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Evaluation and Implementation of HV Dry-Type Shunt Reactors into a 420kV Transmission Grid

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SUMMARY

The paper presents different steps and considerations to qualify dry-type air-core reactors for the use in the German 420kV transmission grid of TenneT. Due to the high amount of renewable energy introduced into the German grid, the transmission grid, especially from north (renewable generation) to south (load centers), needs investments into new lines. Some of these lines are involving one or more cable sections. The charging power of these cable sections needs reactive shunt compensation which will be supplied by fixed reactors. For some of these cable sections it turned out to be beneficial to use air-core dry-type shunt reactors.

When implementing a new solution into the transmission grid, such as dry-type HV shunt reactors, it’s not only necessary to compare the different solutions such as oil immersed shunt reactors and dry-type shunt reactors directly. It is also necessary to compare the interfaces and necessary prerequisites when installing them. The main interfaces of HV shunt reactor are: necessary civil work, primary connection and breaker, monitoring and control equipment.
Especially the design of the necessary civil construction is significantly influenced by either using an oil-immersed solution or a dry-type solution. The absence of oil, the presence of a magnetic stray field, the lower weight and the fact that air-core dry-type reactors are always arranged as single-phase banks impacts the design of the necessary foundations.
Other aspects like different behaviour during switching and different acoustic behaviour will be addressed accordingly.

Additional topics which are important from an asset management point of view are, necessary spare units, transportation and necessary time to put the shunt reactor bank back into service in case of an outage. Since dry-type high voltage shunt reactors are always installed as individual single-phase assemblies, only a single-phase reactor as spare unit is required to have the full availability.

KEYWORDS

shunt reactors, renewable, air-core dry-type, resilience

INTRODUCTION

Generally, the demand for reactive power compensation is increasing due to the following reasons:

- Strongly varying line loading,
- Cable Sections in AC transmission lines,
- AC offshore connections,
- Limitation of reactive power demand/generation,
- Increasing cabling at distribution and sub-transmission level.

Shunt compensation reactors are required globally at a wide range of voltage levels. However, 78% of installed units operate at voltages above 150kV, as shown in Figure 1. Traditionally, shunt reactors utilising oil-paper insulation systems are used at transmission levels, but due to technological developments, material improvements and changing environmental requirements nowadays dry-type air-core shunt reactors are used up to a system voltage of 420kV or even 500kV [1]. For shunt reactors connected to the tertiary winding of power transformers the air-core dry-type remains the preferred solution.

In the present use case, the shunt reactors are installed in "cable transition stations" to compensate the reactive power of HV cables inserted in the overhead line due to environmental reasons when crossing urban areas

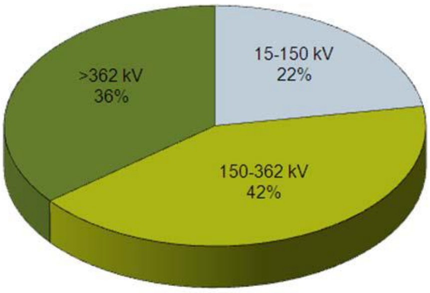


Figure 1 - Split of shunt reactors between different voltage levels [2]

TYPICAL LAYOUT OF A 420kV DRY-TYPE SHUNT REACTOR BANK

Transportation and Installation

Typically, 420kV dry-type shunt reactors are designed as single-phase units. Each of the phases is divided into two reactor towers and each of these towers is again split into two series connected coils. Figure 2 and Figure 3 are showing the basic layout of a 420kV shunt reactor installation consisting of 12 sub coils.

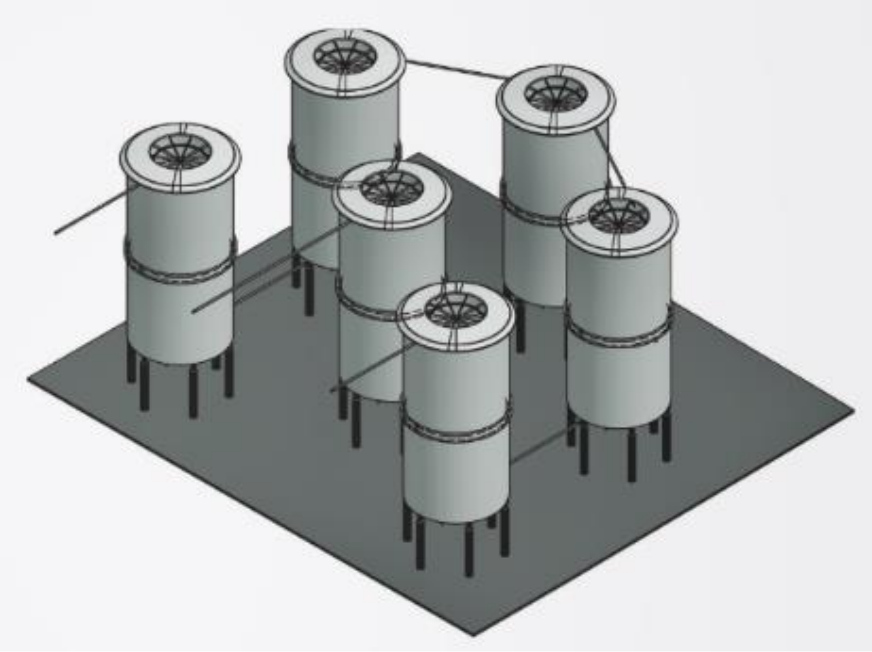


Figure 2 - Typical arrangement of a 420kV dry-type shunt reactor

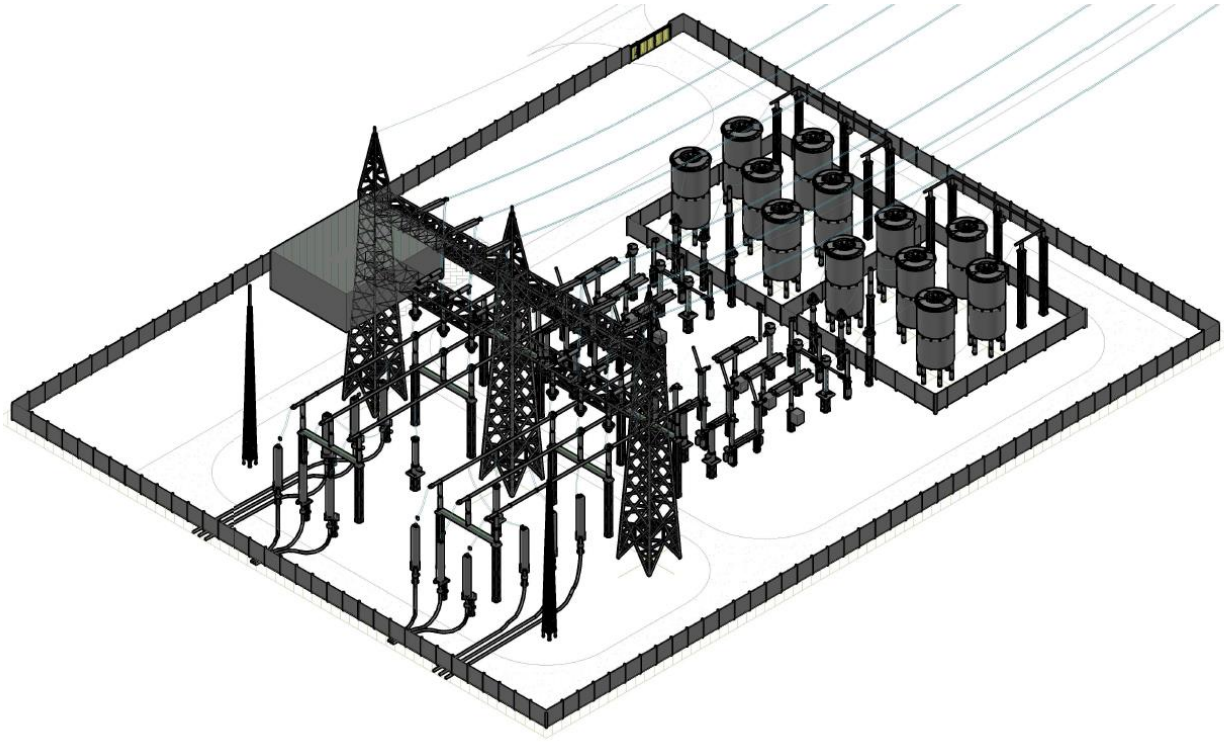


Figure 3 - Layout of a 420kV cable transition station – 2 parallel systems

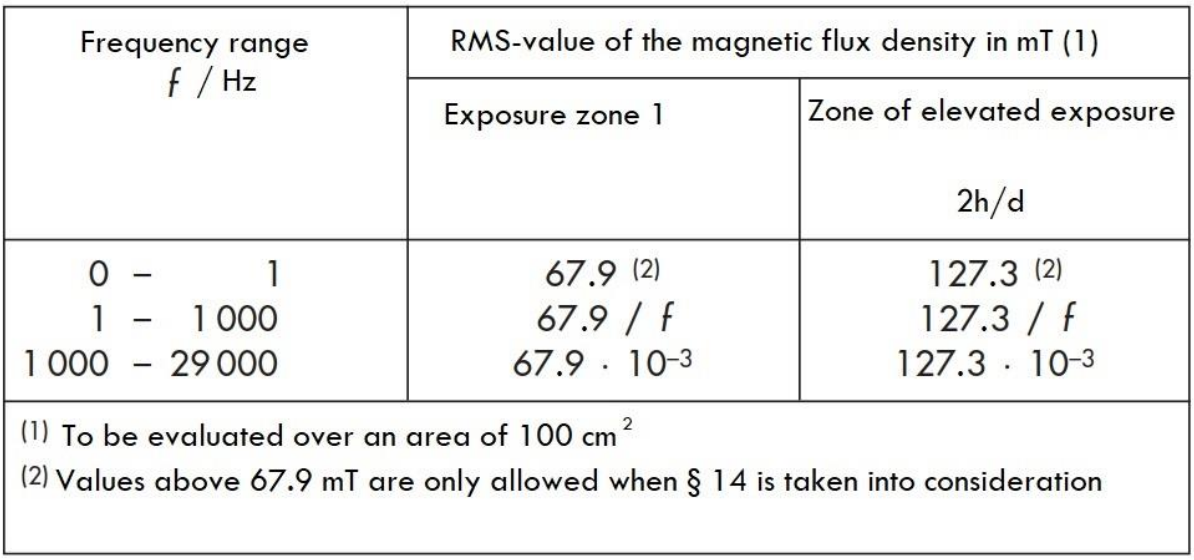
The 12 sub coils are also the handling units for transportation, whereby each item has dimensions of 4,4m x 4,4m x 4,3m (W/L/H) and a weight between 15to and 30to. Especially due to the very low weight, transportation is simplified and allows a transport of the reactors on light roads or even non-permanent roads, which is of special importance for remote installations.

Magnetic Field

The basic information about magnetic field emissions of air-core dry type reactors is already given in [3].

In the present case an extensive magnetic field study has been performed to give guidance about clearances based on the German BGV B11(Table 1, Figure 4) – which deals with occupational health and safety rules for electromagnetic exposure for site personnel [4].

Table 1 - magnetic field limits as rms values



Frequency range f / Hz	RMS-value of the magnetic flux density in mT (1)	
	Exposure zone 1	Zone of elevated exposure 2h/d
0 – 1 1 – 1 000 1 000 – 29 000	67.9 (2) $67.9 / f$ $67.9 \cdot 10^{-3}$	127.3 (2) $127.3 / f$ $127.3 \cdot 10^{-3}$

(1) To be evaluated over an area of 100 cm^2

(2) Values above 67.9 mT are only allowed when § 14 is taken into consideration

The TSO requires a fenced area for spaces with a magnetic field density $> 67{,}9\text{mT}_{rms}/f$ which for 50Hz evaluates to $1{,}358\text{mT}_{rms}$. For general public the perimeter fence shall be placed at a distance with a magnetic field of less than $100\mu\text{T}_{rms}$. Details how the fenced area was implemented is shown in Figure 3. The inner fence (occupational safety distance) was finally realized utilizing electrically non-conducting material to avoid any interaction with the magnetic field of the shunt reactor.

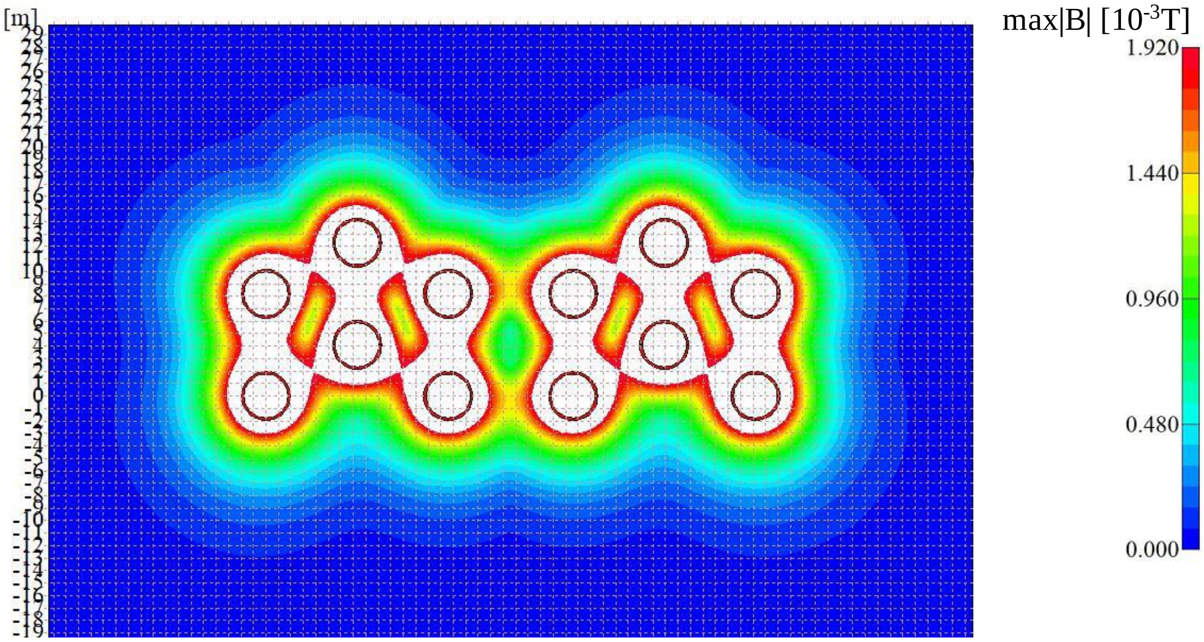


Figure 4 - Magnetic field distribution of 2 parallel shunt reactor banks

Sound Emission

The audible noise of a reactor is caused by the Lorentz forces to the winding conductors, which causes a vibration of the winding surface with the main contribution in the radial direction. The Lorentz force acting on the reactor windings is the vector cross product of the reactor magnetic field density and the current flowing in the windings. The magnetic field of a reactor is linearly proportional to the current in the windings and therefore the force is linearly proportional to the square of the current.

$$\vec{F} = I \cdot \vec{I} \times \vec{B} \quad \rightarrow \quad F \sim I^2 \tag{1}$$

In the above equation (1), “F” is the Lorentz force, “I” is the current in the windings and “B” is the magnetic field density.

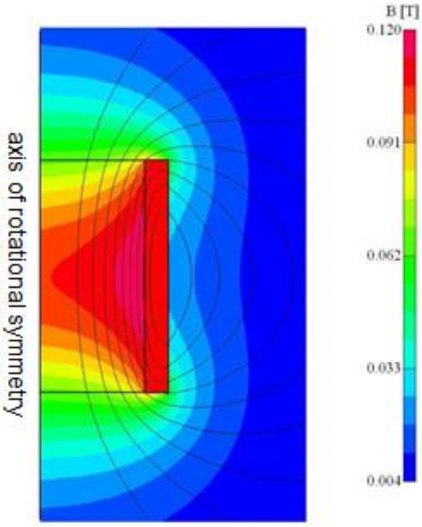


Figure 5 - Magnetic field density [5]

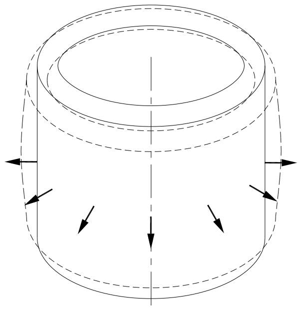


Figure 6 - Schematic of resulting forces on reactor winding [5]

The sound power of a typical 420kV 120MVA shunt reactor is in the range of $L_{w(A)}$=90dB(A), which results in a sound pressure of Lp(A)=72dB(A) measured at 3m distance. Due to the absence of vans and iron core, air-core dry-type reactors only generate a tone at 100Hz if loaded with just the fundamental frequency of 50 Hz. In case of additional current harmonics, noise at higher frequencies is also generated. It can be observed from Table 2 that the fundamental current together with one harmonic current already generates 4 audible frequencies (Table 2).

Table 2 - The amplitudes of the vibrational forces for two excitation currents [5]

Vibrational Frequency	Vibrational Force Amplitude
$2\omega_1$	$\lvert F_{s1}\rvert = c \cdot I_{1eff}{}^2$
$2\omega_2$	$\lvert F_{s2}\rvert = c \cdot I_{2eff}{}^2$
$\omega_1 - \omega_1$	$\lvert F_{s12}\rvert = c \cdot 2 \cdot I_{1eff} \cdot I_{2eff}$
$\omega_1 + \omega_1$	$\lvert F_{s12}\rvert = c \cdot 2 \cdot I_{1eff} \cdot I_{2eff}$

Therefore, the current spectrum for the sound study must be carefully evaluated. More details about the sound generation of air-core reactors can be found in [5].

Based on the sound power level given by the manufacturer, which is verified as a type test according to IEC60076-10 [6] the TSO performed an extensive sound study to evaluate the sound emission of the cable transition station and the noise pollution to the closest neighbour.

Typically, air-core dry-type reactors have a lower natural sound emission compared to oil immersed units of the same rating. However, if very low sound emission is specified, which requires additional sound enclosures, such measures can only be applied to a limited extend to air-core dry-type shunt reactors at transmission voltage levels.

Electrical connections

A connection arrangement as shown in Figure 7 is recommended. For a small power rating of the reactor, the basics outlined here become less critical, but they still represent good guidance for the connection of air-core reactors.

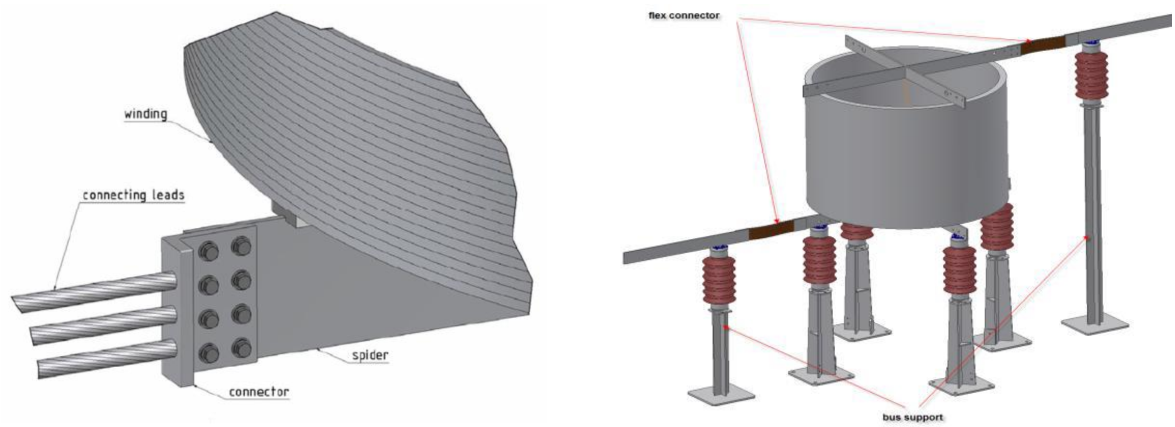


Figure 7 - Connector Design and Connection Arrangement

In general, the following rules when connecting reactors should be followed:

- The connector flag (as well as the terminal) should be arranged vertically.
- The height of the connector flag should preferably be the same as the height of the terminal and all holes of terminal should be used for bolting; use stainless steel bolts with Belleville spring washers on both sides.
- The thickness of the connector flag should not exceed approximately 12mm.
- The material of the connector may be either aluminum alloy or copper (in case of copper to aluminum, a bi-metal plate should be inserted). Nickel plating of the contact surface area may be considered, in order to allow a higher terminal temperature (115°C instead of 90°C).
- The connecting leads in the vicinity of the reactor shall be placed in a radial direction and perpendicular to coil vertical axis, to minimize the heating effect and the magnetic force caused by the magnetic stray-field of the reactor.
- In cases where parallel cables are utilized they should be axially aligned in order to avoid the induction of closed loop currents between the cables by the axial magnetic field of the reactor. Refer to Figure 7.
- Connection leads should be provided with sufficient sag to provide adequate mechanical decoupling of the reactor terminals from connecting bus-work.

DIFFERENCES IN THE OPERATION COMPARED TO OIL IMMERSED UNITS

Maintenance

Generally, air-core dry-type reactors do not need any special maintenance. The units should be visually inspected at least once a year. During such inspection special attention should be given to the pollution of the reactor surfaces, tightness of all bolt connections, paint condition and any other change in the appearance of the reactor surface. In case the reactor surface is coated with hydrophobic material a check of the hydrophobic characteristics shall be made according to IEC TS 62073 [7]. It's also advisable to check the sound of the reactor prior to de-energization. Abnormal noise, that is other than a predominant 100Hz tone, is typically a good indicator of ongoing mechanical changes in the reactor e.g. loose parts.

There are additional aspects to consider when operating two air-core shunt reactor banks close to each other. For example, it's important that the reactor bank under maintenance is grounded at both terminals of each individual stack since the magnetic stray field of the neighboring unit, which is still energized, might induce a significant voltage. It is necessary to initially de-energize both shunt reactor banks to allow a safe grounding of the installation planned for maintenance. After grounding, the second shunt reactor bank can be energized again and the maintenance work can start on the de-energized unit. To estimate the amplitude and probability of induced voltages for a planned layout it is necessary to consult the reactor vendor.

Protection

The shunt reactor fault protection can be achieved through 50 / 51-[1]) overcurrent or 46 negative-sequence relaying schemes. Furthermore, a zero-sequence overcurrent 50N relay scheme by a current transformer connected between the neutral and ground can be provided. This relay system will securely isolate the shunt reactor from the line in case of a flashover in one of the shunt reactor phases along the winding and, for transmission class reactors consisting of two separately mounted sub-reactors, across the intermediate insulators to ground. If desired, protection for low-level turn-to-turn faults can be provided by directional control of the zero-sequence overcurrent 50N relay by a 67N directional zero sequence relay. Both relays are connected to the CT in the neutral to ground connection.

Since all major fault scenarios are longitudinal faults (faults between the terminals without connection to ground or other phases) typically used protection schemes like differential protection are not required. In the given use-case it was finally decided by the TSO to keep the differential protection due to the small remaining risk that big pieces of plastic film from nearby farmland are carried by the wind into the station which finally might create phase to phase or phase to ground faults. Especially if a ground fault is triggered between the two stacked reactors, still half of the impedance is limiting the current and the fault will probably not be picked up by the overcurrent protection.

Monitoring

In contrast to oil immersed reactors air-core dry-type reactors do not have any monitoring devices or other devices which need secondary power such as oil level meter, PT100, Buchholz relay, winding thermal monitoring or cooling fans.

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[1] The code numbers of the relay functions refer to ANSI/IEEE C37.2

In the special case of a cable transition station no or very limited secondary power is available. Therefore, the absence of any device in need of secondary power was one of the decisive factors to use dry-type reactors in such cable transition stations.

Shunt reactor switching, transient recovery voltage (TRV) and its mitigation
Normal circuit-breakers are designed to interrupt large inductive currents during short-circuit faults in the grid. Because of the low energy in the arc when switching small inductive currents, the breakers more easily extinguish the arc and break the current before current zero, which can lead to higher chopping currents. The CIGRE paper A3-101 (2014) [1] describes the details of TRV and the usage of RC damping circuits to limit the TRV on the shunt reactor breaker. Furthermore, it describes the fact that it is not necessary a good choice to use breakers suitable for higher voltage levels to withstand the TRV. The shunt reactor breaker should be chosen based on its chopping current behavior. Another way to limit the TRV and to avoid re-striking is described in paper [8] which presents specially developed breakers with longer arcing times for inductive load switching.

Measures to reduce TRV and rate of rise of recovery voltage (RRRV):

- Use breakers with low chopping currents
- Connect (R)C-damping elements parallel to the shunt
- Use breakers with longer arcing times
- Use point on wave (controlled) switching
- Use of pre-insertion resistors
- Use solid grounding (if possible)

Generally, the oscillation frequency of the TRV and therefore also the RRRV is higher for air-core dry-type reactors compared to oil-immersed iron-cored reactors. This results from the lower stray capacitance of air-core reactors due to the absence of iron-core and tank. The non-linearity factor (equation 2) is a function of series and ground capacitance [9].

$$\alpha = \sqrt{\frac{C_e}{C_s}}$$
$$g = \alpha \cdot \coth \alpha \qquad (2)$$

where:

g	Non-linearity factor of winding
Ce	Capacitance of winding to ground
Cs	Series capacitance of winding

Another important aspect is the voltage distribution between the reactors if two stacked reactors are connected in series. For practical reasons the lightning impulse routine test is usually carried out at one individual reactor stack (half phase). However, to prove that such simplification is still stressing the reactors adequately, the voltage distribution between the stacks needs to be evaluated.

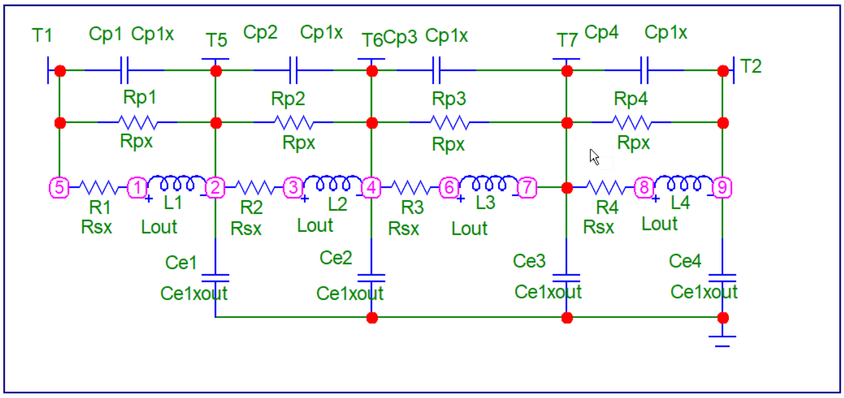

Figure 8 - Basic transient model of one part coil (L1)

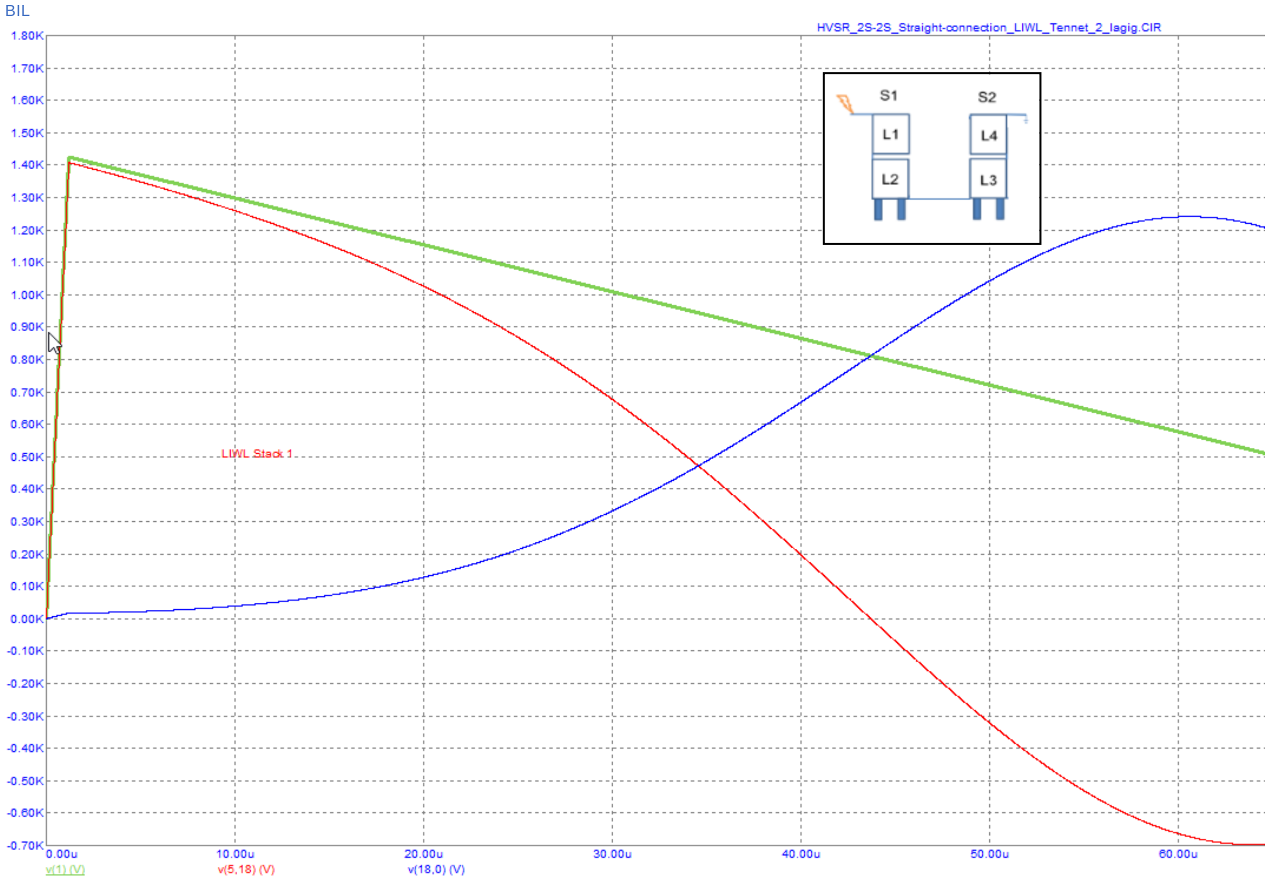

Figure 9 - Transient voltage distribution across the shunt reactor stacks

Detailed simulations (Figure 8) have shown that the initial voltage distribution is such, that the first reactor stack is stresses with almost 100% of the rated impulse voltage level (BIL). The green graph in Figure 9 represents the applied BIL level (L1-L4). The red graph shows the voltage across the first stack (L1-L2) and the blue graph the voltage across the second stack (L3-L4). Based on the simulation results it is recommended to design and to test the individual stacks (half phase) for the full BIL, which is typically 1425kV for a system voltage of 420kV.

Losses

Reactor losses and loss penalisation is becoming a more and more important topic. Nowadays loss penalisation numbers between 5000€/kW and 10000€/kW are common. For air-core dry type reactors the levers for loss optimization are limited. Beside the use of conductor bundles to mitigate the eddy losses, the only lever is the increase of conductor cross-section assuming an already optimized shape factor of the reactor. The increased cross-section of course also results in much lower temperatures of the winding, in some cases this design approach results in hot-spot temperatures below 80°C. Typically, air-core dry-type reactors are designed for temperature class F, which means a maximum allowable hot-spot temperature of 155°C. As a rule of thumb insulation systems utilising thermoplastic and thermoset insulation materials are doubling their lifetime with every 10K the temperature is reduced. Therefore, the loss penalization mentioned above has also a positive impact on the lifetime and the reliability of the shunt reactor.

Another effect of high loss penalization is the increasing quality factor (X/R ratio) of such reactors. They can be as high as 600 or even above. During factory testing even very small deviations in the measurement of the phase shift between measuring voltage and measuring current, which is almost 90° can lead to significant deviations in the measurement result. As air-core dry-type reactors are not confined in a tank also atmospheric influences (receiver effects) or structures of neighboring buildings can adversely impact the measurement since the magnetic stray field of the reactors will penetrate such structures and creates losses which are influencing the measurement. In some cases the loss measurement needs to be performed as a type test at a ”green field” to verify a correction factor for the routine test results in the factory. It is advisable to discuss this topic already at tender stage but latest at time of order to avoid misunderstandings and to align expectation.

SPARE UNITS AND REPLACEMENTS

A 420kV shunt will typically be constructed in two reactor columns of two windings connected in series. To have full availability as soon as possible after a failure event, it’s recommended to attain one complete phase, which means 4 windings or two columns, as a spare. In a typical shunt reactor failure, only a single column is damaged, or a single winding of the column will fail. This means that for two column per phase designs only one column needs to be replaced. If a complete phase (two columns) has been purchased as a spare, one column is still available as a spare after a failure has occurred. Traditional oil filled iron core units are manufactured either as 3 phase unit in a single tank or as three separate single phase units. In the case of 3-phase unit a complete 3-phase shunt reactor must be used as a spare. If the shunt reactor is constructed as three separate single phase units, a complete phase must be replaced in the event of a failure. The major drawbacks in both these cases are a higher overall cost for spares and the unavailability of a spare following a failure until a new reactor can be delivered. The modular construction of dry-type air-core HV shunt reactors overcomes this problem and furthermore opens the opportunity to distribute the spares over more than one substation.

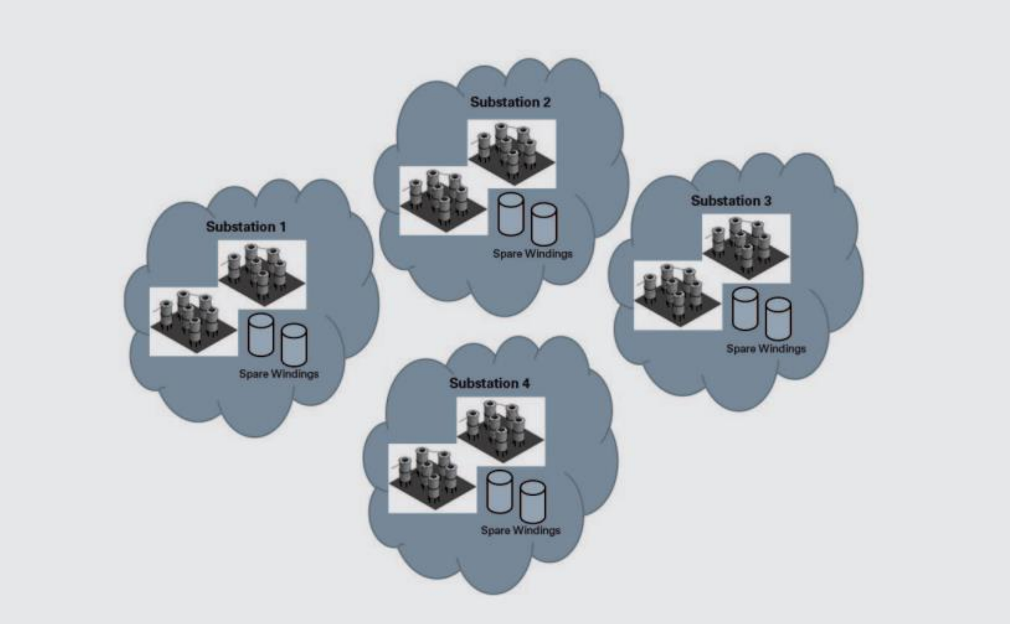

Figure 10 - 4 Substations each having two 420kV shunt reactor banks

Example: 4 Substations each having two 420kV shunt reactor banks

For this example (see also Figure 10, the spare strategy could be as follows: To have two complete phases as spares. This can be translated into a total of 8 windings. The 8 spare windings could be distributed to have two windings per substation. The example outlined will provide the user with much more security, better logistics, faster re-energization time and all of this at significantly reduced spare costs.

LIMITATION WHEN USING TRANSMISSION CLASS AIR-CORE SHUNT REACTORS

There are also limitations when air-core dry-type shunt reactors can be used. The major limitations are:

- Applications where variability of the reactive power is needed
- Existing installations: Typically, there is not enough space in an existing substation with previously installed oil-immersed shunt reactors
- Maritime/ Offshore Environment due to the windings being more exposed to the environment compared to oil-immersed shunt reactors
- Indoor applications due to the required space (physical dimension of the units and electrical and magnetic clearances needed)
- Very low sound reqirements. Since it’s not possible/not economical to build a big housing around a dry-type shunt reactor.
- Voltages above 550kV

CONCLUSION

The conducted studies have shown that air-core dry-type reactors are a viable solution/ alternative for transmission class shunt reactors. There are significant differences to oil-immersed shunt reactors when executing such projects using dry-type air-core reactors. Transport, handling and erection is simplified, the station layout planning needs to take into account the effects of the stray magnetic field. Topics such as maintenance, protection and switching also need a different consideration.

Due to the various simplifications the total costs of the station decrease; this is especially true for greenfield projects. The modular concept in particular has advantages in spare and replacement management and results in reduced outage times. The limitations of air-core dry type shunt applications were also outlined at the end of the paper.

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