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A2
PS1 – Experience and New Requirements for
Transformers for Renewable Generation

Mobile Load Flow Reactor for 220kV

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SUMMARY

Decentralized power generation and local infeed of renewables such as wind power and photovoltaic may negatively influence grid stability and grid resilience against network disturbances. Additional short circuit power may also lead to short circuit currents beyond the rated switching capability of the switchgear or connected equipment. Such situations may require short-term measures to harden the network and to mitigate adverse effects to the overall network performance and outages or failures due to operation beyond the nameplate ratings.

In the current paper, the possible use and benefits of a temporary system hardening by using the load flow control and current limiting features of an air-core dry-type series reactor connected to the 220kV network is discussed. The rating and size of the reactor is selected so that the versatile use at different sites with different boundary conditions is possible. These considerations include the accessibility of the station, available space, possible magnetic field effects to installed equipment, occupational and general public exposure to electromagnetic fields as well as minimum requirements for switching and protection of the temporary equipment. A possible use case at a Transmission System Operator (TSO) for insertion of such reactors at a critical substation at the 220kV voltage level and the derived benefits is presented.

A critical success factor of the application of a mobile solution of HV equipment is an easy and safe relocation from substation A to substation B as well as short dismantling and set-up times at the new site. Usually, this type of equipment is permanently installed in a substation and the design and selection of the components are made accordingly. The requirement for a rapid movement adds a further dimension to the design parameters, which needs to be addressed. Additionally, there will be no foundation platform at site. Thus, the reactor needs to come with and be moved with a suitable foundation slab with provisions for anchoring of the reactor. This reactor-foundation system needs to withstand the acting static and dynamic mechanical forces such as ones caused by wind, short circuit as well as possible seismic events. An elevation structure with a height of 2.3m to allow safe access to the substation when needed is implemented as well.

The study addresses the design and verification procedures, which are applied to meet the mentioned design criteria. Using a typical equipment specification, a possible layout will be presented and verified.

A magnetic field analysis including an application guide with reference to international guidelines such as the ICNIRP guideline dated 2010 is shown. The reasoning behind the selection of the mechanical parameters of the support structure as well as of the insulators is given and verified by modelling of the structure using FEM tools. A brief consideration of the possible mitigation measures regarding transient recovery voltage effects during a switching operation is included. Finally, the mobilization, movement and re-installation concept of the reactors is presented. An optimized design of the reactors and foundations minimizes the effort required for dismantling and assembly. The dimensions and weights of the individual moveable components including the foundation slab are kept under the common transport limits, allowing easy and simple movement within a short period of time. The design of the components shall be as robust as possible to minimize the risk of damage to them during the various steps of relocation.

KEYWORDS

Renewable, mobile, load flow, current limiting, air-core dry-type, resilience

1. INTRODUCTION

Decentralized power generation and local infeed of renewables such as wind power and photovoltaics may negatively influence grid stability and grid resilience against network disturbances. Thus, electrical transmission grids require additional flexibility and adaptability as the generation and demand increasingly vary. Some of the main advantages of more flexible grids are: 1. integration of additional variable renewable energy production is viable, 2. maintenance and construction of the grid is possible with fewer outages.

One of the adverse effects that may arise from changes in load sharing at certain substations between feeders is their overloading. Such situations may within a short period of time require measures that harden the network and that mitigate adverse effects to the overall network performance and prevent outages or failures due to operation beyond the nameplate ratings. Well-known measures to harden the network, such as phase-shifting power transformers, series compensation, or insertion of a static var compensation (SVC) allow a better use of the existing facilities. Their functionality is especially important when it is not feasible to improve the existing infrastructure by adding new lines or transformers or by uprating the existing ones. Through the aforementioned compensation methods, it is possible to redirect the flows to less congested areas, thereby relieving the load on components that cause bottlenecks. The disadvantage is however, that they typically need years of development including systems studies, layout planning, construction, and erection. In some cases, the space and infrastructure requirements prohibit retrofitting such standard solutions.

However, **mobile equipment** that can be transported and installed in a simple way and that allows **limiting overloads** temporarily in selected power lines would be an effective way to increase the flexibility of the electrical transmission grids. In cases where a rather quick improvement is required, the insertion of series reactors for load flow control may be considered. A temporary solution can be used while a long-term solution is being developed or during maintenance and construction works to avoid the overloads of lines and to limit short-circuit currents.

In the current use case, the TSO made evaluations and studies based of which it suggested typical ratings for such a solution be it a long-term approach or a temporary solution. This approach shall be:

- Universal: it can be installed over the power lines that required it.
- Mobile: it is quick and easy to transport, install, and uninstall the equipment.
- Autonomous: auxiliary services, communications, control, etc. are not required.

These are characteristics that a mobile version of a series reactor can provide.

Usually, this type of equipment is nowadays based on the dry-type air-core reactor concept, with the benefits of the fully linear inductance, well defined insulation to ground, low weight and low requirements for civil works and auxiliary protection [1]. Additionally, such a reactor will act as a current limiting device leading to lower short circuit currents at the failure location.
However, there are new challenges regarding the relocation/mobilisation of the equipment including a robust design, easy dismantling and erection and well-known boundary conditions regarding electrical/magnetic clearances, switching interactions and foundation requirements. Furthermore, the standard size limits for road transportation shall be kept avoiding time delays caused by missing road transport permissions.

2. FUNCTIONAL PRINCIPLE

Although the functional principle of a mobile load flow reactor is quite simple, it is explained here. Active power flowing from substation A to substation B through a powerline that is up to 100 km long can be expressed by equation (1):

$$P_1 = \frac{U_A \cdot U_B}{X_L} \cdot sin(\Theta_A - \Theta_B) \qquad (1)$$

where:

P_1 is the active power flow through the power line

U_A is the module of the voltage phasor in substation A

Θ_A is the angle of the voltage phasor in substation B

U_B	is the module of the voltage phasor in substation A
Θ_B	is the angle of the voltage phasor in substation B
X_L	is the reactance equivalent of the power line

Therefore, a quick and simple way to reduce the power flow through this line is the installation of a mobile reactor in series to the power line as represented in Figure 1.

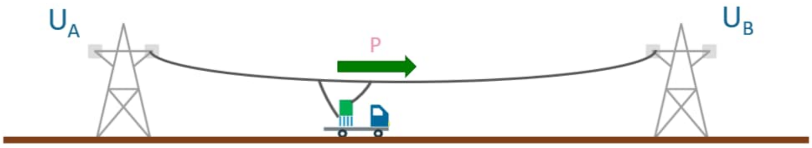


Figure 1 – sketch of the reactor arrangement

Now the power flow through the power line will be:

$$P_2 = \frac{U_A \cdot U_B}{X_L + X_{MSR}} \cdot sin(\Theta_A - \Theta_B) \quad (2)$$

where, X_{MSR} is the reactance of the mobile series reactor.

3. NOMINAL RATINGS AND PROPOSED ARRANGEMENT OF THE MOBILE LOAD FLOW REACTOR

The right selection of design parameter values of a universal mobile series reactor is of critical importance. On one hand, the reactor needs to have a nominal current and reactance that allow it to operate at any part of the transmission grid. Increasing these parameters also increases the size and weight of the reactor. On the other hand, the equipment has to be mobile.

With this premise, an analysis was done on the Spanish transmission grid identifying the powerlines susceptible to overload, and a common reactance value that would solve this problem. The conclusion is, that the oldest 220kV power lines with only one conductor per phase are susceptible to be overloaded and the main parameters of the reactor design are presented in Table 1.

Table 1- reactor ratings

maximum system voltage	245	kV	rated frequency	50	Hz
rated system voltage	220	kV	BIL across reactor/to ground	1050	kV
impedance / phase	10	Ohm	system S/C current	50	kA
tolerance	± 5	%	USCD e-very heavy	53.7	mm/kV
rated current	1100	A	seismic NSCE-02	≤0.16	g
overload current 20 minutes	1265	A	max. ambient temperature	45	°C
			wind speed	140	km/h

A possible layout solution in an existing substation is presented in Figure 2.

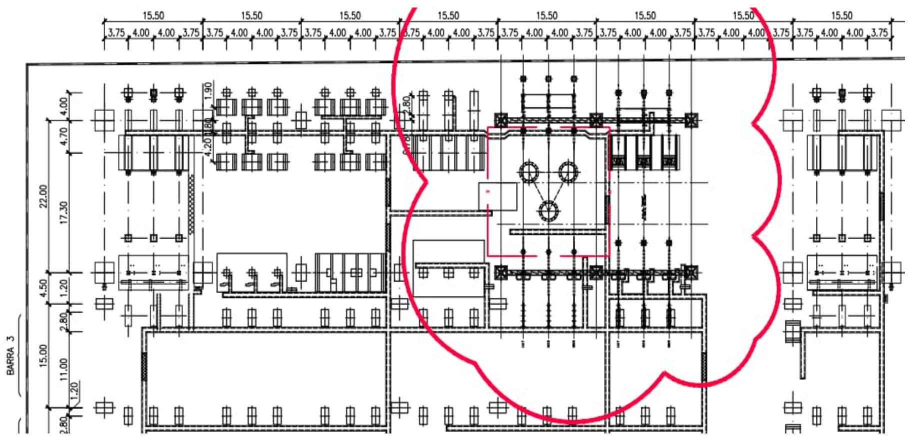


Figure 2- General layout

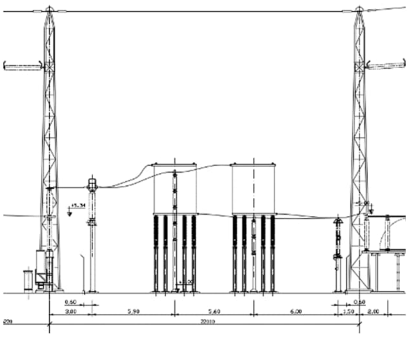


Figure 3 - detail reactor arrangement

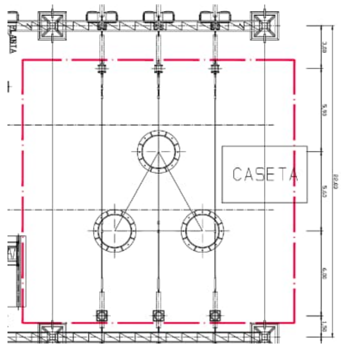


Figure 4 - available space

4. BASIC DESIGN CONCEPT OF THE REACTOR

The above specification leads to an air-core dry-type reactor [1] with the following ratings.

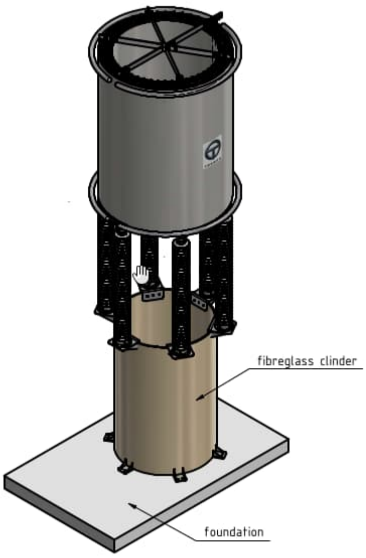


Figure 5 - general layout

- aluminium winding material
- aluminium top and bottom winding structures (spiders)
- multi package coil (5 packages concentrically arranged) with a mass of approx. 4400kg
- coil dimensions: h=3040mm, da=2160mm
- 6 insulators C8-1050, length 2300mm, 184kg each with minimum creepage distance of 7875mm
- Support cylinder made of fiber-glass composite – height 2500mm (accessible substation requirement), diameter 1639mm, mass 625kg
- Base concrete slab, minimum size 3940mm x 2500mm x 250mm (min), mass approx. 6650kg
- Total mass (coil+insulators+support+slab): 12788kg
- S/C current with the series reactor
  rated short circuit current (1 s, rms) Ikd = 11.2kA$_{rms}$ /
  rated peak short circuit current Iks = 28.56kA$_{peak}$

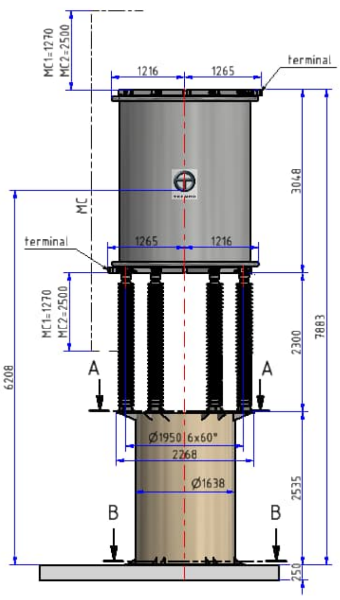


Figure 6 - complete assembly

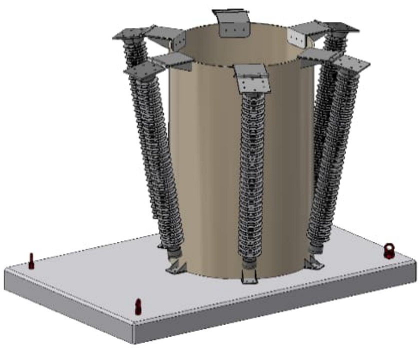


Figure 7 - handling unit support + latched insulators – mass ~ 8400kg

Figure 8- handling unit reactor coil + wooden pallet – mass ~5500kg

The design concept proposes that the reactor assembly will be shipped in 2 parts per phase plus a small box with accessories. One part will be the self-supporting concrete slab with the support cylinder and the insulators already installed. The second part is the reactor coil with a suitable interface to accommodate the top fittings of the insulators. Either standard porcelain insulators or composite insulators can be used. They may come with a tiltable adapter for the insulator base fittings to allow an upside-down transport and to reduce the transport height. The insulators may be secured at the fiber-glass cylinder for a safe movement.

For verification of such a novel design approach with a self-supporting concrete slab, the static stability of the arrangement needs to be verified – forces such as wind, seismic, and short circuit forces need to be applied to the structure and verified regarding the component stresses, but also against tilting and slipping. The pre-condition is a prepared site with a straight, level, and compressed bed of gravel, which can bear the weight and the forces that are applied to it. A moderate friction coefficient of $\mu=0.4$ between the gravel and concrete is assumed. Wind speed and seismic requirements are given in the specification. The short circuit forces are calculated based on the short circuit currents. The short-circuit current of the line after insertion of the reactor can be calculated with Ikd = 11.15kA$_{rms}$ and Iks = 28.56kA$_{peak}$ based on the short circuit current of the system.

5. STATIC AND STABILITY VERIFICATION BASED ON FEM MODELLING

As seen earlier in the design study, the reactors are placed on a prepared bed of gravel using the concrete slab which is used for transport and storage as well. To ensure safe operation all typical mechanical loads on the installed reactors need to be verified to prevent slipping and tilting of the installed units. During such analysis, also the components such as the base cylinder, insulators and interfaces are verified. Typically, such verifications are performed by using FEM [2] modelling.

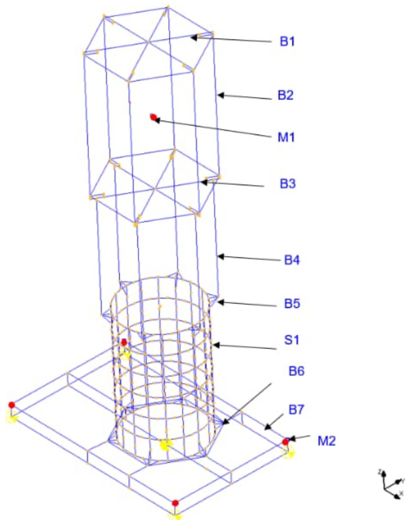


Figure 9- reactor FEM model

Beam elements:

B1	top spider
B2	reactor winding (stiff)
B3	bottom spider
B4	insulator C8-1050
B5	top mounting bracket
B6	bottom mounting bracket
B7	concrete slab (stiff)

Shell elements:

S1	fibreglass pipe

Mass elements:

M1	reactor mass - lumped to the c.o.g. of the reactor
M2	concrete slab mass - lumped to the four corners of the slab, ¼ of total mass each

5.1 Short Circuit Forces

The structural behaviour during short circuit has been analysed with full 3-phase S/C current (11.2kA$_{rms}$/28.56kA$_{p}$) and phase-to-phase S/C current (8.94kA$_{rms}$/22.75kA$_{p}$). Due to the dynamic mechanical behaviour of the reactor, an attenuation factor to the electromagnetic force between the reactors can be applied to evaluate the maximum static force F_{static} that will act on the reactor during the S/C event.

For the reaction forces between the reactors a transient analysis has been made based on the excitation by the asymmetrical S/C current of 50Hz and the mechanical rocking mode frequency (self-resonance frequency of the inverse mass pendulum) of the reactor assembly has been made.

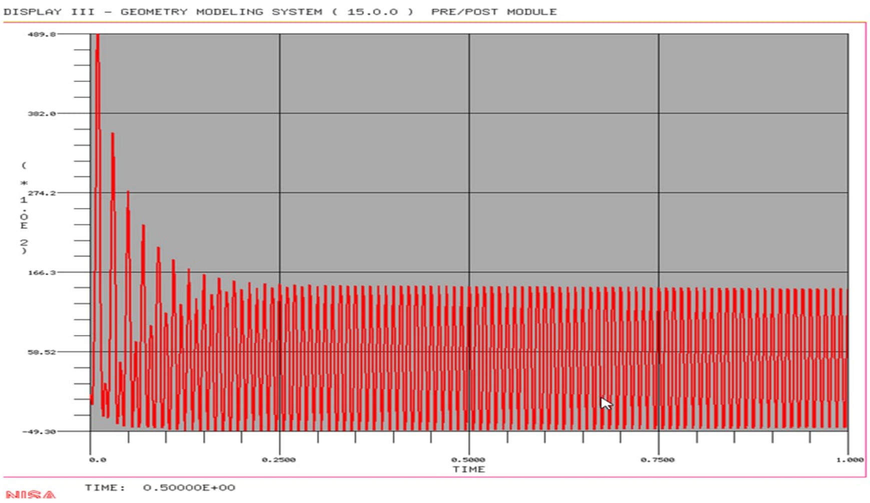
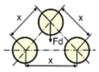
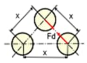


Figure 10- transient structural force reaction at short circuit

This assessment has shown a significant attenuation of the reaction force resulting in an attenuation factor of $SC_{\_ATT}$=3.6 considering the rocking mode frequency f_{mech} of 2.42Hz

Table 2- S/C load cases

Load case	Peak dynamic electromagnetic force	$SC_{\_ATT}$	Equivalent static force
 3-phase S/C	61.1kN	3.6	16.9kN
 2-phase S/C	45.27kN	3.6	12.58kN

Note: As the force vector changes between the S/C cases, both load cases need to be verified regarding the reaction forces on the foundation.

5.2 Wind Forces

The wind pressure p_w is calculated in accordance to DIN EN 1991-1-4 EUROCODE 1 [3]:

$$p_w = q_b * C_e * C_sC_d * C_f \qquad (3)$$

$$q_b = \rho/2 * v_w{}^2 = 1.25\text{kg/m}^3 / 2 * (140/3.6\text{ m/s})^2 = 1.563\text{kN/m}^2 \qquad (4)$$

whereby:

C_e	exposure factor:	1
C_sC_d	structural factor:	1 for structures of height < 15m
C_f	force coefficient:	see Table 3
ρ	density air	

The force coefficient C_f is different for cylindrical and rectangular surfaces and depends also on the roughness of the surface and on the dimensions of the object. Formulas and diagrams are given in EUROCODE 1.

Table 3- component wind forces

structure	roughness	C_f	Area [m²]	pw [Pa]	Wind-force [N]
Reactor winding	0.02	0.455	6.01	430	2586
Spider arm	0.02	1.57	0.11	1484	163
Insulator	0.002	0.775	0.36	733	263
Fibreglass tube	0.02	0.661	4.15	625	2594

The wind-force in the reactor winding plus the wind-forces on the spider arms is applied on the c.o.g. of the reactor winding. The wind force on the insulators is applied as uniform beam-load along the insulator (103N/m) and the wind-force on the fibreglass tube is applied as pressure load acting on the shell-elements (625Pa).

5.3 Seismic Forces

The seismic study is performed by using NCSE-02 [4] with a base-acceleration of a_b=0.16g for the horizontal acceleration and a_b=0.08g for the vertical acceleration. The corresponding response spectra based on a 2% damping and soft soil (worst case) are shown in Figures 11 and 12.

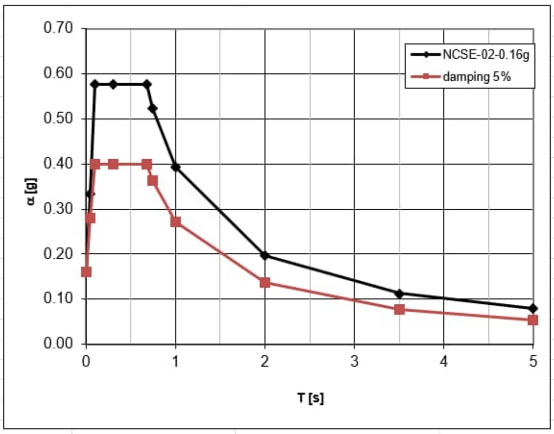


Figure 11 - horizontal response spectrum: NSCE-02, ab=0.16, red Ω=5, black Ω=2

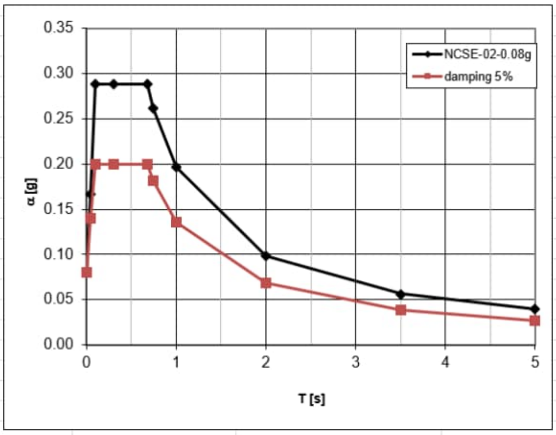


Figure 12- vertical response spectrum: NSCE-02, ab=0.08, red Ω=5, black Ω=2

The seismic load is applied within the 'shock-spectrum analysis', whereas the response spectra as given are applied in horizontal direction (a_b=0.16g) and vertical direction (a_b=0.08g) simultaneously.

5.4 Summary of the static and stability study

Table 4- Static and Stability Study - Summary

load case	max. horizontal deflection at top terminal	max. bending moment on insulators	max. axial force on insulator	mechanical stress in glass fiber cylinder	remaining axial reaction force	horizontal slipping force
	[mm]	[kNm]	[kN]	[MPa]	[kN]	[kN]
3-phase S/C	18.1	6.9	24.3	11.7	20.1	16.9
2-phase S/C	13.4	4.6	18.8	8.1	15.2	12.5
Wind force	4.6	1.7	11.8	3.4	23.5	7.5
Seismic	22.4	8.2	19.3	14.7	18.1	21.9

<u>Limits:</u>

Insulator bending moment: 18.4kNm; compression strength 500kN; combined safety factor ≥ 2

Glass fiber cylinder: Ultimate strength 350MPa

Retaining friction force: $F_f = \mu_r * F_w = 0.4*125kN = 50kN$ (5)

Retaining vertical force: $F_{react\text{-}weight} = F_w /4 = 125kN/4 = 31.25kN$; (6)

safety factor ≥ 30% remaining force

After verification of the different specified load cases, it can be concluded that the seismic event is causing the highest component stresses and highest reaction forces. All the analysed cases show that the proposed design concept using the concrete slab as storage, transport and site installation platform is feasible without additional fastening provisions.

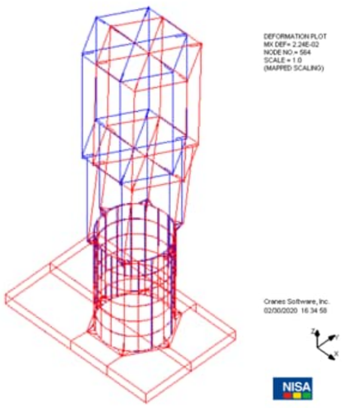


Figure 13- max. deflection seismic

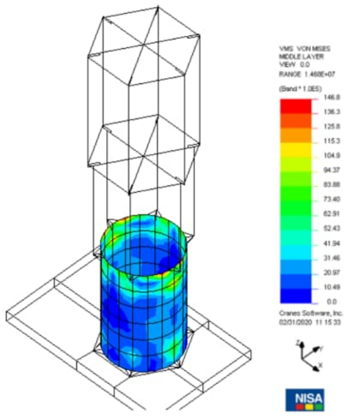


Figure 14- max. stress cylinder seismic

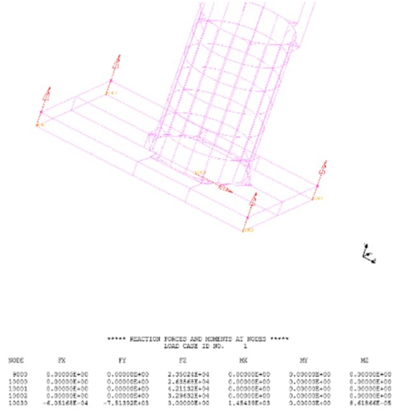


Figure 15 - remaining reaction forces seismic

6. VERIFICATION OF MAGNETIC AND ELECTRIC FIELD LIMITS

A study of the magnetic flux density and electric field strength was conducted using the EleFAnTs (electromagnetic field analysis tools) software [5]. This FEM-tool was used for pre-processing, generating the finite element mesh, numerical solving of the electromagnetic fields, and visualizing the results with a graphical post-processor. The exposure domains according to the guidelines of ICNIRP (International Commission on Non-Ionizing Radiation Protection, 2010) [6] for occupational personnel and general public for B- and E-fields were visualized using the EleFAnTs graphical post-processor. The exposure limit values for time-varying fields at 50Hz are listed in Table 5. Only the symmetrical three-phase operation mode with nominal currents and voltages was considered. However, any other load conditions may be verified due to the linear correlation between B-field and load current. Additional information regarding magnetic field effects in context of air-core dry-type reactors can be found in Air Core Reactors: Magnetic Clearances, Electrical Connection, and Grounding of their Supports Mipsycon 2017 [7].

Table 5- The exposure limits according to ICNIRP (International Commission on Non-Ionizing Radiation Protection, 2010) for B- and E-field at 50 Hz

	General Public	Occupational
B-Field (mT_{rms})	0.2	1
E-Field RMS (kV/m_{rms})	5	10

In the B-field calculation, the reactors are not part of the finite element model but are simulated as cylindrical coils with a defined time-harmonic current density across their cross-section. The B-field at the elevation of 1.5 meters from the ground is presented in Figure 16.

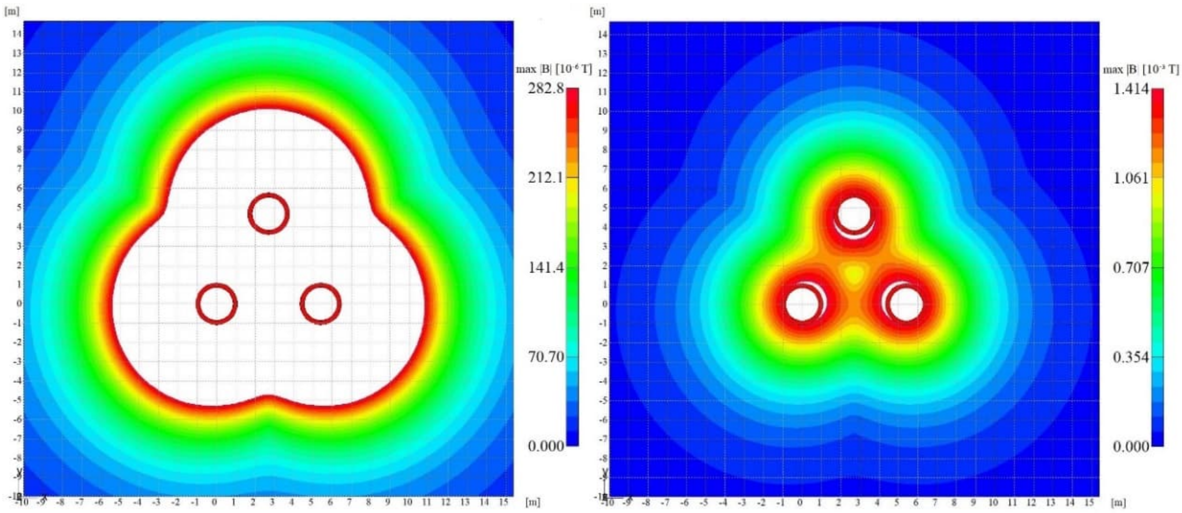


Figure 16: B-field limits for general public (left) and occupational (right) exposure at 1.5 meters above the ground level. The plotted value is the peak field value and thus by √2 larger than the RMS value specified in the guideline. The white area represents the area where the exposure limits of $0.2mT_{RMS}$ and $1mT_{RMS}$ respectively, are exceeded.

For the E-field calculation, the reactors are modelled as single package cylindrical coils whose surfaces have a time-harmonic voltage boundary condition. The voltages of the coil ends were set in the following way: the top of each coil has a voltage of $U_{top} = 220kV_{rms}/\sqrt{3} \approx 127kV_{rms}$ and the bottom of each coil has a voltage of $U_{bottom} = U_{top} - Z * I = 127kV_{rms} - 10\Omega * 1100A_{RMS} \approx 116kV_{rms}$. The voltage drop vertically along the coil is assumed to be linear. The E-fields at 1.5-meter elevation from the ground are presented in Figure 17.

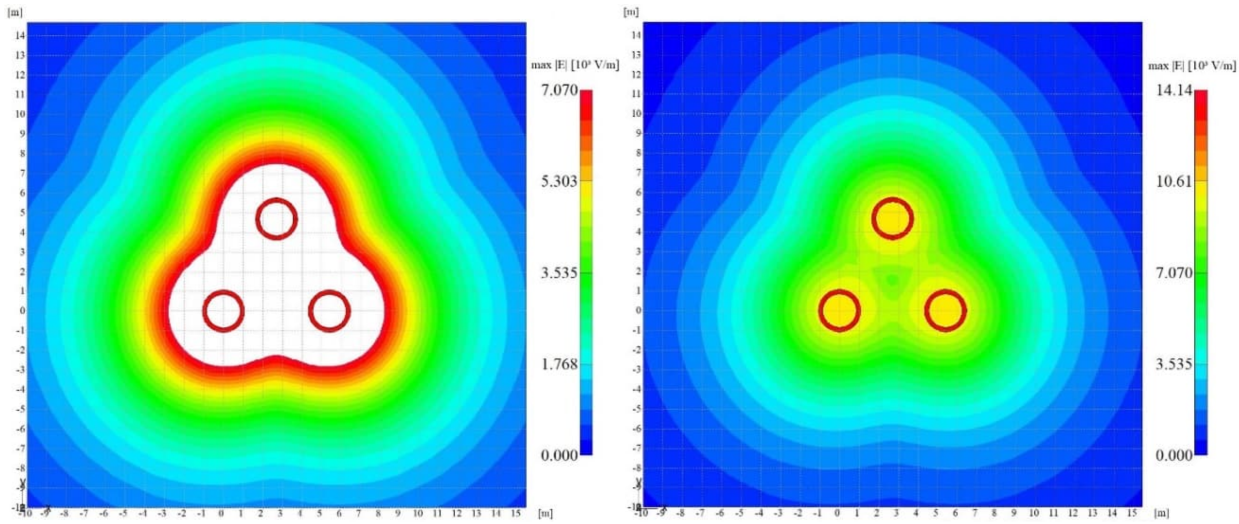


Figure 17: E-field limits for general public (left) and occupational (right) exposure at 1.5 meters above the ground level. The plotted value is the peak field value and thus by √2 larger than the RMS value specified in the guideline The white colour represents the area where the exposure limits of 5 kV/m$_{RMS}$ and 10 kV/m$_{RMS}$ respectively, are exceeded.

The B-field verification shows that for the selected reactor size, the limits for occupational exposure are only exceeded directly under the equipment. For the E-field, the occupational exposure limits are not exceeded anywhere at 1.5m elevation from the ground. Thus, no specific precautions or warnings for site personnel are needed.

Also, the distances to "general public" exposure limits are only about 5m from the coil axis, which is a distance that is typically still within the site boundaries. However, it is recommended and common practice to place a warning sign with regards to magnetic field exposure at the site boundaries, to raise awareness (e.g. for pacemaker carrier)

7. BASIC (SIMPLIFIED) TRANSIENT RECOVERY VOLTAGE (TRV) STUDY

It is known that the insertion of a series reactor in a system is causing a negative impact on the TRV [1] [8] and particularly on the rate of rise of recovery voltage (RRRV), which may cause a malfunction (re-striking) of the associated breaker in case of a short circuit event. A common mitigation method is the insertion of TRV capacitors, preferably parallel to the winding [9] [10]. The system is specified with a 50kA short circuit which also is the assumed capability of the existing circuit breaker. After insertion of the 10 Ohms reactor, the load side short circuit current will be limited to $11.2kA_{rms}$, which is 23%. Therefore, as a safe approach the T30 envelope (5kV/µs) as per table 20-Values of prospective TRV for circuit-breakers, of IEC62271-100 [11] will be used for the following basic assessment, which is based on the simulation of a single phase of the 220kV system using the Thevenin equivalent which is an acceptable simplification in case of an effectively grounded system assuming the short circuit directly after the reactor.

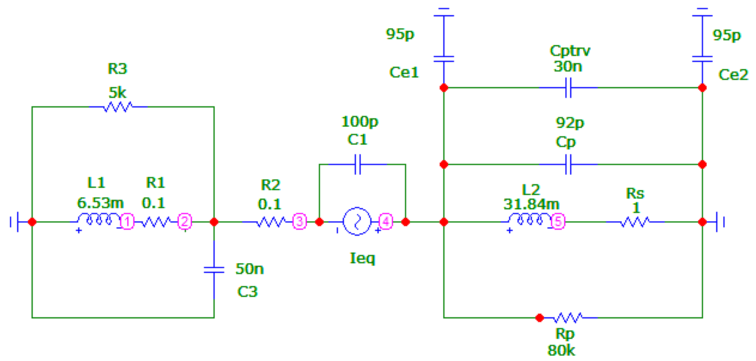


Figure 18 - equivalent single phase Thevenin reduction

equivalent network representation based on S/C of 50kA using the Thevenin reduction method.

equivalent load flow reactor data: L =31.84mH, stray capacitance between turns Cp=92pF; total capacitance to ground Ce=190pF

load side S/C directly after the reactor is assumed

Results of the simulation using EMTP software:

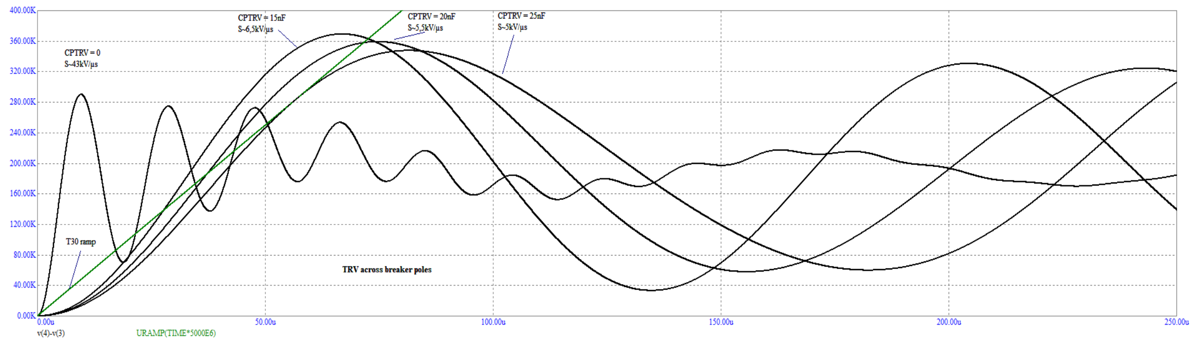


Figure 19 - TRV across breaker poles

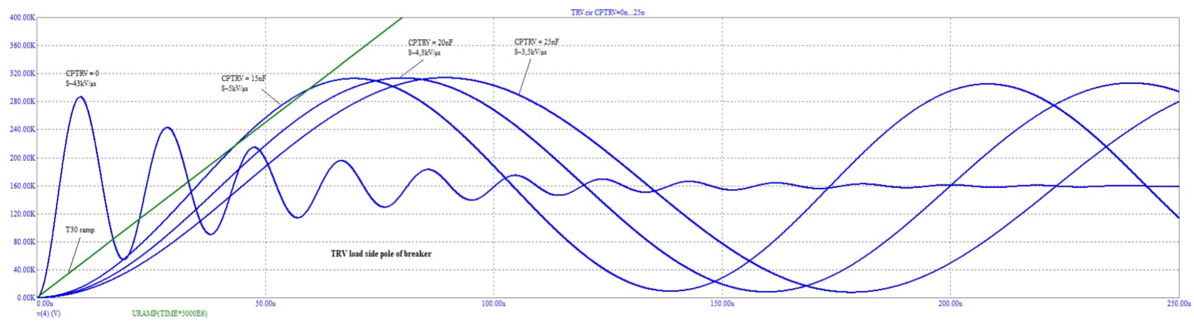


Figure 20- TRV at the load side pole of the breaker

The basic and simplified TRV study shows, that a TRV capacitor in parallel to the reactor winding with a capacitance between 15nF and 20nF is required to mitigate the RRRV of the TRV to about 5kV/µs. Such capacitors are typically available as a single column in a porcelain of composite housing and may be mounted on an individual support structure or on extension elements directly on the reactor.

8. CONCLUSION

Based on the presented study it is shown that a dry-type air-core load flow reactor together with the support insulators and support structure can be designed to allow installation on a prefabricated concrete platform with dimensions and weights of the handling units that are suitable for standard transport vehicles. The boundary conditions regarding magnetic field and electric field limits have been evaluated. The structure has been verified to withstand the specified wind, seismic, and short circuit forces based on the placement of the concrete platform directly on a levelled and compressed bed of fine gravel. Due to the easy assembly and dismantling concept, the mobilization of such installation can be accommodated within a few days to allow a relocation cycle of less than 4 weeks. This solution is a viable way to increase the network resilience thanks to its mobility and speed of installation. However, thorough systems studies (e.g., TRV mitigation, changed X/R ratio) need to be performed prior to final installation at the target sites / substations. A mobile load flow device such as the described reactor solution can be useful in various scenarios, a clear one can be during the execution of a permanent subsequent solution. For example, legalization and construction of powerline upgrades take a long time, in Europe years. During this period, the mobile solution can avoid overload of the power line and allows to run the system cheaper and more efficient. The commissioning of such a system is limited to well known procedures for substation equipment and can be done by the TSO itself. The life-time expectation of modern air-core dry-type reactors is 40 years with little condition-based maintenance only, which make them to robust and reliable high-voltage equipment.

FACTS devices based on power electronics may provide smarter solutions, but they are much more expensive, complex and require a longer installation period as well as a larger footprint.

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