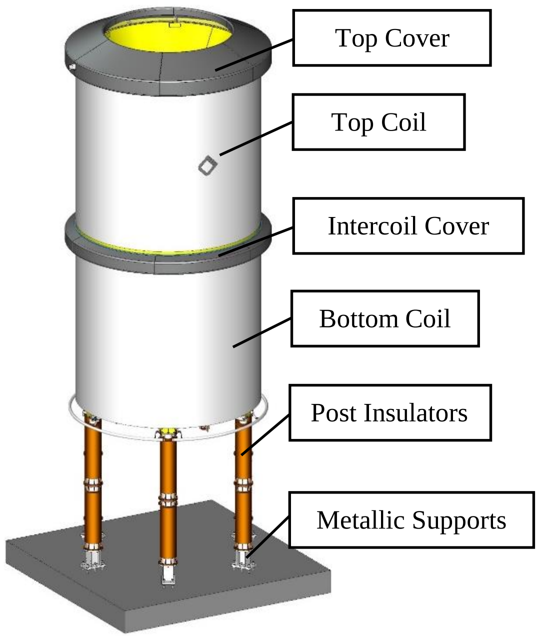

Figure 1: HVSR phase made of 2 cascaded coil units

The external insulation of an air-core reactor is essentially determined by the necessary air clearances as well as by the type of post insulators. As post insulators are available for the highest system voltages, there are no limitations to provide sufficient external insulation.

In the case of HVSR, one of the critical design parameters is the voltage across the coil winding, in particular the specific voltage along the winding surface. The system voltage and creepage distance requirements determine the total length of the reactor winding. In order to keep the physical coil dimensions within limits, given by the aspect of reasonable transportation and handling, the total reactance per phase may be split up in two or more coil units. These coil units will then be series connected and arranged in cascaded configuration.

Figure 1 exemplifies two stacked coils. Depending on the system voltage more of these double coils can be connected in series (see Chapter 5).

Air-core reactor coil units consist of either one single layer or several concentrically arranged electrically parallel-connected layers. For economic reasons, air-core dry-type reactors are generally made of aluminum conductor material, which is insulated with high performance film insulation and woven tapes made of glass and polyester fibers.

The winding layers are radially spaced from each other by fiberglass sticks, which also create the vertical ducts for natural convective air-cooling of the winding. Furthermore, these fiberglass reinforced duct sticks clamp the winding between the metallic structures attached to the ends of the winding, the winding spider arms or the winding end beams.

Windings comprised of only one layer do not have any duct sticks and are, therefore, clamped together by means of impregnated glass fiber ties attached along the outer winding surface. Fiberglass end spacers are affixed between the winding spiders and the active part of the winding.

Impregnating the winding with a thermo-set heat curing epoxy resin gives the coil its high mechanical strength and superior electrical properties as well as a high resistance against weathering.

Finally, all surface areas of the winding that are directly exposed to the outer environment (sun, rain, pollution, etc.), are coated with a UV-protective paint then a protective room-temperature vulcanizing (RTV-) silicone coating is applied. The coating of RTV adds hydrophobic properties to the exposed surfaces, prevents water filming and reduces the risk of surface tracking.

The reactors may also be equipped with top and intercoil covers. Especially the top-covers may further provide the function of corona protection. For windings comprising of more than one layer, the covers provide an additional functionality, namely to protect the winding surface inside the vertical cooling ducts from the direct impact of rain and thus from water filming. Depending on the type and level of pollution as well as the specific voltage along the winding surface, water filming may be a contributory factor for electrical tracking and treeing deterioration.

As mentioned earlier, the insulation to ground is merely provided by support insulators. Air-core dry-type HVSRs are typically mounted on a structure consisting of a number of aluminum or non-magnetic steel supports and post insulators. The metallic supports are suitable for direct mounting on the concrete foundation.

Almost all air-core HVSRs for power systems are made of aluminum and are provided with aluminum terminal pads. Commonly vertically oriented flat aluminum terminal pads are used. If reactor terminals made of aluminum are directly connected to aluminum connectors, there is commonly no need for special metallic coating of the reactor terminals.

3) Comparison between Oil- and Dry-Type Reactor Technology

European Green Deal – Circular Economy

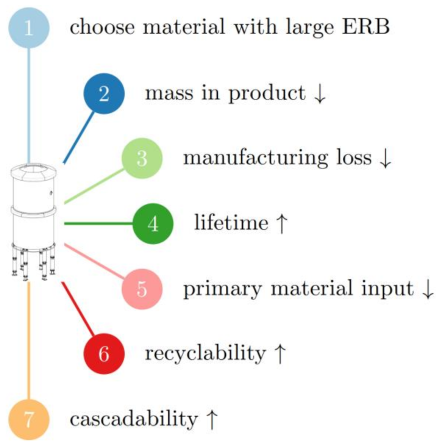

Figure 2: Design guideline to reduce the Ecological Resource Budget (ERB), based on [2]

In the European Green Deal, the circular economy is seen as a blueprint towards changing to a sustainable economic system. The aim is to create a closed material cycle based on the nature's example. The circular economy and sustainable economy are not the same. The circular economy focuses more on goals and the ability to tackle environmental challenges through the use of the economic system [1]. A sustainable circular economy therefore builds on the sustainable resource base and aims to make the best possible use of the limited resources. This should allow for unrestrained economic growth [2].

In order to enable a sustainable circular economy for the respective product, the entire production process of all materials used must be considered and analyzed. Furthermore, several fundamental principles must be adhered to. Longevity is the key principle towards maintaining the material's value and optimizing the output per input unit for all resources (i.e. efficiency), thus making the best use of the sustainable resource base (see Figure 2).

Strategies for a circular economy are runtime extensions, function combinations, upgrading old products to new technological standards, repairs, reuse functions, reuse of parts, recycling of materials, redundancy optimization, etc. In [1], these points are also called ReSOLVE (Regenerate, Share, Optimize, Loop, Virtualize and Exchange). The optimal solution in each case must always be selected by requiring the least consumption of resources and minimizing the environmental impact. This will lead to a sustainable circular economy. Air-core dry-type HVSRs set a new technological standard exhibiting several advantages over conventional shunt reactors with respect to a circular economy, for instance due to the lower degree of complexity of the product.

Material Use

Air-core dry-type reactors are composed of aluminum, insulation tapes, resin, glass fiber reinforced duct sticks and accessories, varnish, RTV silicone, stainless steel fittings and porcelain insulators for insulation to ground. Whereas iron-core oil-filled reactors – also called liquid-immersed or liquid type in this paper –consist of copper windings, insulation tapes, core material (special steel), a steel tank, bushings, insulation oil, glass fiber reinforced clamping equipment, oil expansion tanks, radiators, valves, relays, gauges, etc. [3]. The design and construction of a liquid-immersed shunt reactor is a more complex piece of equipment than an equivalent air-core dry-type reactor. Most of the materials used in both types can be recycled in a certain way. For air-core dry-type reactors up to 90 % of the used mass can be recycled.

Technology Comparison

Technology comparison is challenging as high-voltage air-core dry-type reactors are a rather new development and reliable data for liquid-immersed shunt reactors is not published to a large extent.

A comparison of 220 kV liquid-immersed shunt reactors with 220 kV air-core dry-type shunt reactors [4] concludes that air-core dry-type HVSR are cheaper, comparable in losses but the space requirement is slightly bigger. This broad statement, however, is project dependent and even for 220 kV air-core dry-type shunt reactors the design can be optimized to fit onto smaller areas. A 420 kV conventional shunt reactor bay [5] has a dimension of ~25 m times ~22.5 m, resulting in a ~563 m² land requirement. 420 kV air-core dry-type shunt reactors can be placed within a fenced area with 24.6 m times 23.8 m which is a yard area requirement of 585 m². The distance to the reactor coil due to magnetic field issues, referred as RMC2, is already considered with this arrangement

To design the foundation for an air-core dry-type HVSR, the civil engineer will require the anchor bolt configuration and type, an overall outline with shunt reactor dimensions and the center of gravity. The foundation must be designed for wind, ice, and seismic loading along with the specific soil conditions. Short circuit forces normally play an insignificant role for the design of the foundation for air-core dry-type HVSRs. As a rule-of-thumb, to ensure that no vibration occurs, the concrete foundation should be built with at least two to three times the mass of the shunt reactor including the support structure. If the site soil conditions allow, a reduced mass of reinforced concrete can be used [6]. For 420 kV air-core dry-type shunt reactors, the foundation for six coil-stacks per system requires approximately 135 m³ of concrete and reinforcement steel. For a conventional shunt reactor, the above rule-of-thumb for the weight still applies, and is valid for any piece of large equipment. However, the overall consumption of concrete and reinforcement steel for a conventional shunt reactor is higher. Additionally to the concrete used to form a support base for the reactor, walls for oil containment and a rail system or similar, at least one fire wall and the cable routing must also be created.

In [7] it is stated that the primary advantages of dry-type air-core reactors, when compared to liquid-immersed types, are lower initial capital costs and operating expenses, and the absence of insulating oil and associated maintenance. There is no magnetizing inrush current when an air-core reactor is energized which is also a benefit in terms of CT saturation and protection. An insignificant drawback of dry-type reactors might be the external magnetic field, which however can be considered in the station layout during design stage.

Iron-core liquid-type shunt reactors have a less complex winding design than transformers [3]. The dielectric strength of the insulation system must be able to withstand transient voltages between the coils and to the earthed tank. The winding design for air-core dry-type reactors is again less complex than that of iron-core liquid-type shunt reactors. Insulators provide the insulation to earth (see Figure 1) and the turn-to-turn insulation is designed to withstand predictable stresses (see chapter 6). There is no complex distribution of different capacitances to the tank, to the core, to neighboring phases, etc. for air-core dry-type reactors. This distribution of capacitances together with the inductance of the HVSR causes the impulse response for a transient surge. A complex transient voltage distribution may lead to difficulties in terms of insulation design.

Sound values given in the following Table 1 are based on the sound level achieved for the air-core dry-type HVSR project presented in Figure 6. The sound values for liquid-immersed type is based on the specified level for this project.

Table 1 : Comparison of air-core dry-type HVSR with iron-core liquid-type HVSR

	Air-core Dry-type HVSR	**Iron-core Liquid-type HVSR *)**
Floor requirement in m²	585	~ 563
Weight in p.u.**)	1.00	< 0.93
Losses in p.u.**)	1.00	< 1.33
Height in m	~ 11,6	~ 10.5
Concrete & reinforcement in p.u.	1.00	> 1.00
Sound in p.u. based on dB(A)	< 0.95	1.00

*) data based on [5] and [3]; **) Weight and losses are inversely proportional - equivalent design can be possible

It is possible to design the upper and lower coil of the stack in Figure 1 such that they are identical which can potentially lower costs when considering spare parts. It might be possible to use just one coil as a spare part, instead of a complete stack, which would only add a cost of approximately 1/12 of the overall investment cost for the equipment. However, it is recommended to use one stack as a spare part, which increases the overall investment cost by ~16 %. This amounts to an immense investment cost saving potential when compared to an iron-core liquid-type shunt reactor where one full unit must be ordered as spare.

Other factors favoring air-core dry-type reactors are shorter lead times, no fire hazard risk due to oil leaks or spills, and, in some cases, lower transportation costs. In the event of repair or replacement, relatively quick air-core dry-type reactor spare deliveries and easier installation would result in a very short mean repair time.

4) HVSR Testing

Testing of a HVSR is done according to [8]. There are some demanding tests as explained below.

Measurement of Losses

According to [7] fundamental losses in a shunt reactor with an iron core are composed of 60-70 % resistance losses in the winding, 20-30 % core steel losses and 5-15 % eddy current losses in the winding and from mechanical parts. For air-core dry-type HVSRs the total losses are composed of 70-80 % resistance (ohmic) losses and 20-30 % additional losses in the winding and mechanical parts. The ohmic loss portion is taken to be equal to I_r^2 times R, R being the measured DC resistance, I_r being the rated continuous current. The additional loss portion is the difference between the total loss and the ohmic loss. The total loss in W for an iron-core liquid-type SR is generally in the range of 0.2 % times VAr of the HVSR [3].

The loss measurement of air-core dry-type HVSRs compared to conventional shunt reactors is different. As explained in [9], air-core dry-type reactors cause stray losses, which occur in the metallic structural elements of the test facility. The magnitude of these losses is a function of the proximity, type of material, geometric considerations and rating of the reactor. Therefore, accurate reactor loss measurement is an important subject and is challenging for the manufacturer [3].

The measurement of the losses is carried out according to [8] paragraph 7.8.6.2. For the measurement, the two quantities, voltage u(t) and current i(t), are measured simultaneously, digitized in the measuring device and the corresponding parameters such as phase shift, active power, apparent power, power factor etc. are calculated. Due to the linearity of air-core dry-type reactors, the loss measurement can be performed at any voltage and the losses can be extrapolated to the rated voltage.

The measurement of the total losses of the air-core dry-type reactors is performed with a high precision power analyzer at rated frequency with a low current. The measurement set-up is optimized for the reactor under test (RUT), e.g. systematic measurement errors are actively considered during the measurement. Such systematic errors can be related to the physical size of the RUT (see Figure 5) or due to the magnetic field of the RUT. Current and potential leads are used to reduce contact resistance. In order to avoid interference with the 50 Hz fundamental frequency, the measurement is carried out at 49 Hz and 51 Hz and an average value is calculated from the recorded values. The applied frequency, voltage, current, losses are measured at ambient temperature and recorded at the same time.

Normally, contractually specified losses are based on reactor operation with rated continuous voltage at rated frequency and at reference temperature. Measured losses are corrected to rated continuous current and reference temperature (typically 75°C) according to generally accepted formulae stated in [8]. The measurement of losses is a routine test and must be carried out on every unit. As a three-phase arrangement consists of six stacks, this task should be incorporated in the manufacturing process flow. Therefore, it is common practice to perform loss measurements in a metal free environment and derive a correction factor for the test facility loss measurement. This correction factor accounts for the stray losses in the building; it is < 1; and the losses obtained in the normal test facility are multiplied with this factor. The issue of measurement errors is addressed in [3], [6] and [8] and needs to be considered as for any other air-core dry-type reactor application.

Measurement of Axial Resonance

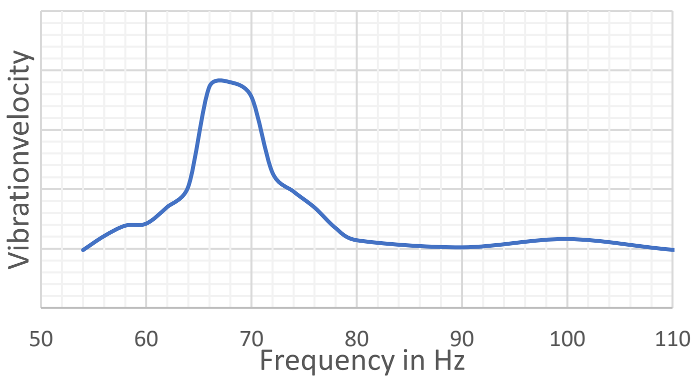

Figure 3: Typical result of axial resonance measurement

A vibration measurement is made on the lower face of each layer of the coil. The velocity is determined with a laser vibrometer by means of optical measurement. The RUT is excited sinusoidally with a regulated voltage source. A constant test current is injected at each frequency and the frequency is increased step by step.

The purpose of the test is to demonstrate that the axial resonance of the reactor winding is not coincident with the mechanical frequency of 100 Hz/120 Hz originating from the system frequency of 50 Hz/60 Hz. Figure 3 shows the envelope of all measured axial resonances of two stacked coils forming approximately half of the inductance for one phase of a multilayer HVSR.

Measurement of Acoustic Sound Pressure Level

According to [10] HVSR sound testing requires the full reactor power and voltage to be supplied by the test laboratory. It may not be possible to energize large RUT at rated voltage due to limitations in the testing facility. Therefore, a special test set up may be agreed between the purchaser and the manufacturer at the time of order. It is either possible to perform the test on site, which bears the risk that the delivered equipment may exceed specified sound levels or, in case of air-core dry-type reactors, consisting of several in series connected coils, to test individual units/stacks and subsequently calculate the total sound levels. The relevant standard [10] does not include this specific approach in detail. However, based on the explanations in this standard, a worst-case calculation can be derived. It is common knowledge that two identical reactor coils in a stacked configuration result in +3 dB total sound power compared to the single coil. For a phase arrangement consisting of two identical stacks connected in series, again, +3 dB will lead to the total sound of a HVSR phase. The complete 3 phase arrangement will then have the phase units sound level plus 4.77 dB ($10 \cdot \log_{10}(3)$). Adding 10.77 dB to a single coil sound level leads to the total sound power of a three-phase set.

The measurement of acoustic sound level is performed according to [8] Clause 7.8.12. A series resonant circuit provides the necessary high voltage for the tested shunt reactor units. With the help of the compensation capacitors, the resonance frequency can be adjusted to create the required voltage drop at the reactor. The sound measurement is then made with a precision type 1 sound level meter. The sound pressure is measured at a distance of two meters from the coil surface from several equidistant positions arranged on the coil circumference. The measuring instrument is calibrated before and after the measurement. The sound pressure level is then converted to a sound power level according to formula 22 in [10]. The measurement of the acoustic sound pressure level is performed in the high voltage test area as a routine test. The test environment in this laboratory is not ideal for acoustic measurements due to the fact that it is equipped with transformers, capacitors, reflecting walls, etc. It may be agreed with the purchaser to measure the sound pressure of several stacks in an optimal outdoor environment, an acoustic free field over a reflecting plane, and in the indoor test lab in order to obtain a correction factor K. The measured sound values may also be corrected according to [11] if the meteorological conditions do not meet reference conditions in the outdoor test field. This factor K, estimated as a mean value of all outdoor measurements, is then subtracted from the values obtained in the factory environment.

5) HVSR Installation

Single-Phase Arrangement

Reactor units can be stacked above each other. This is common practice and also technically beneficial by making use of the high mutual coupling between the units. Nevertheless, stacking of more than two large units is usually not reasonable from a mechanical aspect. Therefore, the logical arrangement of four reactor units per phase is to have reactor stacks composed of two units and placing two of those stacks side-by-side. For the arrangement of the electrical connections, there are different possibilities differing in several aspects like stress on the insulators, efforts for bus work, coupling and the external magnetic field. Three possible solutions are sketched in Figure 4.

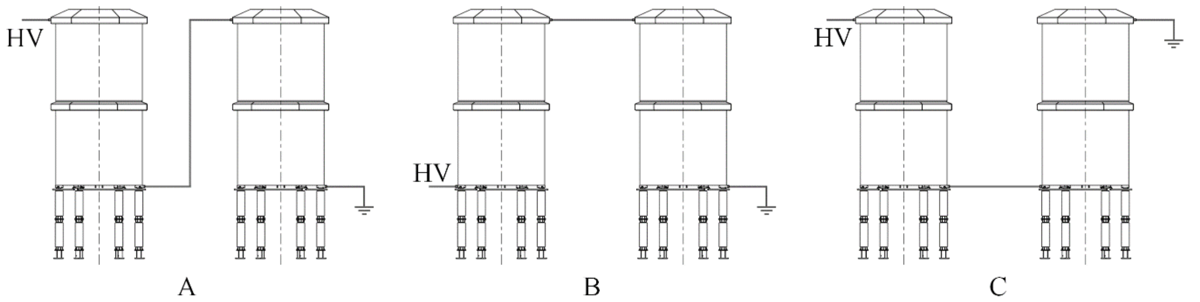

Figure 4: Exemplary schemes for electrical connection of two reactor stacks

Arrangement A has the high-voltage connection of both stacks on the top terminal. This layout has a minimized voltage stress for the insulators since the bottom terminal of the ground-side stack is at ground potential and also the insulators of the line-side stack are not exposed to the full system voltage. But the electrical connection between the stacks has to pass from the bottom to the top resulting in additional support structures and space demands to keep the electrical clearances. In addition, the magnetic field of both stacks is oriented in the same direction leading to a negative mutual coupling and a higher external magnetic field. This could be compensated by an opposite winding direction of the stacks with the drawback of higher production costs and loss of interchangeability.

In scheme B the high-voltage connection of the line-side stack is changed to the bottom terminal. This allows for a straight and short connection between the stacks from top to top. Savings regarding space demand and bus work supports can be achieved. Also, with a concordant winding direction of the reactor units this arrangement benefits from positive mutual coupling of the stacks, reduced external magnetic field due to cancellation effects and interchangeability of the windings (if considered in the dielectric design). However, here the insulators of the line-side stack are exposed to the full system voltage level.

By switching all connections from top to bottom and vice versa as shown in scheme C all the advantages regarding the winding (coupling, field-cancellations, interchangeability) are kept. In addition, there is a reduced stress on the insulators of the line-side stack but the same demands are also valid for the ground-side stack insulators leading to a slightly higher cost for them. One benefit is the insulators of the stacks are interchangeable possibly resulting in savings on spare parts. The small drawback of this arrangement is that the neutral-point bus work is placed at the top terminal resulting in higher costs for the neutral-point installation.

Three-Phase Arrangement

For the geometrical arrangement of the three phases, it has been shown that a shift of the middle phase as sketched in Figure 5 can have some advantages. In order to keep the minimum center-to-center distance between the stacks an arrangement according to Figure 5 B can lead to a reduced width that better fits the system bus works. Also, due to the unequal mutual coupling between the stacks of different phases there is always a minor unbalance in side-by-side reactor arrangements. In this regard, the shifted scheme also has a slight advantage because of better cancellation effects.

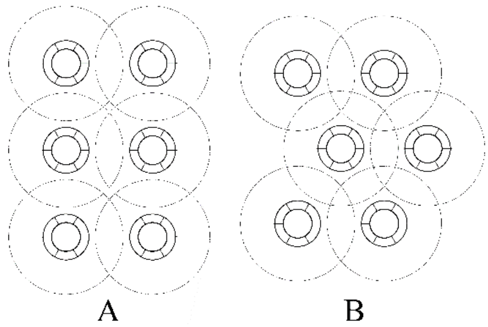

Figure 5: Exemplary 3-phase schemes

Grounding / Earthing / Electrical Connections

Figure 6: Example of HVSR installation in the 420-kV-system (courtesy of TENNET)

As for every installation with air-core dry-type reactors, the layout of the grounding grid must meet certain special considerations. As an alternating magnetic field passes through an electrically closed loop it induces a voltage and hence drives a current. Thus, it is generally recommended to avoid loops as much as possible [12]. Nevertheless, arrangements according to Figure 4 B and C feature a reduced external magnetic field lowering the risk for unwanted currents in the grid. Since loops cannot be avoided completely in a grounding grid, it is beneficial to place a big loop in a uniform distance around a 3-phase set of reactors. Equipment within this loop should have their grounding connections via single lines. Due to the 120° phase shift of the currents, and thus the magnetic fields, the induced voltages cancel each other to some extent.

The fact that two stacks preferably with positive mutual coupling are connected per phase results in a special earthing connection requirement. During maintenance it is not sufficient to only make ground connections on both sides of the reactor arrangement. Rather, it is necessary to also earth the connection point between the stacks since an external magnetic field (e.g. from nearby reactors, overhead lines, etc.) could otherwise raise the potential by induced voltages in the windings.

For the design of connectors and the electrical connections their high-voltage suitability as well as general rules presented in [13] should be taken into consideration. In general, it can be said that due to the moderate magnetic field of HVSRs, issues like induced voltages, forces on current-carrying parts and heating of accessories and connectors are less critical than for other reactor applications (e.g. HV current limiting reactors and TCRs).

6) Transient Voltage Issues of HVSR

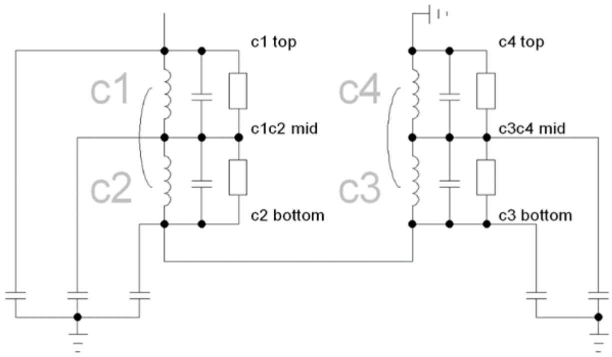

Figure 7: HVSR simplified electrical network

Table 2: Measured maximum voltages

Single coil	Umax of BIL in %
c1	72
c2	43
c3	33
c4	41
Coil-stack	Umax of BIL in %
c1c2	92
c3c4	62

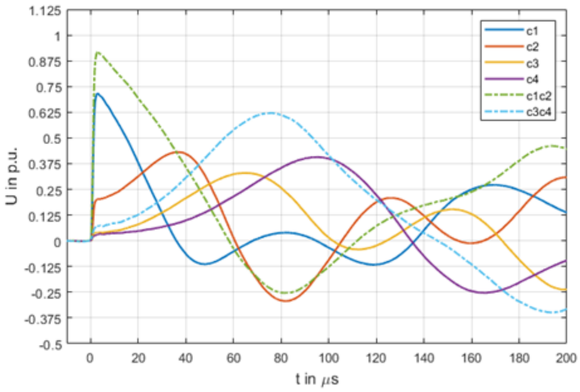

Figure 8: Measured voltage drop across coils and coil-stacks (normalized)

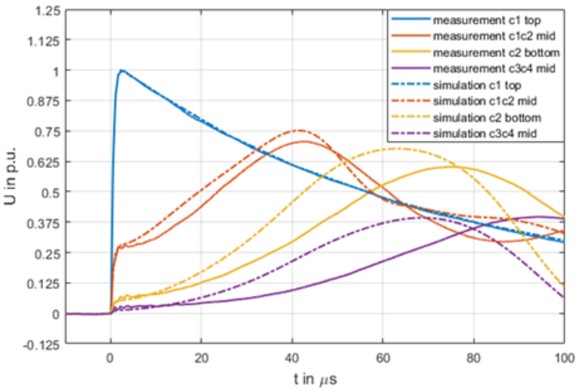

Figure 9: Comparison of measurement and simulation of the HVSR

The transient voltage distribution along shunt reactors connected in series is non-linear and is affected by the capacitances between the windings and the winding to ground. Figure 7 shows a simplified electrical network of one phase of the 420 kV HVSR corresponding to scheme C of Figure 4. In this example, the total peak transient overvoltage across the top coil of the phase-side stack (c1) is about 72 % of the total 1.2/50 µs surge voltage applied to the HV-terminal. This is about three times the voltage at linear distribution.

The determination of the transient voltage stresses can be done via measurement or simulation. For the measurement, a transient repetitive voltage is applied to the HV-Terminal of the shunt. The voltages of each reactor connection joint to earth and the voltage difference of each reactor is recorded with an oscilloscope. In the following figures the waveforms are scaled to the maximum peak voltage applied to the HV-Terminal of the shunt reactor.

Figure 8 shows the voltage of each single coil and of each reactor stack as determined by the voltage difference of the reactor connection joints. In Table 2 the maximum voltages of a single coil and of a complete coil-stack are listed. The transient voltages can also be determined with a simulation model, where every layer of the air-core reactor is separated into several subparts. The inductive, capacitive and resistive parameters for this model are calculated in a FEM-program or analytically. Then, they are used in a circuit simulation program where every subpart of the reactor is linked to each other. The model considers the inductive coupling of all winding parts, the capacitive coupling of each winding part within the reactor and the capacitive coupling of each winding part to earth. The transient behavior depends on the exact design, the manufacturing process of the air-core HVSR and can vary to the simulation model. The influence of the winding structure (dielectric material, dimensions between windings, manufacturing process, etc.) on the transient voltage loads can be considered with a parameter study. Figure 9 shows a comparison of the measurement and simulation of each reactor voltage joint to earth.

7) Conclusion

Air-core dry-type reactors are a well-known and proven technology. For HVSRs, this technology is built upon by series cascading several single coil units forming the necessary inductance while respecting electrical limits. As shown in this paper, air-core dry-type HVSR technology is economically preferred, even more so once spare parts are required to meet specific reliability and availability indices. Air-core dry-type HVSRs are environmentally friendly; they can be largely recycled; the necessary area requirement is in the same range as for conventional HVSRs; and HVSRs can be designed to meet low loss and low sound requirements. Another compelling reason for the trend towards using this technology is a shorter lead time, which is a result of product standardization as a phase of an air-core dry-type HVSR consist of several identical units.

The HVSRs shown are used to compensate the reactive power of HV cable in a transmission system. It has been demonstrated that the simulated electrical stresses, which have been the basis for the insulation design, can be confirmed with measurements. Thus, the electrical design of the HVSR is based on solid simulation and measurement results.

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