

UNIVERSIDADE FEDERAL DE ITAJUBÁ
PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA ELÉTRICA
INSTITUTO DE SISTEMAS ELÉTRICOS E ENERGIA

**HV SHUNT REACTORS: an overall comparative analysis
between dry-type air core and oil-immersed iron core
technologies**

Antônio César Costa Ferreira Rosa

Itajubá, agosto de 2021

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Dissertação submetida ao Programa de Pós-Graduação em Engenharia Elétrica como parte dos requisitos para obtenção do Título de Mestre em Engenharia Elétrica.

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Orientador:

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This work is dedicated to uncle Jozaldo Costa, one of the smartest and strongest people I have ever met. He taught me to face the challenges of life with hope and joy, made me fall in love by engineering and has supported me in everything even beyond his possibilities. Uncle, all my acknowledgment and gratitude.

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Thank you all so much for everything. I love you!

If you want to find the secrets of the universe, think in terms of energy, frequency and vibration.

Nikola Tesla

RESUMO

Reatores em derivação em alta e extra alta tensão, historicamente sempre foram fabricados em tecnologia com núcleo de ferro imersos em óleo, devido prioritariamente a questões relacionadas ao isolamento dos enrolamentos. Contudo, com o avanço dos materiais isolantes e de técnicas de fabricação, tem sido possível a fabricação destes equipamentos utilizando tecnologia com núcleo de ar, a qual tem se demonstrado eficiente, ambientalmente amigável e, em muitos casos, com menores custos de curto, médio e longo prazo. Fazendo-se necessário portanto, o estudo de quais as implicações quando se opta por esta tecnologia, que tem sido cada vez mais aceita no mercado mundial. São abordados os principais aspectos da aplicação destes equipamentos, estabelecendo um paralelo entre ambas tecnologias, no que tange os aspectos construtivos, a viabilidade de substituição (quais os casos em que ela é ou não indicada), comparativo de perdas, aspectos de proteção, todas as precauções e observações em termos de campo magnético, aspectos transitórios (incluindo estudo de caso de dois equipamentos idênticos nas duas tecnologias, com cálculos e simulações das frequências e tensões transitórias, TRT e TCTRT, bem como um comparativo percentual entre os resultados calculados e simulados). Tais comparações visam auxiliar a comunidade técnica, de modo a contribuir com a tendência global em adotar a tecnologia do tipo seco, enfatizando as principais diferenças e particularidades a serem consideradas quando da substituição da tecnologia tradicional.

Palavras-chave: reator shunt, tipo seco com núcleo de ar, núcleo de ferro imerso em óleo, aplicação, projeto, instalação, transitórios, proteção e custos.

ABSTRACT

Shunt reactors in high-voltage and extra high-voltage, have historically been manufactured using oil-immersed iron core technology, mainly due to issues related to the insulation of the reactor windings. However, with the improvement of the insulating films as well as on the manufacturing techniques, it has been possible the manufacturing of these equipment using dry-type air core technology, which has demonstrated to be efficient, environmentally friendly and, in many cases, with lower costs in short, medium and long-term basis. It is required therefore, the study of which are the changes when it is adopted this air core technology, which has been the more and more accepted on worldwide market. The main aspects regarding the application of these equipment are disclosed, establishing a parallel between both technologies, with regards to the construction aspects, the viability of replacement (which are the cases at which they are or not indicated), the losses comparison, all the precautions and remarks in terms of magnetic field, the protection and the transients aspects (including a study case of two identical equipment in both technologies, with calculations and simulations of transient frequency and voltage, TRV and RRRV, as well as a percentage comparative analysis between the calculated and simulated results). These comparisons, aim to contribute with technical community and the global trend in adopting dry-type technology, highlighting the main differences and particularities to be considered when replacing traditional type.

Key-words: shunt reactor, dry-type air-core, oil-immersed iron-core, application, design, installation, transients, protection and costs.

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LIST OF ACRONYMS

ABNT	Brazilian Association of Technical Standards, or “ <i>Associação Brasileira de Normas Técnicas</i> ”, in Portuguese
ACR	Air-core Reactors
ANEEL	Brazilian Electricity Regulatory Agency, or “ <i>Agência Nacional de Energia Elétrica</i> ”, in Portuguese
ATP	Alternative Transients Program
BIL	Basic Impulse Level
CB	Circuit Breaker
CT	Current Transformer
CVT	Capacitive Voltage Transformer
DC	Direct Current
Ds	Outer Diameter of Air-core Reactor Windings
GFRP	Glass Fiber Reinforced Polymer
HV	High Voltage
IARC	International Agency for Research on Cancer
ICNIRP	International Commission on Non-ionizing Radiation Protection
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
I _{max}	Maximum Current
I _r	Rated Current
ISO	International Organization for Standardization
IT	Instrument Transformer
LV	Low Voltage
MC1	Magnetic Clearance from Metallic Parts not Forming Closed Loops
MC2	Magnetic Clearance from Metallic Parts Forming Closed Loops
MC3	Magnetic Clearance for Occupational Exposure
MC4	Magnetic Clearance for General Public Exposure
MV	Medium Voltage
N/A	Not Applicable
NGR	Neutral Grounding Reactor
OIR	Oil-immersed Reactors

ONS	Brazilian National Electric Systems Operator, or “ <i>Operador Nacional do Sistema Elétrico</i> ”, in Portuguese
PEN	PolyEthylene Naphthalate film
PET	PolyEthylene Terephthalate film
PI	Polyimide film
POW	Point-on-Wave Switching
RMS	Root Mean Square
RRRV	Rate of Rise of Recovery Voltage
SA	Surge Arrester
SLD	Single Line Diagram
TCR	Thyristor-Controlled Reactor
TRV	Transient Recovery Voltage
TRT	Transient Recovery Voltage, or “ <i>Tensão de Reestabelecimento Transitório</i> ”, in Portuguese
TCTRT	Rate of Rise of Recovery Voltage, or “ <i>Taxa de Crescimento da Tensão de Reestabelecimento Transitório</i> ”, in Portuguese
UHV	Ultra High Voltage
U _{max}	Maximum Voltage
U _r	Rated Voltage
VT	Voltage Transformer
WHO	World Health Organization

LIST OF SYMBOLS

A	Ampere
°C	Degree Celsius
T	Tesla
C_s	Series Stray Capacitance of a Reactor
C_g	Phase-to-ground Stray Capacitance of a Reactor
L_R	Total Inductance per Phase of Reactor
R	Resistance of Reactor Windings
I_k''	Symmetric (thermal) Short-time Current
I_s	Asymmetric (mechanic) Short-time Current
f_L	Load Oscillation Frequency
X_0	Zero-sequence Impedance
X_L	Rated Reactance of Reactor per Phase (Positive Sequence)
X_N	Impedance of Neutral Ground Reactor
VA _r	Volt Ampere Reactive
VA	Volt Ampere
W	Watts
P	Active Power
S	Apparent power
D_s	Outer Diameter of ACR Coil
pu	Per Unit

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1 INTRODUCTION

With the development of modern society, which is more and more energy-dependent, the energy demand is increasing at each year, being crucial that electrical equipment present in these power systems, operate closer to their operational limits. Besides, it is known that today, despite the growth on the contribution of distributed generation, most energy sources are still very far to the consuming centers.

In the context of power transmission between those two endings of the power flow (production and consumption), mainly in long distances, it is essential the use of reactive power compensation systems, which allow, for example, to control the voltage levels across the power line, by the use of shunt capacitor or reactor banks. These systems also optimize the capacity of active power transmission and/or system stability, by the use of series capacitive compensation. Without the use of such systems, besides the less-efficient and poor-quality operation, the power system is subjected to risks that can even lead to its complete collapse, by the stability loss, for example [1].

This work focuses on one equipment used for Reactive Power Compensation: the shunt reactor, establishing a comparison between the standard technology used for High Voltage (HV) and Extra High Voltage (EHV) systems: the oil-immersed iron core reactor (OIR) and the technology that is nowadays a reality for these voltage levels, but used to be applied to lower voltages: the dry-type air core reactor (ACR).

1.1 MOTIVATION

During normal conditions, the operating voltages of transmission systems must be maintained within very tight limits, typically, from 0.95 and 1.05 per unit (pu) of the rated value. At low system loading, operating voltages increase due to the capacitive nature of the grid, shunt reactors are then used to “absorb” this excess of reactive power generated by the capacitances of the grid and thereby regulate the operating voltages of transmission and distribution systems.

Shunt reactors applied to HV and EHV systems (typically greater than 145 kV) have been constructed in iron-core oil-filled technology. However, due to the improvement of insulating materials as well as of manufacturing techniques, today it is possible to apply dry-type air-core technology, typically for voltages up to 500 kV. There are some major particularities from the application and standards perspective. It is required therefore, to compare both technologies and the advantages and disadvantages of each one.

Dry type air core shunt reactors are a very cost-effective solution for reactive power compensation of transmission and distribution systems. Its feasibility depends primarily on the combination of required voltage and power.

This work aims to contribute with technical community, professors, students and all the other actors of power community in a better understanding of shunt reactor application with regards to the comparison of both OIR and ACR types.

1.2 OBJECTIVES

This work focuses on the application of shunt reactors to systems with voltage above 145 kV and establishes a parallel between these technologies from several perspectives (construction, installation, special requirements, protection, connection and insulation, behavior during switching events, costs, etc). Transient aspects are also presented with calculations and simulations for a case study, being possible to make a direct comparison between both technologies.

1.2.1 General objectives

The objectives of this work are to compare ACR and OIR technologies from the application point of view, mainly:

- To present main construction and design aspects to each technology;
- To present the viability of the replacement of OIR by ACR and which are the main points impacting on overall costs of both;
- The losses aspects and design particularities of each technology;
- The protection requirements especially with regards to turn-to-turn insulation and the critical aspects associated to each type;
- The electrical and magnetic aspects as well as the precautions to be taken specially when considering dry-type reactor;
- To present the main transient models to be used to each equipment type (for several arrangements), in order to ensure reliable simulations;
- To perform a **quantitative analysis performing the calculations and the simulations** of the switching transients (energizing and de-energizing) to equipment with same ratings on both technologies. Afterwards, to perform the comparison between these results (simulated vs calculated) in order to check the error/accuracy of the equations and the models adopted;

- To present which are the conditions at which a technology is more favorable than the other and which are the main evaluating points;

1.2.2 The sections and their main content

The sections of this work as well as their main content summary are presented in Table 1.

Table 1 - Sections of work and their main content

Section	Title	Content
2	THEORETICAL FOUNDATION	Theory regarding the use of reactive power compensation systems, especially the shunt reactor.
3.1	DESIGN ASPECTS	Construction of both technologies, detailing the insulation aspects including materials, temperatures and some aspects from equipment standards
3.2	OVERALL COSTS COMPARISON	Main aspects that impact on overall costs to both types
3.3	LOSSES	Main aspects that impact on losses to both types
3.4	MAGNETIC FIELD ASPECTS	Main precautions in terms of magnetic field involved specially in the use of dry-type equipment. A definition of main aspects and which are the precautions to be taken are presented.
3.5	MAINTENANCE	A comparison is established showing the particularities of each type
3.6	INSTALLATION ASPECTS	A comparison is established showing the particularities of each type
3.7	PROTECTION	The protection requirements are presented, especially with regards to turn-to-turn insulation and the critical aspects associated to each type;

3.8	TYPICAL ARRANGEMENTS OF SHUNT REACTOR BANKS	The main arrangements to be used to each equipment type (for several arrangements) are presented. Based on these arrangements, transient models are presented in section 4.2.
3.9	INSULATION LEVEL ASPECTS	The insulation level of the equipment depends on the arrangement and the connection point. The highlights regarding these aspects are presented and a comparison is established.
4	TRANSIENT ANALYSIS OF SHUNT REACTORS	An overall analysis related to transients is presented, including calculations, simulations and a comparison of both.
4.1	STRAY CAPACITANCES	It is presented the definition of stray capacitances and some remarks concerning these elements.
4.2	TRANSIENT MODELS	The main transient models to be used to each equipment type (for several arrangements) are presented. The use of these models ensures reliable and conservative simulation results.
4.3	ENERGIZATION INRUSH CURRENT	The main points regarding energization are presented.
4.4	DE-ENERGIZING OVERVOLTAGE	The main points regarding de-energization are presented (chopping and reignition overvoltage, TRV, RRRV, oscillating frequencies, etc)
4.5	OVERVOLTAGE MITIGATION ON CB AND REACTOR WINDINGS	The main overvoltage mitigation techniques adopted to protect the reactor as well as to ensure proper operation of circuit breakers are presented.
4.6	SWITCHING TRANSIENTS – CALCULATION AND SIMULATION (CASE STUDY)	This section presents the calculations and simulations of the switching transients to equipment with same ratings on both technologies. Afterwards, a comparison between them is performed in order to check

		the error/accuracy of the equations and the models adopted. Main remarks regarding the results are detailed.
5	SUMMARY OF GENERAL ANALYSIS	A general table with the main comparison points is presented as a summary of the main differences of both types.

2 THEORETICAL FOUNDATION

The following sections present some basics behind the use of shunt reactors on the power system, showing an overview of such systems as well as some typical ratings found in utilities worldwide.

2.1 POWER FACTOR AND REACTIVE POWER COMPENSATION

The concept of active, reactive and apparent powers is very important in power engineering world. These terms apply to steady-state condition. The active power (P) is expressed in watts [W], the reactive power is expressed in reactive volt-ampère [Var] and apparent power (S) is expressed in volt-amperes [VA].

The apparent power does not depend on the angle between the voltage and the current. The active power is the one to be actively consumed by the load. Resistors are considered active loads where the voltage and the current are in phase. The active power depends on the cosine of the phase angle θ between the current and the voltage and is composed by a series of positive pulses as observed in Figure 1.

Capacitors and reactors are reactive loads. It was conventioned that the inductive loads (motors, under-excited synchronous machines, reactors, etc), “absorb” the reactive power from the system while the capacitors and other capacitive nature loads (such as capacitor banks, long transmission lines, overexcited synchronous machines, underground insulated cables, for example), “supply” reactive power to the grid.

Unlike what occurs to purely resistive systems, inductive and capacitive systems present mismatch in phase between the voltage and current waves. In purely capacitive systems, the current wave is 90 degrees ahead the voltage wave. On inductive systems, the opposite occurs. Therefore, the current on capacitors is 180 degrees from the current on the inductors, as shown in Figure 2, Figure 3 and Figure 4 [2].

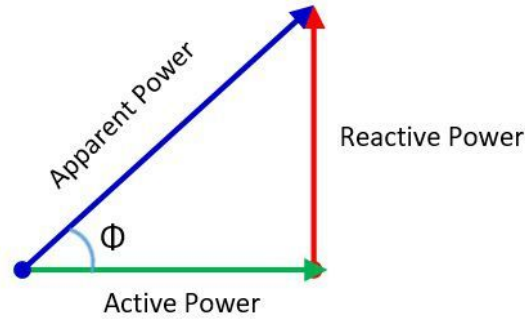


Figure 1 - Triangle of powers [3].

From power triangles, the following equations are obtained:

$$S = U * I \quad (1)$$

$$P = U * I * \cos \varphi \quad (2)$$

$$Q = U * I * \sin \varphi \quad (3)$$

$$S = P \pm jQ \quad (4)$$

Where:

U: System voltage in Volts (V)

I: Current in Ampere (A)

Φ: angle between real (or active) power and apparent power

P: real (or active) power in Watt (W)

Q: reactive power in Volt-Ampere reactive (Var)

S: apparent power in Volt-Ampere (VA)

The wave of instant power as well as associated voltage and current for a resistive load is presented in Figure 2. Current and voltage are not shifted, presenting the same phase angle.

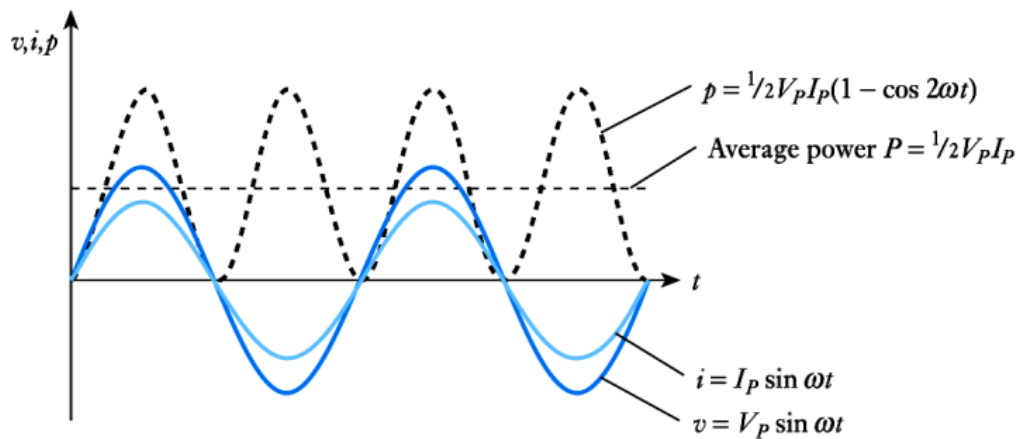


Figure 2 - Instant power in a resistive load [2].

The wave of instant power as well as associated voltage and current for an inductive load is presented in Figure 3. Current and voltage are shifted and current is delayed when compared to the voltage, presenting a positive phase-angle (ϕ).

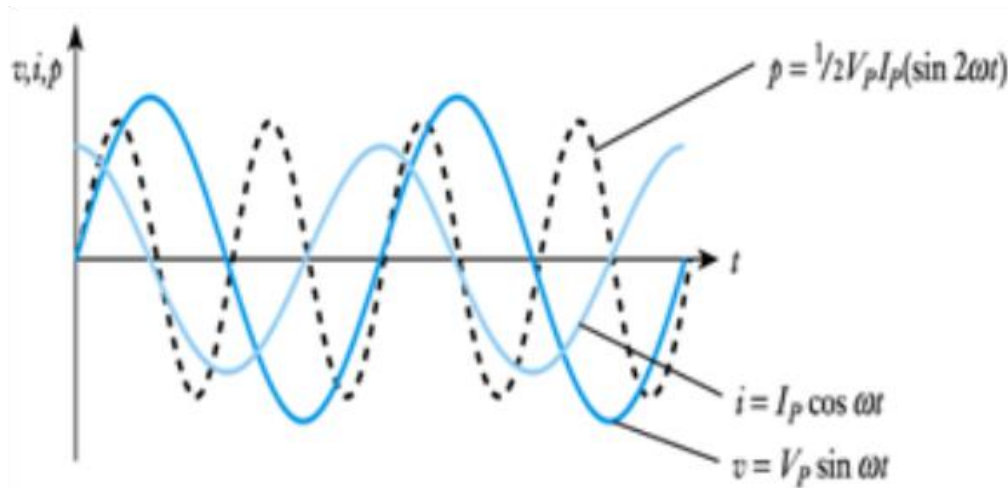


Figure 3 - Instant power in an inductive load [2].

The wave of instant power as well as associated voltage and current for a capacitive load is presented in Figure 4. Current and voltage are shifted and current is in advance when compared to the voltage, presenting a negative phase-angle (ϕ).

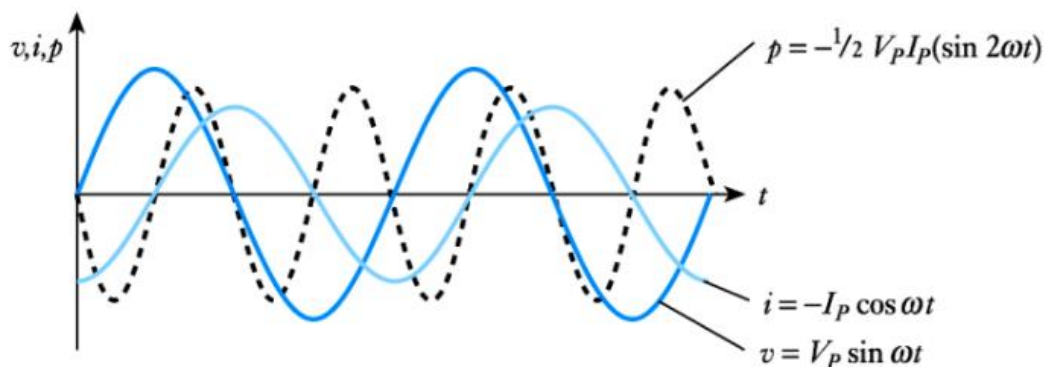


Figure 4 - Instant power in a capacitive load [2].

Based on the theory presented, it is possible to conclude that the operational effect of inductive systems is inverse to the predominantly capacitive systems. Therefore, it is also possible to conclude that the reactors can be used to reduce the capacitive effects of the systems, to "consume" the reactive power, in the same way that capacitors can "supply" capacitive reactive power.

2.1.1 Shunt Compensation

In the world of power transmission systems, it is possible to highlight two major compensation types: 1. Series compensation, which aims to reduce the electrical length of the transmission line, increasing the capacity of transmission of active power as well as improving the system stability and 2. Shunt compensation, used to regulate the voltage on the line ends (line shunt banks) as well as on busbars (bus shunt banks).

In shunt compensation, compensation systems are connected in shunt with the transmission line. A reactive power is “injected” (shunt capacitor banks) or “absorbed” (shunt reactor banks) in the line to keep the voltage constant across the variation of parallel impedance.

2.1.2 Inductance Reactive Compensation

Shunt reactors are used to increase the power system stability and efficiency when the load is low. At this moment, very low currents circulate across the transmission line, making the energy to concentrate as electric field, due to natural stray capacitances-to-ground present throughout the line, elevating the terminal voltage. This is known as ‘Ferranti effect’. The voltage at the ending of the line, may be the double of the one present at source side (generally in very long power lines). To reduce them, shunt reactors are connected in parallel to the power line, consuming the reactive power from natural capacitances of the power line [2].

The main functions of shunt reactors in transmission and distribution systems may be summarized as:

- Control of operating voltages;
- Support of reactive power compensation;
- Reduction of switching transients on transmission lines.

2.2 APPLICATION OF SHUNT REACTORS

Shunt reactors can be installed at both transmission and distribution grids, being directly connected to substation busbars, line endings and to the tertiary windings of large power transformers, as shown in Figure 5.

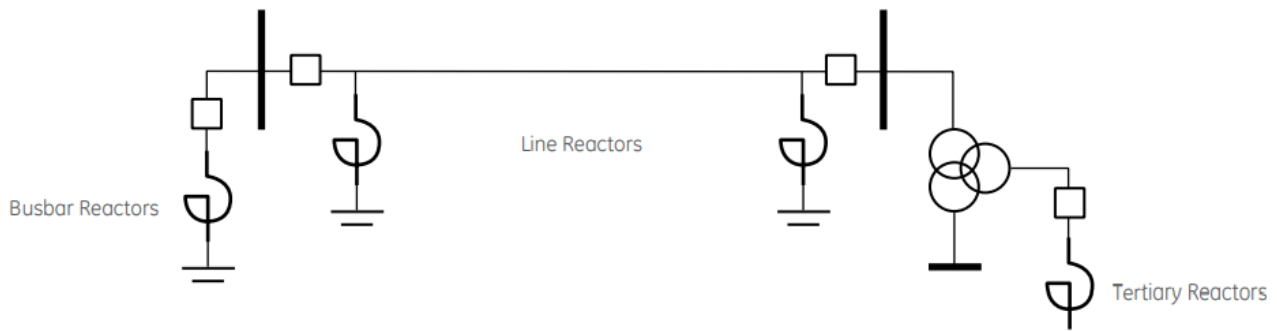


Figure 5 - Shunt application in power systems [4].

The rated voltage and reactive power of a shunt reactor, as well its location, are normally determined by system studies, such as load flow and transients. Moreover, the ratings of shunt reactors also depend on the following factors:

- Current and voltage capabilities of the switching devices - the introduction of inductive currents may create severe transient recovery voltages (TRV) over the shunt reactor and across the switching devices. The magnitude and rate-of-rise of the TRV depend on the inductance of shunt reactor and stray capacitances which, in turn, depend on the voltage, reactive power, grounding and construction of the shunt reactor. A typical TRV associated with the switching-off of the shunt reactor is around 1.7 to 2.5 pu of the rated voltage.
- Connection and grounding type of the shunt reactor – in HV systems, shunt reactors are connected in star (or wye), being ungrounded for system voltages of 72.5 kV and below and grounded for system voltages of 115 kV and above. For line reactors, when single-phase auto-reclosing of transmission lines is required, shunt reactors can be grounded by a neutral reactor or resistor. The neutral grounding reactor can also be a dry type air core reactor, with similar construction to the shunt reactors. Medium Voltage (MV) and Low Voltage (LV) systems, may present reactors connected in delta, mainly related to industrial applications. Both types of connection are presented in Figure 6.

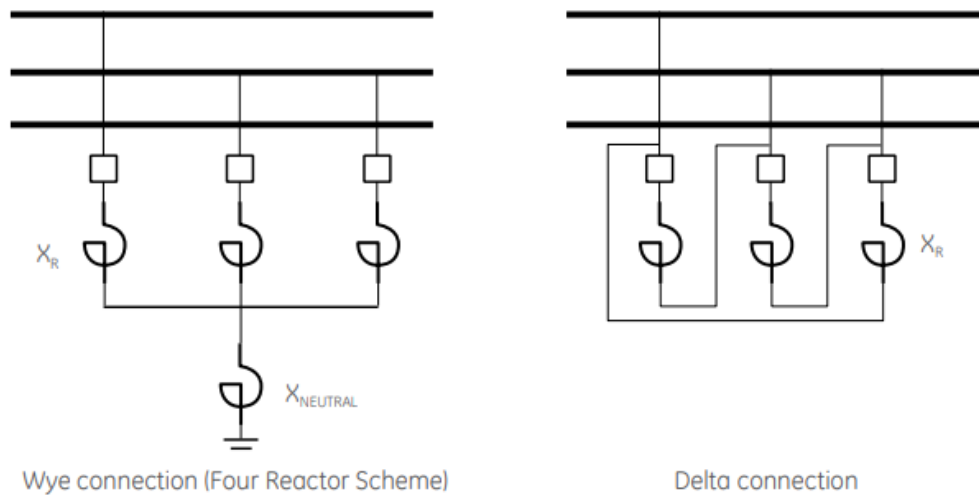


Figure 6 - Winding connection of shunt reactors [4].

- Design/manufacturing capabilities - The size of a shunt reactor depends primarily on its inductance and current. The higher the inductance and/or the current, the bigger the coils. For very low reactive power, the inductance may be extremely high, increasing the number of turns and/or diameter required. For higher reactive power values, the current is higher, requiring large cross section area of the wires to achieve a desirable temperature rise and/or losses, increasing the mass of the equipment. In both cases, the selection of a proper topology and installation location, may or may not eliminate or minimize the impacts on the operation of the reactor to the system as well as overall costs such as transportation and the price of the equipment itself.
- Rated voltage and power of reactors - The reactive power of a shunt reactor depends heavily on its operating voltages. The typical ranges of reactive power (three-phase basis) for each system voltage that result in feasible and competitive design to both reactor types, are presented below:
 - 15 kV and below: 0.5 Mvar to 25 Mvar
 - 25 kV and 38 kV: 2.5 Mvar to 60 Mvar
 - 72.5 kV: 5 Mvar to 100 Mvar
 - 138 kV: 7.5 Mvar to 150 Mvar
 - 245 kV: 15 Mvar to 200 Mvar
 - 345 kV and 400 kV: 50 Mvar to 250 Mvar
 - 500 kV: 100 Mvar to 350 Mvar

In Brazil, to guarantee the efficiency and equity to the contractors that are connected to the Brazilian Interconnected grid as well as the expected performance of the whole grid, the Brazilian National Electric Systems Operator (ONS), or “*Operador Nacional do Sistema Elétrico*” in Portuguese, in a document called Grid Code (or “*Procedimentos de Rede*”, in Portuguese), gives operational design criteria for transformers, reactive power compensation equipment among others [5].

In Brazil, the Grid Code document, in its submodule 2.3, contains specific requirements applied to Shunt Reactors concerning voltage, temperature rise, service operational and reactance limits as well as grounding schemes, losses and lifespan [6].

The section 8.2.2 of submodule 2.3 presents the specific information related to Shunt Reactors which are:

- Rated voltage - Shunt reactors shall be designed to withstand at least the mean value of the admissible voltage ranges listed on Table 1 of ONS sub-module 23.3 (from 0.9 to 1.1 pu, depending on voltage level [7]). If the reactor is installed next to series capacitor banks, power flow studies shall verify if the design voltage should be increased to be higher than maximum operating voltage of the system, taking care at the same time with temperature-rise of the equipment, which shall be done by using maximum operating voltage.
- Tolerances - The maximum variation on reactance is $\pm 2\%$ of the specified value. This parameter shall not deviate more than 1 % of the mean value of the measured values for the three-phase set.
- Grounding schemes - Shunt reactors can be grounded directly or throughout an impedance and the need to use a neutral reactor shall be identified in a monopolar reclosing study.
- Service conditions - Shunt reactors should be designed to operate continuously at rated voltage during its lifetime. It shall also withstand all switching transients and do not cause overvoltage to the system.
- Lifespan - The submodule requires shunt reactors lifespan to be specified according to requirements of the Brazilian National Electric Energy Agency (ANEEL), or “*Agência Nacional*

de *Energia Elétrica*”, in Portuguese. This lifespan specification depends on the auction of ANEEL for the supplied equipment.

- Losses - For shunt reactor banks to be supplied to Brazil, the losses of the equipment, at rated voltage, shall be as per Table 2 [6]. The power references are the ones equivalent to the three-phase set of the reactor.

Table 2 - Brazilian losses limits for shunt reactors

Maximum Losses for Shunt Reactor on Brazilian Interconnected Grid	
<i>Rated Power (Rp)</i>	<i>Maximum Losses Allowed (in % of Rated Power) ^a</i>
5 ≤ Rp < 10 Mvar	0,70 %
10 ≤ Rp < 15 Mvar	0,60 %
15 ≤ Rp < 20 Mvar	0,50 %
20 ≤ Rp < 30 Mvar	0,40 %
Rp ≤ 30 Mvar	0,30 %

a. Table 6 of sub-module 2.3 of ONS Grid Code [6].

In general, for rated power values below 15 Mvar, the losses required by Brazilian ONS Grid Code cause huge impact on the costs of the ACR equipment. In such cases, additional cross section area on the windings is necessary to reduce the losses and allowing a compliant design.

2.2.1 Main Shunt Reactors Equations

For the calculation of the positive sequence reactance and current requirements of a shunt reactor, it is necessary to know the rated three-phase reactive power and the rated system voltage.

The zero-sequence reactance (X_0) depends on the winding connection and grounding of the shunt reactor. The equations (5) and (6) show the reactance calculation for Wye and Delta connections, respectively.

$$X_{L_wye} = \frac{U_N^2}{S_{R3\phi}} \quad (5)$$

$$X_{L_delta} = 3 \times \frac{U_N^2}{S_{R3\phi}} \quad (6)$$

The equations (7) and (8) show the rated current calculation for Wye and Delta connection respectively.

$$I_N = \frac{S_{R3\phi}}{\sqrt{3} \times U_N} = \frac{S_{R1\phi}}{\frac{U_N}{\sqrt{3}}} = \frac{U_N}{\sqrt{3} \times X_L} \quad (7)$$

$$I_N = \frac{S_{R3\phi}}{3 \times U_N} = \frac{S_{R1\phi}}{U_N} = \frac{U_N}{X_L} \quad (8)$$

The maximum continuous current (design current) for both Wye and Delta connection depends on the maximum system voltage and can be calculated according to equation (9).

$$I_{MAX} = \frac{U_{MAX}}{U_N} \times I_N \quad (9)$$

Where:

X_{L_wye} : rated reactance of reactor per phase (positive sequence) of wye-connected reactors

X_{L_delta} : rated reactance of reactor per phase (positive sequence) of wye-connected reactors

$S_{R3\phi}$: rated three-phase reactive power

$S_{R1\phi}$: rated reactive power per phase

U_N : rated system voltage

U_{MAX} : maximum system operating voltage

I_N : rated current

I_{MAX} : maximum continuous current

Neutral grounding reactors are generally associated with shunt reactors installed in transmission line terminations to provide a faster extinguishing of the secondary arc current, allowing the automatic reclosing of the transmission line after a fault elimination [8]. Typically, the reclosing time varies from 0.5 to 1.5 seconds.

The zero-sequence reactance (X_0) depends on the winding connection and grounding of the shunt reactor. For air-core dry-type units, it can be calculated as follows.

- Wye connection with neutral directly grounded (10):

$$X_0 = X_L \quad (10)$$

- Wye connection with neutral grounded through a reactor (11):

$$X_0 = X_L + 3 \times X_N \quad (11)$$

- Wye connection with neutral ungrounded and Delta connection (12):

$$X_0 = \infty \quad (12)$$

Where:

X_0 : zero-sequence impedance

X_N : impedance of neutral ground reactor

2.3 HIGH-VOLTAGE REACTOR TECHNOLOGIES FOR TRANSMISSION LINE APPLICATIONS

Shunt reactors for HV line applications can be of two major types: *dry-type* or *oil-filled* reactors. The first type does not present an iron core to conduct the magnetic flux, being known as

dry-type air core reactors. The second type may be ***oil-immersed air-core*** or ***oil-immersed gapped iron-core*** [9].

This work is focused on the two major types of reactor technologies applied to be used as shunt reactors for HV and EHV systems: ***oil-immersed gapped iron-core*** and ***dry-type air core*** reactors.

- **Oil-immersed Iron-core reactors (OIR)**

Shunt oil-immersed reactors are by far the most common technology applied to HV and EHV systems, due to the fact that only in recent years, the technology allowed reactor manufacturers to develop techniques to withstand the transients associated to shunt reactors switching without the use of insulating oil. These are consisted of coils immersed in insulating oil, which is contained within a grounded metallic enclosure.

These reactors can be three-phase (generally up to 245 kV, inclusive) or single-phase (generally above 245 kV).

This equipment is generally more complex than dry-type air core reactors, due to the reasons to be presented on the following sections. Moreover, the presence of an iron-core, also generates higher inrush transients than the ones associated to air-core technology, as discussed in more details in the following sections of this work.

- **Dry-type Air core reactor (ACR)**

These reactors are cooled by air-natural and the banks are composed by single-phase coils (for all the voltage levels). The equipment is considered as live parts, insulated from the ground by using standard insulators to get the suitable clearance for Lightning and Switching Impulses as well as with suitable creepage to prevent discharges due to power frequency voltages.

These reactors do not present relevant inrush transients, since those transients are caused by core magnetizing.

3 GENERAL COMPARATIVE ANALYSIS – AIR CORE AND OIL-IMMERSED HV/EHV SHUNT REACTORS

Air-core reactors are relatively simple equipment, which allow a great variability of design (according to the characteristics of each manufacturer), and can be adjusted to various configurations, which enables optimized solutions for each type of system. Its simplicity is not only structural because, unlike oil-immersed reactor, the air-core reactor has a linear characteristic of the magnetic flux, so all concerns regarding magnetic saturation are not applicable [10].

Among the benefits of air-core reactors, it is worth mentioning that it is oil free, which in addition to making it an environmental-friendly solution, entails other very significant benefits such as greater safety in operation and simplification of infrastructure (fire walls and oil leakage containment are not required, for example). In addition, shunt air-core reactors are lighter, and the required installation area is similar for both technologies.

Due to its simplicity, the air-core reactor has shorter manufacturing time and shorter delivery time. Transportation is also simpler and less costly.

The benefits extend to the operation. An air-core reactor presents greater availability and less maintenance costs since it demands less maintenance (there are no moving parts present on cooling system and it is not required oil dielectric strength analysis, for example). The absence of cooling fans can also reduce the noise levels. Regarding losses, both technologies are similar since both can be designed to present specific losses values depending on technical specification.

Air core reactors are also safer in case of an insulation failure, since there is not oil to burn, making easier to extinguish the fire.

Despite the advantages of dry-type air core reactors, major aspects may elect oil-immersed equipment the best choice for some cases, for example in substations where the installation of the reactor is intended to be close to general public sidewalks and/or very close to control room and worker circulation areas, since the spread of magnetic field lines (negligible for OIR, from magnetic safety clearance perspective), may require this equipment to be installed farther from such areas. Moreover, reactors with very low power levels are usually more competitive in oil technology, since the existence of an iron core, allows to reach the same impedance with a lower number of turns in a more “compact” and less costly equipment. Other aspects such as the possibility to have tertiary windings to feed auxiliary services (no need to have extra transformer for this purpose), the absence of need to have fencing to access control, are also examples of advantages of OIR.

The following sections of this work as well as their main content summary are presented in Table 1.

3.1 DESIGN ASPECTS

Single-phase shunt reactors may be observed in Figure 7 and Figure 8. Notice that ACR is much simpler than OIR. Other major differences are highlighted in the following sections.

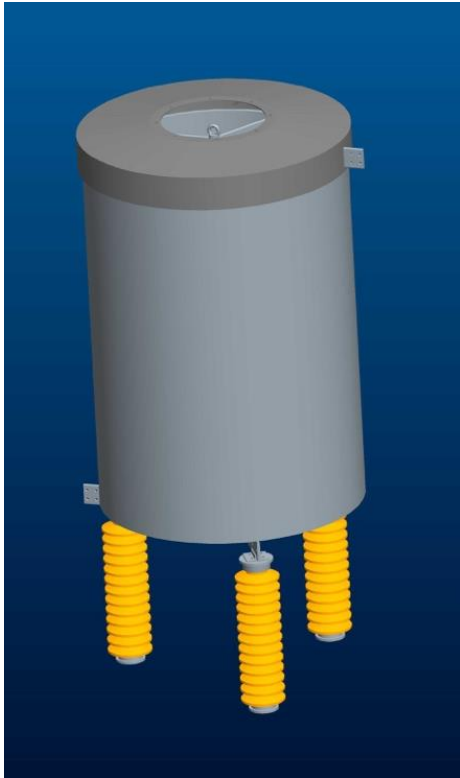


Figure 7 - Typical construction of ACR [11].

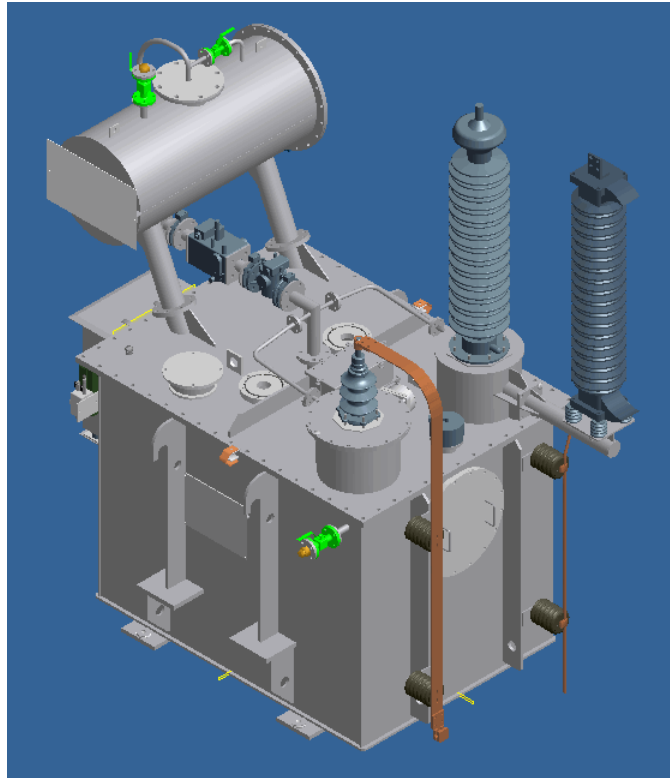


Figure 8 - Typical construction of OIR [11].

- **Dry-type Air core reactor (ACR)**

Typically, dry type air core reactors for shunt application are designed using fiberglass encapsulated construction. The winding consists of numerous insulated aluminum conductors, which are mechanically immobilized and encapsulated in epoxy impregnated fiberglass filaments, forming layers and then, cylinders. Depending on the reactor ratings, one or more cylinders may be connected in parallel between the aluminum spiders. The individual cylinders are separated by vertically oriented fiberglass spacers, forming cooling ducts for heat dissipation by means of air flow from the bottom to the top of winding. This construction allows the use of compact coils even for high inductance, reducing installation footprint.

Two technologies are commonly applied to shunt air core reactors: the Fiberglass Encapsulated Design and the Flat Transposed Cable design.

The construction of a fiberglass encapsulated design dry-type reactor, detailing its cylinders, formed by individually-insulated aluminum wires, assembled in layers (three layers in this example) can be seen in Figure 9. A cylinder is then formed by one or more layers of aluminum wiring (the reactor of this example is formed by four cylinders). This is the most common construction type for shunt reactors.

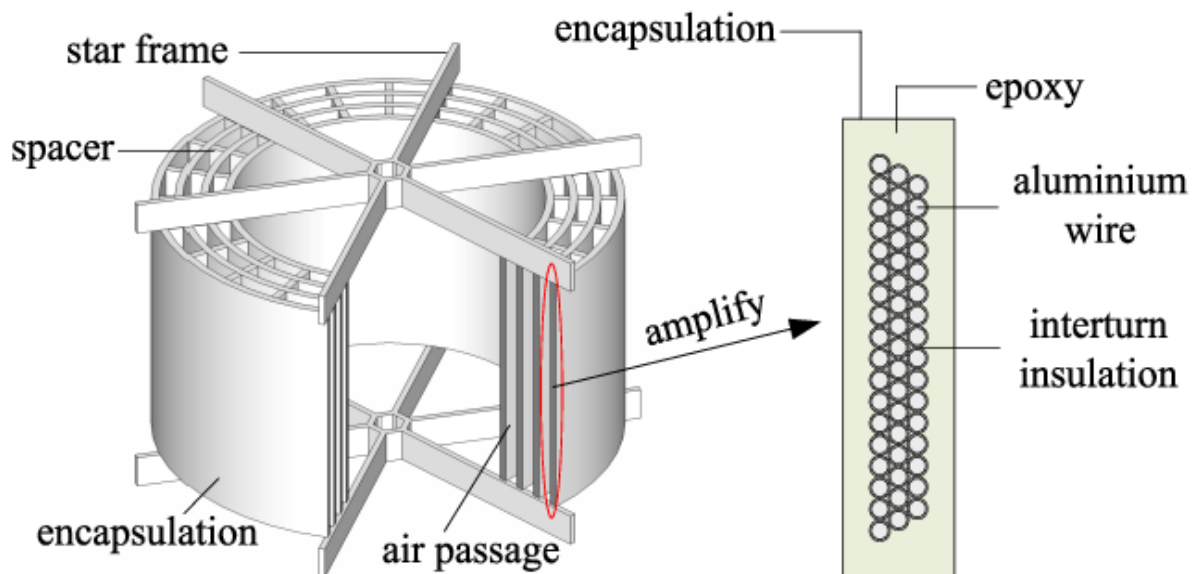


Figure 9 - Detail of Fiberglass Encapsulated Design dry-type air core reactor layers forming the cylinders, showing its turn-to-turn insulation and encapsulation [12].

In the other construction type used for shunt reactors (the flat transposed cable design), the layers formed by individually-insulated wires are replaced by transposed cables. This construction tends to reduce the losses and allow construction equivalent to the previous type with much more layers per cylinder (which is a challenge to the standard wiring type). This type may become a cost-effective solution specially to reactors where very low losses target should be guaranteed by reactor manufacturer. It is commonly referred to as “low-losses type”.

In Figure 10, it is possible to see the construction and how the transposition of the wires is done within the cable.

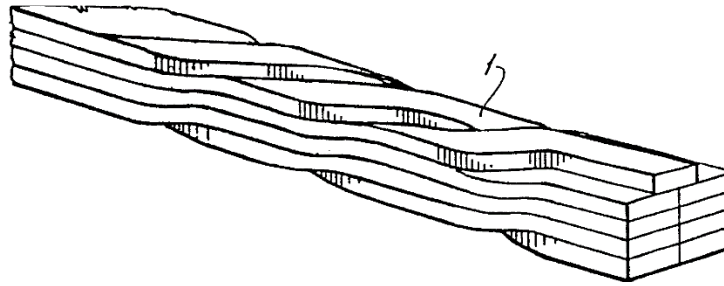


Figure 10 - Flat Transposed Cable design conductor [13].

Medium voltage shunt reactors are typically designed with a single coil per phase. For high voltage applications, the shunt reactors can be split into two or more coils in series per phase, to meet insulation requirements (dielectric creepage length).

A typical dry type air core reactor and its main parts, which are normally included in the standard scope of supply is presented in Figure 11. Other accessories may be part of the supply, upon demand and/or based on design criteria of the manufacturer, such as corona rings, top hats, elevating structures, line/grounding connectors, etc.

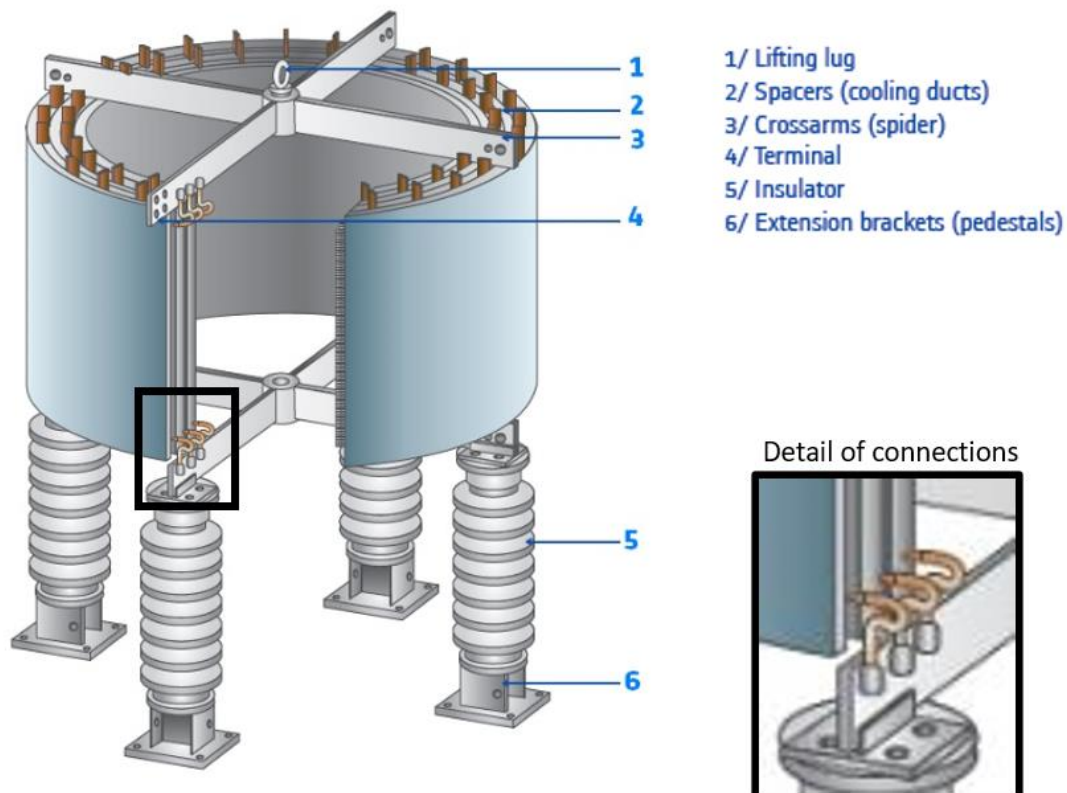


Figure 11 - Single phase air core reactor (main construction parts) [4].

- **Insulating materials**

The insulation of dry-type reactor windings depends on insulation class guaranteed. They can be typically B (hotspot 130 °C), F (hotspot 155 °C) or H (hotspot 180 °C) classes [14], being more common B or F classes. The higher the insulation class, the higher shall be the thermal index of insulating material.

Insulation is nowadays composed by polyurethane films, being common the use of PolyEthylene Terephthalate (PET), PolyEthylene Naphthalate (PEN) and/or Polyimide films (PI). The insulation system can be composed by one of these materials or a mix of them and can be divided into main system (intended to ensure proper dielectric properties, mainly against lightning and switching impulse waves, and secondary system, working as a shield to ensure mechanical protection to the main system. Multiple layers of films are then the common practice to reactor insulation.

The windings are encapsulated with fiberglass impregnated with resin, which is not intended to provide any **internal** turn-to-turn insulation, but to protect insulation system from external agents (mainly water, pollution and mechanical damage) as well as ensuring suitable **external** insulation between terminals, to maximum operating voltage.

- **Thermal class selection**

During thermal class selection, the most important is not the requirement of a specific thermal class, but the relationship between thermal index of insulation material and the operating temperature of the equipment (average temperature and hot-spot). In other words, the safety margin between the maximum temperature allowed for the material and the maximum operating temperatures expected for the equipment.

An example of insulated wire ready to be wound, composing reactor layers is shown in Figure 12.



Figure 12 - Example of wire with polyester film insulation [15].

A summary showing thermal index for each insulating material and the thermal class indication for each material is presented in Table 3. It is important to highlight that the PET film can be used to compose F class insulation system, however, as secondary insulation to protect the main one. The same applies to PEN film applied to H class insulation system.

Table 3 - Materials used in ACR construction and thermal class selection

Insulating material	Type of insulation	Continuous temperature	Thermal class indication [14]
PET film	Polyester film	+150 °C [16]	B (130 °C)
PEN film	Polyester film	+180 °C [17]	F (155 °C)
PI film	Polyester film	+260 °C [18]	H (180 °C)

Important: The thermal class indication refers to the main insulation. Continuous temperature index may be used as reference when the insulation is intended to be secondary insulation. Therefore, PET film may be used along with PEN film to compose F class insulation, for example, without risks to the equipment from thermal perspective.

- **Relative Humidity and Dielectric Withstanding**

Unlike OIRs, water vapor bubbles are not a concern to turn-to-turn insulation, due to the use of polyester films instead paper-based insulation. However, the manufacturer should construct the equipment in a way that the top part of windings (more exposed to water deposition), prevent the water to enter in the first part of the windings. This is very usual and not a challenge to the best manufacturers nowadays available in the market. This is advisable because the presence of humidity can slightly reduce dielectric withstanding of insulating films.

Notice however in Figure 13, that even in the presence of humidity, the reduction of dielectric withstanding is not very expressive (around 16% of reduction, varying the relative humidity from 20% to 80%), for films up to 50 μm , which is the practice for ACR. This reduction might be covered by safety margin applied by reactor manufacturer.

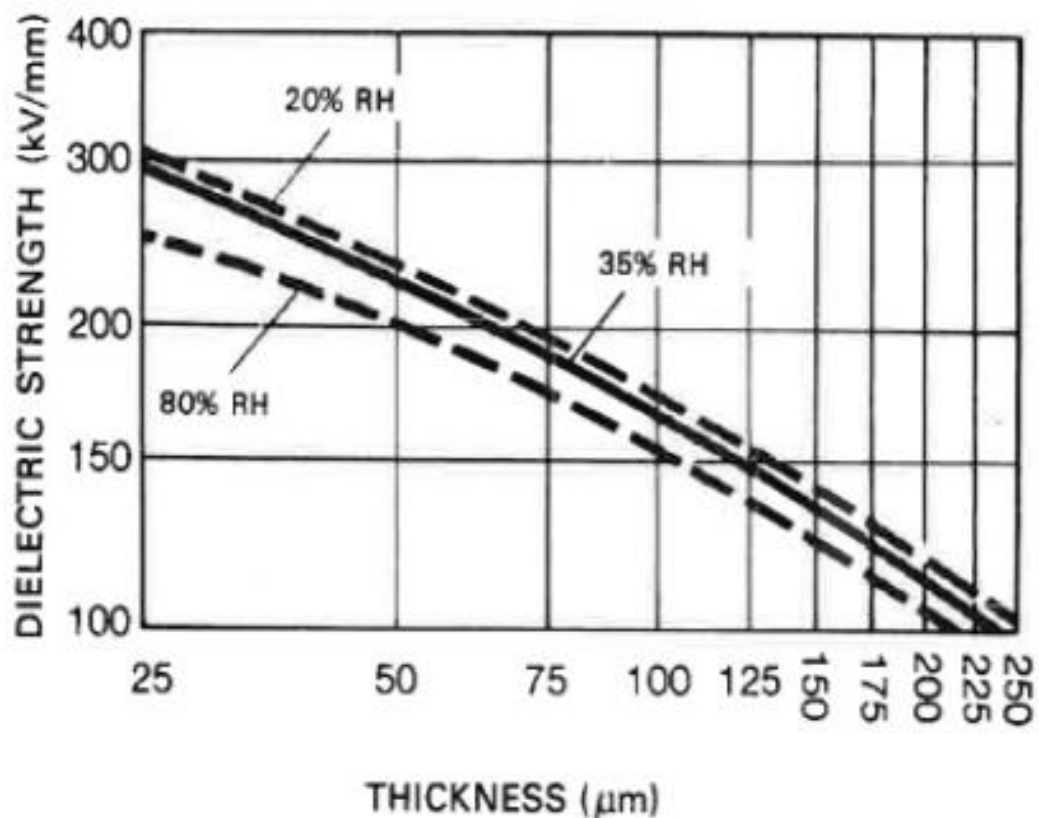


Figure 13 - Dielectric strength at Various Levels of Humidity for PET film [19].

- **Oil-immersed Iron-core reactors (OIR)**

Typically, oil-immersed reactors for shunt application are designed using a structure very similar to power transformers (both are often equipped with fans for cooling, for example), with some major differences. These can be core-less or with gapped iron core, which are installed within tanks that hold the oil and acts as metallic magnetic shields.

Oil-immersed reactors can be used within a wide range of voltages, being up to some years ago, the only solution for shunt reactors for voltages greater than 138 kV.

The typical single-phase oil-filled reactor is shown in Figure 14.

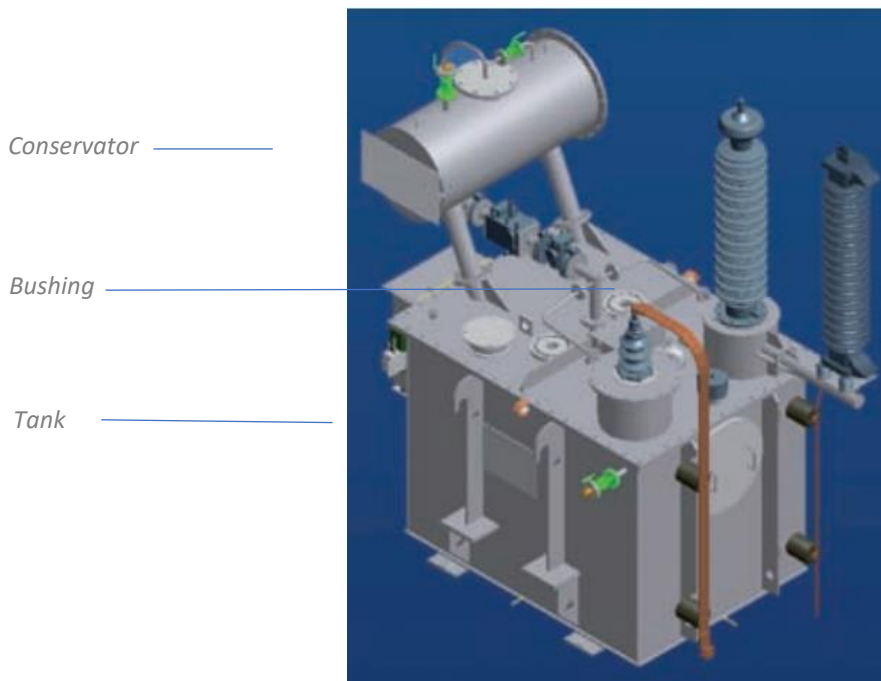


Figure 14 - Single phase oil-filled reactor (main construction parts) [11].

The magnetic structure of a one-phase gapped iron core with magnetic return circuit is shown in Figure 15.

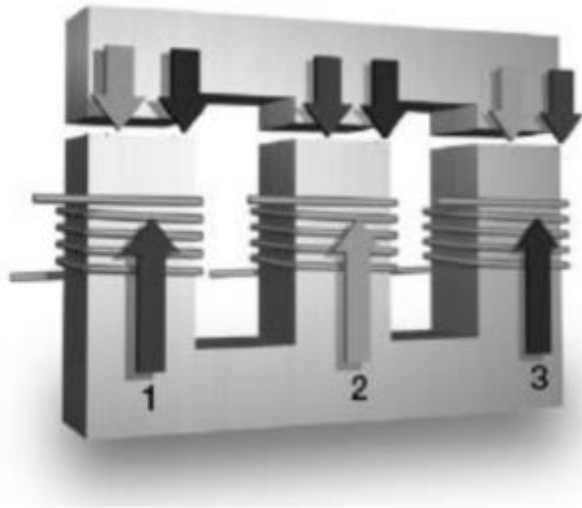


Figure 15 - Single phase oil-filled gapped iron core [20].

The magnetic structure of a three-phase gapped iron core with magnetic return circuit is shown in Figure 16.

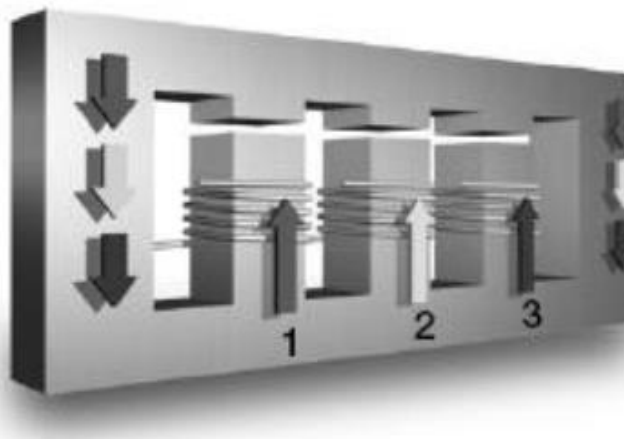


Figure 16 - Three phase oil-filled gapped iron core [20].

- **Relative Humidity and Dielectric Withstanding**

The excessive presence of water in paper insulation are a concern to the life of the OIR equipment. This happens because when the temperature increases, so do the water vapor bubbles, reducing dielectric properties on the material of the affected zone. This is more likely to occur when the hotspot temperature is above 140 °C [20].

An equilibrium chart relating water vapor pressure over oil to water concentration in insulation (kraft) paper vs. temperature for oil immersed reactors is shown in Figure 31. Notice that there is a huge variation on water vapor bubbles with the increase of temperature and humidity.

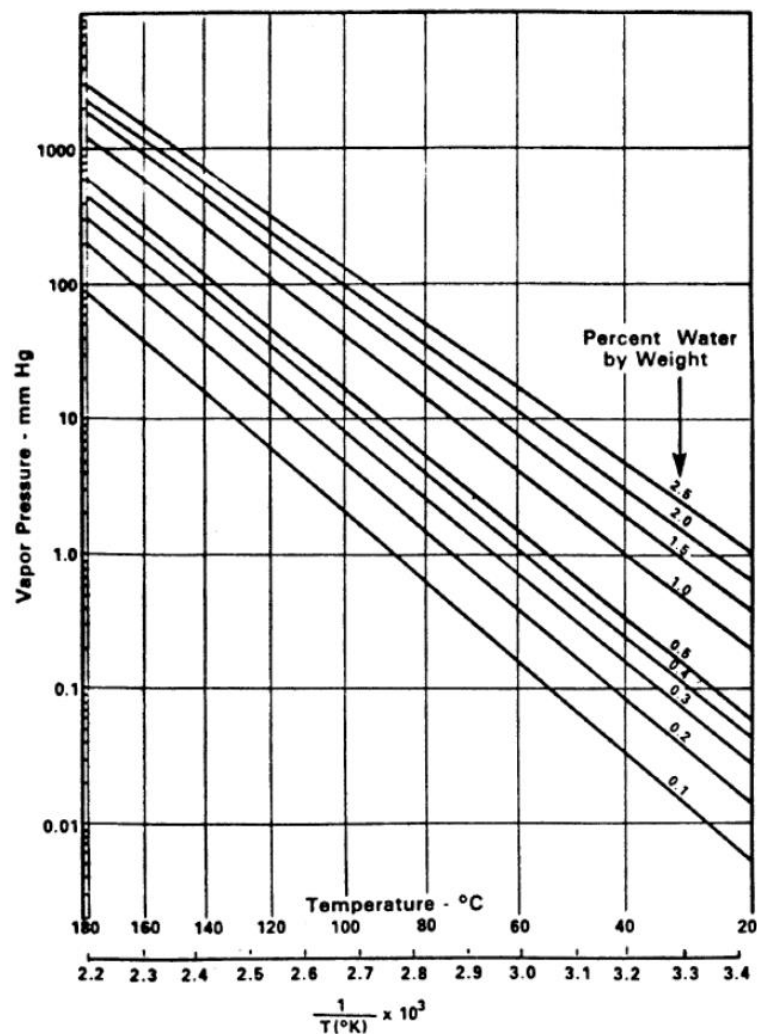


Figure 17 - Equilibrium chart relating water vapor pressure over oil to water concentration in insulation (kraft) paper vs. temperature [20].

A summary with the most advantageous aspect to each technology, in terms of design is presented in Table 4.

Table 4 - Advantages of each technology in terms of construction

Advantages	OIR	ACR
Simpler design	X	✓
Low impact of humidity on failure on turn-to-turn insulation	X	✓

3.2 OVERALL COSTS COMPARISON

Manufacturing costs and therefore, sales price, is strictly related to the reactor design aspects. It is known that air core reactors, due to their simplicity (does not require fans, oil, special built-in accessories, etc) tends to be cheaper than oil-immersed ones. However, there are some aspects that also play a role in terms of sales price of the equipment.

- **Costs related to the reactor design**

Recalling the fact that the reactor impedance and system voltage are the defining parameters for the current passing across the reactor (as per equations 7 and 8), and that the reactive power is proportional to the current square; for the same system voltage, the lower the impedance, the higher the reactive power.

For typical power levels for shunt reactor banks, air core reactors tend to be cheaper (due to the reasons above). This difference is even more expressive for the higher reactive power values and the reason is simple. Looking at the equation (14), used for inductance calculation of reactors coils [21], oil-immersed equipment can reach higher impedance values “easily” with a lower number of turns, what make them more competitive for very low reactive powers (not very common) when compared to air core reactors. This is truth since for this last technology, the absence of an iron core, makes harder to achieve very high inductance values, due to manufacturing limitations such as on height and diameter of the coils and the need to include more coils in series per phase to achieve the required impedance, for example.

The equation (14) can be used to calculate the self-inductance of a cylinder, which is the shape of power reactors [22].

$$L = 0.002\pi^2 \cdot \frac{2a^2}{b} N^2 \cdot K \quad (14)$$

Where:

L: inductance

a: mean radius of the coil windings

b: height of windings

N: number of turns

K: Nagaoka constant (to be obtained in the table reproduced at APPENDIX 1)

- **Costs related to the reactor accessories, installation and maintenance**

For typical reactive power values (specially for systems above 72.5 kV), the tendency to have cheaper ACRs for higher reactive powers tends to be even more expressive when including other associated costs linked to oil-immersed technology (fans, expansion oil-expansion tank, firewall, oil contention bay as well as other special requirements).

Moreover, when considering ACRs, spare parts are also cheaper, since it is possible to have only one replacement coil (half-phase, if each phase is composed by two coils in series, for example), instead the whole phase. For voltages up to 245kV, which is typically three-phase equipment for OIR, spare parts become even cheaper, since the comparison would be one coil (or one phase maximum) vs the whole three-phase equipment.

The replacement of a damaged coreless equipment is also faster, due to simple mounting (only standard bolts and without special parts) and reduced weight. This reduces non-availability costs, generally very expressive.

- **Losses Capitalization vs Loss target**

When a specific loss limit is not indicated by the purchaser, in general, a loss capitalization is given. An extra cost per kilowatt is given with tendering specification and is considered by the purchaser as an extra cost above sales price informed by the seller. Hence, equipment with two different guaranteed losses, can be compared considering the operational costs in long-term basis (with time, equipment with higher losses is more expensive since extra active power is dissipated). This is the most common practice adopted by customers worldwide.

The extra costs due to losses capitalization, that may (when applicable) be imposed to ACRs, in general (not a rule), are commonly compensated by the overall reduction on acquisition and O&M costs, obtained with the simplicity of the ACR (without oil, without special protection accessories, with cheaper transportation, faster assembling, commissioning and replacement, without oil-contention bay under the equipment nor firewall among the phases, etc).

A summary with the most advantageous situation to each technology, in terms of costs is shown in Table 5.

Table 5 - Advantages of each technology in terms of cost

Advantages	OIR	ACR
Low impact on equipment costs due to bank ratings	✓	X
Cheaper spare parts (no need of full equipment)	X	✓
Cheaper transportation	X	✓
Cheaper operation & maintenance	X	✓

3.3 LOSSES

Both equipment technologies may present the same losses value, being possible to state that they are similar on this regard. However, some aspects may impact in different ways on the design and on losses for both equipment types.

- **Ohmic losses**

Shunt reactor losses are intimately linked to the wiring length and cross-section area of the conductors. Therefore, ACR tends to present higher losses, since the absence of an iron-core, increases the number of turns required to reach the same inductance. However, this can be adjusted by ACR manufacturer by increasing wiring diameter and/or number of wires in parallel, which also reduces the temperature rise of the reactor. When the loss target value is very low, the equipment tends to operate “colder” (depending on its ratings), far from its thermal class limits, resulting in a less competitive design of ACR compared to OIR.

Other factors that impact the design of ACR are the ratings of the bank (specially the voltage and rated power). For the same voltage level, banks with higher rated powers requires lower inductances (power depends on square of current). Lower inductances result in lower number of turns, lower wiring length and lower ohmic losses, reducing the chances to be needed to increase cross-section area of the equipment to achieve a specific loss target. For these cases, in general, the design limitation tends to be the temperature rise of the equipment, resulting in a more competitive design of ACR compared to OIR, since the total quantity of conductor (quantity/mass of aluminum, for example), would be reduced, reducing overall costs of ACR. OIR is less affected by this parameter, since it can reach the required inductance “easily” due to the presence of the iron core.

Typically (not a rule), for systems above 138 kV, dry-type reactor banks tend to be more competitive for rated powers above 15 Mvar.

- **Additional losses**

Other losses may impact on overall losses of the equipment. For ACRs, these losses include mainly induced losses on metallic parts, losses due to skin effect as well as losses on other accessories. For OIRs, these losses include mainly induced losses on metallic parts, losses due to skin effect, losses on the iron core as well as losses on other accessories (fans, etc). Skin-effect losses can be considered to be very low to both types, since pellicular effected is more applicable to higher frequencies (negligible to shunt reactors).

A summary with the most advantageous situation to each technology, in terms of design and losses is presented in Table 6.

Table 6 - Advantages of each technology in terms of design and losses

Advantages	OIR	ACR
Losses ^a	✓	✓
Optimized design for banks with high rated power without losses limitation	✓	✓
Optimized design for banks with low rated power without losses limitation	✓	✓
Optimized design for banks with high rated power with losses limitation	✓	✓
Optimized design for banks with low rated power with losses limitation	✓	X

^a. Despite ACR tend to present higher losses when both are designed in the limit of their thermal class (not a rule, depending on bank ratings), this was considered to be similar, since ACR manufacturer can increase cross section area of windings to have the same losses of OIR.

3.4 MAGNETIC FIELD ASPECTS

Due to the absence of an iron core and a magnetic shield surrounding the coils, dry-type air-core reactors have a stray magnetic field that can be found at significant values beyond the equipment boundaries. Hence, when dealing with air-core reactors, further precautions related to the health of personnel and general public and with the impact of these magnetic induction on nearby equipment at the substation, shall be taken.

3.4.1 Clearance between reactor and nearby metallic structures

- **Oil-immersed Iron-core reactors (OIR)**

Oil immersed reactors have an iron core that constrains the magnetic field, which reduces the stray magnetic fields considerably. Moreover, they have an outer metallic shield surrounding the windings, which helps to confine the magnetic field lines to limits within the equipment. Hence, this precaution is not applicable.

- **Dry-type Air core reactor (ACR)**

Considering the fact that air-core reactors have magnetic field lines that are not constrained into an iron-core, some simple precautions must be taken to avoid stray magnetic field lines to reach nearby metallic parts (grounding grids, reinforcement of foundation concrete, etc), which can cause voltage induction and, in case of a closed loop or large metallic part (even not forming closed loops), significant induced current, resulting in temperature rise on these metallic parts and the increase on the reactor losses.

Some rules of thumb have been used to have a rough idea about suitable clearances to avoid the undesirable induction effects associated with the wrong installation of such equipment. These rules are [23]:

- Clearance to small metallic parts not forming closed loops should be at least half outer diameter of the equipment ($0.5 \cdot D_s$). This clearance is commonly known as Magnetic Clearance 1, or just MC1.
- Clearance to large metallic parts or small metallic parts forming closed loops should be one outer diameter from all the surfaces of the equipment ($1.0 \cdot D_s$). This clearance is commonly known as Magnetic Clearance 2, or just MC2.

The representation of the rules of thumb, with approximate clearances given by [23] is presented in Figure 18.

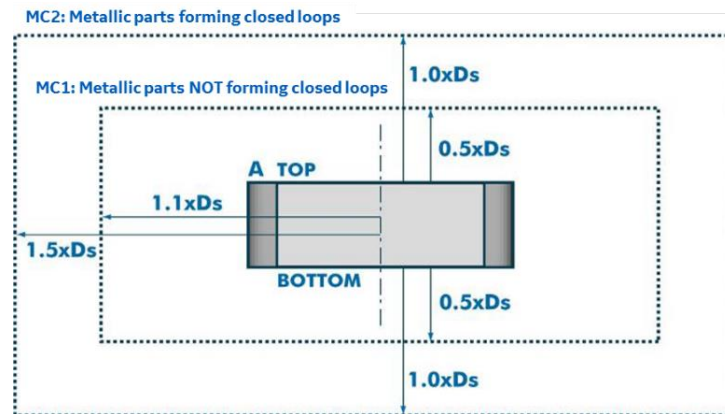


Figure 18 - Typical magnetic clearances for ACR as per [30].

These clearances should be taken into account when defining the electromechanical design of the substation, to determine the minimum distance the coil should be from other metallic parts, from a magnetic point of view.

If the clearance between bottom part of reactor and the foundation is below MC1, no metallic parts are allowed. In this case, Glass Fiber Reinforced Polymer (GFRP) rebars should be used as reinforcement to the foundation concrete, avoiding issues related to induction. An illustration of this use is shown in Figure 19.

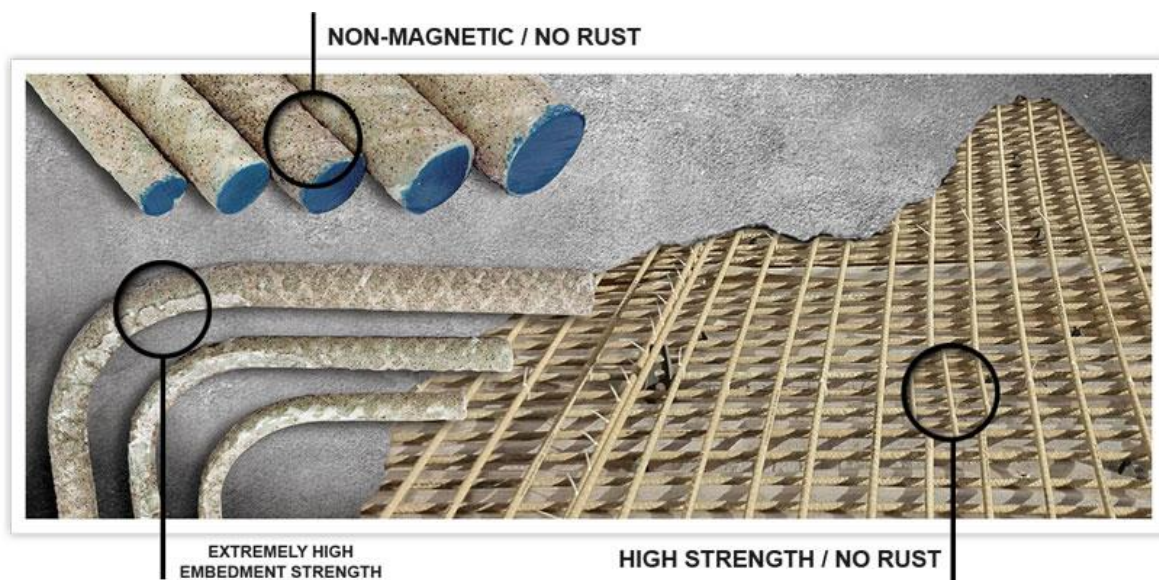


Figure 19 - Example of non-metallic rebars (with GFRP) for foundation concrete (for clearances below MC1) [24].

If the clearance between bottom part of reactor and the foundation is above MC1 but below MC2, standard metallic rebars could be used, but they should be insulated to avoid closed loops (consequently induced currents). An example of this insulation can be seen in Figure 20.



Figure 20 - Example of insulated metallic rebars (for clearances between MC1 and MC2) [25].

For clearances above MC2, no special care should be taken to avoid current induction.

Nowadays, manufacturers have more precise criteria to determine accurate magnetic clearances based on magnetic field intensity and the reactor application, according to their manufacturing expertise. For shunt reactors, typical values of magnetic field intensity are around $3500 \mu\text{T}_{\text{RMS}}$ for MC1 and $11000 \mu\text{T}_{\text{RMS}}$ for MC2.

Field intensities may be calculated by using Biot-Savart's law [26]. The equation (13) is valid for coils with a winding height shorter than three times the winding diameter. For these cases, the external magnetic field of air-core reactor winding, outside the coil, may be approximated by the field of a current loop [26].

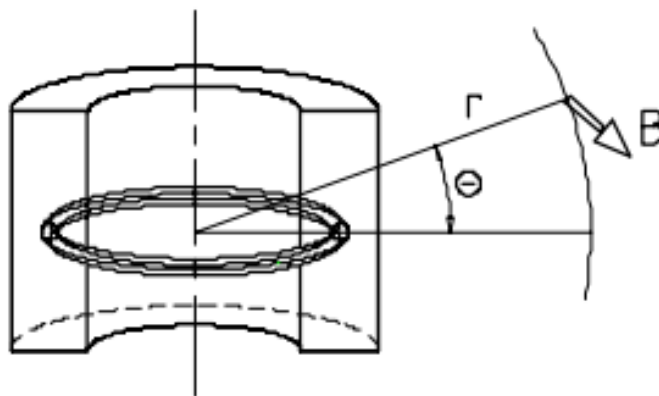


Figure 21 - Reference for coordinates of magnetic field calculation [26].

$$|B| = \frac{\mu_0 \cdot n \cdot I \cdot D^2}{8 \cdot r^3} \sqrt{\sin_*^2(\theta) + \frac{\cos_*^2(\theta)}{4}} \quad (13)$$

Where:

$|B|$ = magnitude of the magnetic field

μ_0 = permeability in air ($\mu_0 = 4\pi \cdot 10^{-7}$ H/m)

n = number of turns

I = current

D = winding diameter

r, θ = polar coordinates

It can be noticed from the equation (13) that the magnetic field of an air-core reactors quickly decays with third power of distance, since coils have magnetic dipole characteristic.

It is worth mentioning that the reactor manufacturer is the responsible to determine these clearances and is the best source to guide the contractor in case of a specific analysis or requirement.

3.4.2 Exposition limits for humans

Biological effects of exposure to low frequency electromagnetic fields have been reviewed by the International Agency for Research on Cancer (IARC), International Commission on non-ionizing Radiation Protection (ICNIRP), and the World Health Organization (WHO) (IARC 2002; ICNIRP 2003a; WHO 2007a) and expert groups.

The World Health Organization says that the limits of safety to the exposure to the electric and magnetic fields known today are a guideline limit (not a precise delineation between safety and hazard). There is no level above which exposures become hazardous to health; instead, the potential risk to human health gradually increases with higher exposure levels. Guidelines indicate that, below a given threshold, electromagnetic field exposure is safe according to scientific knowledge. However, it does not automatically follow that, above the given limit, exposure is harmful [27].

The guidelines adopted by WHO are the ones from ICNIRP. To be able to set the limits on exposure, scientific studies need to identify the threshold level at which first health effects become apparent. Animal experiments are conducted to this end, where abnormal behavior is monitored as a very sensitive indicator of a biological response to the exposure of electromagnetic fields, defining the levels at which behavioral changes become noticeable [27].

The threshold obtained during animal tests is not equal to the guideline limit. ICNIRP applies a safety factor of 10 to derive occupational exposure limits, and a factor of 50 to obtain the guideline

value for the general public. Therefore, for example, in the radiofrequency and microwave frequency ranges, the maximum levels you might experience in the environment or in your home are at least 50 times lower than the threshold level at which first behavioral changes in animals become apparent [27].

In Brazil, WHO recommendations, and consequently ICNIRP, have been established as practice by Brazilian Electricity Regulatory Agency – ANEEL, through its Normative Resolution Nr 915, of February 23rd 2021 [28].

Actual limits can be consulted in ICNIRP guidelines (latest edition published in 2010 up to date) [29]. These guidelines establish safe limits for both occupational and general publics in terms of electric and magnetic field exposures. These limits also aim to protect general public with special health needs, such as pacemakers for example, that could have their performance affected by strong magnetic field intensities.

The guidelines also provide guidance to evaluate the effect of harmonic currents on the equipment, which should be evaluated carefully in case where the equipment is subjected to these currents (Harmonic filter and Thyristor-Controlled Reactors - TCR, for example). For non-controlled shunt reactors however, harmonics currents are negligible since they face a high-impedance path on the reactor branch ($X = \omega L$).

It is common practice to call occupational public clearance as Magnetic Clearance 3 (MC3) and general public clearance as Magnetic Clearance 4 (MC4), following the standardized naming for clearances to metallic parts (MC1 and MC2).

The general limits of magnetic field for shunt reactors (only 50/60Hz content) as per WHO and ICNIRP are presented in Table 7.

Table 7 - General limits of magnetic field for shunt reactors (only 50/60Hz content) as per WHO and ICNIRP

	Magnetic Field (μT) ^a	
	50Hz	60Hz
Occupational public (MC3)	1000.00	1000.00
General public (MC4)	200.00	200.00

^aValues in rms.

The limits established for low-frequency currents (50/60 Hz) shall be taken into account to define fencing location, imposing access and circulation control, to respect these requirements for both occupational and general public.

A representation of magnetic field surrounding a human body is presented in Figure 22.

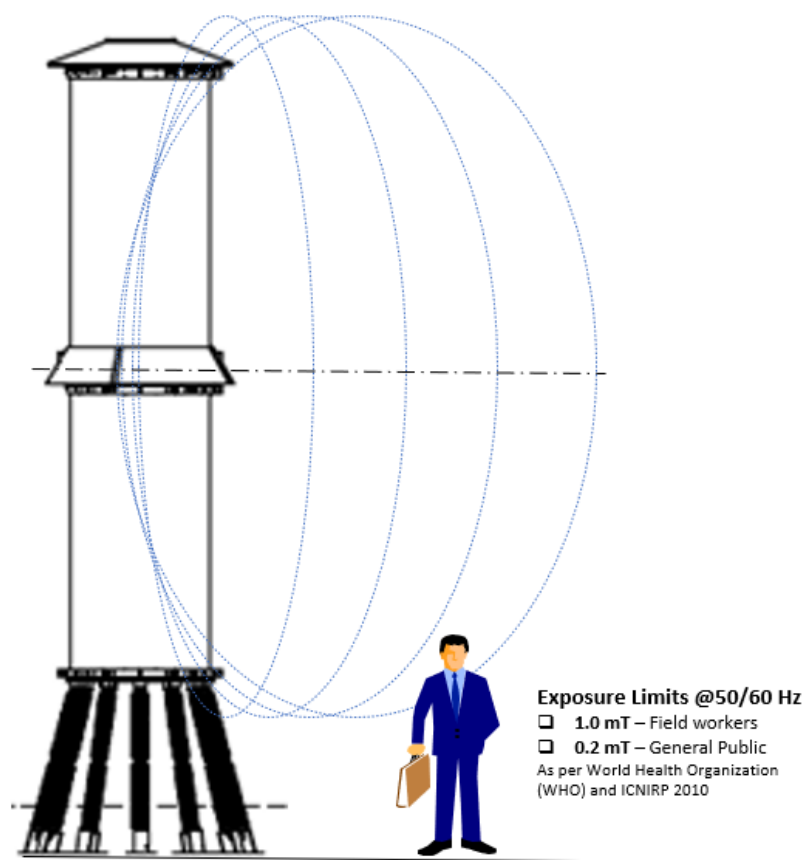


Figure 22 - Representation of magnetic field of ACR on human body [image of GE ownership].

A plot example of two regions of magnetic fields (top view for three-phase installation) is presented in Figure 23. Green line represents a magnetic field region with lower magnetic field intensity and blue line (nearer the reactor), represents a magnetic field region with higher field intensity. To comply with ICNIRP guidelines, a similar plot should be performed to each project, showing the regions equivalent to $1.0 \text{ mT}_{\text{RMS}}$ (MC3 / workers) and $0.1 \text{ mT}_{\text{RMS}}$ (MC4 / general public).

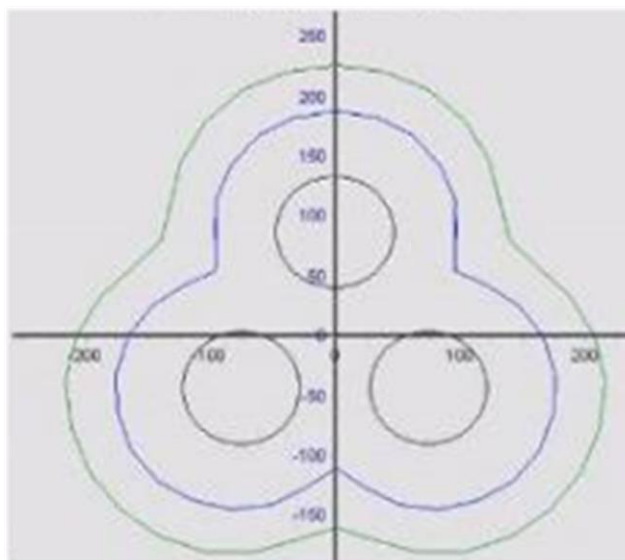


Figure 23 – Plot example of two regions of magnetic fields (top view for three-phase installation) [30].

The advantages for each technology are pointed out in Table 8, with regards to magnetic field aspects.

Table 8 - Summary of advantages comparing both technologies

Advantage	OIR	ACR
Lower magnetic field lines spread on area surrounding the equipment and reduced distance from the reactor to occupational and general public	✓	X
MC1 clearance: no need of calculation and precautions (foundation and metallic parts nearby the reactor)	✓	X
MC2 clearance: no need of calculation and precautions (foundation and metallic parts nearby the reactor)	✓	X
MC3 clearance: no need of calculation and precautions (installation area and fencing for access control)	✓	X
MC4 clearance: no need of calculation and precautions (installation area and fencing for access control)	✓	X

3.5 MAINTENANCE

The maintenance of dry-type reactor is simplified when compared to oil-filled equipment. The main divergences found to both types are presented in Table 9.

Table 9 - Typical maintenance requirements

Advantage	OIR	ACR
Faster and cheaper replacement in case of failure	X	✓
No need to clean and lubricate radiators and cooling system	X	✓
No need to perform tank inspection	X	✓
No need to check core insulation resistance	X	✓
No need to clean conservator from inside (typically every three years)	X	✓
No need to check insulation resistance (typically every 6 months)	X	✓
No need to dehydrate the silica gel of the breather	X	✓
No need to perform oil level checking	X	✓
No need to perform oil BDV (break down voltage) & acidity checking at regular intervals.	X	✓
No need to perform filtration to remove sludge, dust, dirt and moisture	X	✓
No need to inspect with thermal camera	✓	X

Notice that many requirements applied to OIR are not applicable to ACR.

3.6 INSTALLATION ASPECTS

The required area for installation of air core shunt reactor banks is similar to the area required for oil-immersed reactors. Examples of air core and oil-immersed reactor installations are presented in Figure 24, Figure 25 and Figure 26.



Figure 24 - Installation layout for air core three-phase shunt reactor [4].

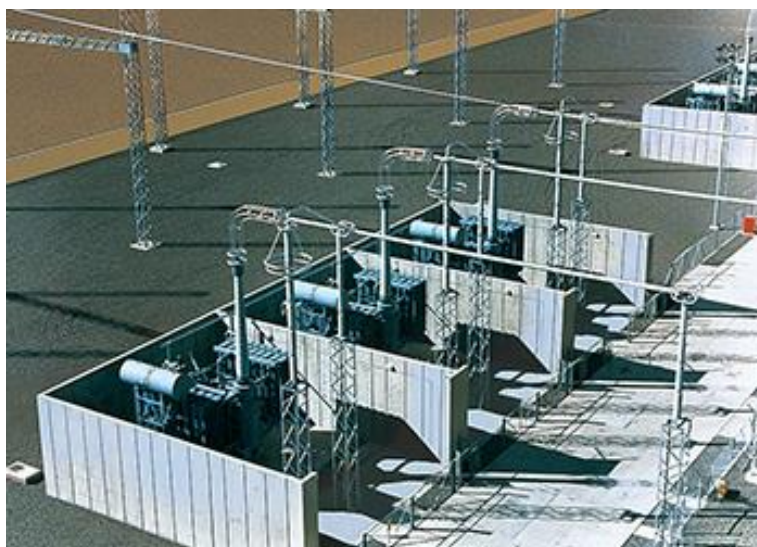


Figure 25 - Installation layout for three oil-filled single-phase shunt reactors [31].

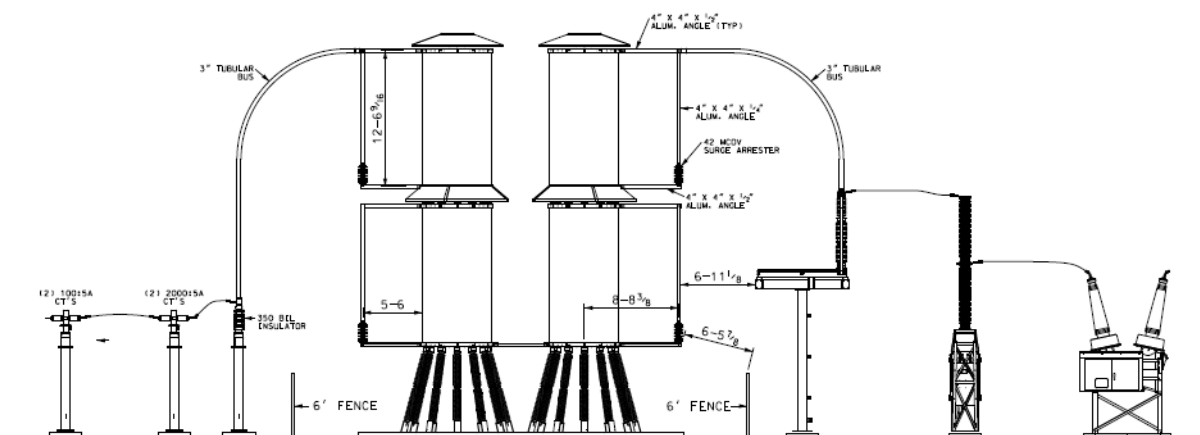


Figure 26 - 345 kV / 55 Mvar drawings and substation layout [image of GE ownership].

A dimensional comparison between both technologies is shown in Figure 27. Notice that ACRs tend to be slightly higher, but in general, both present similar installation area on substation footprint.

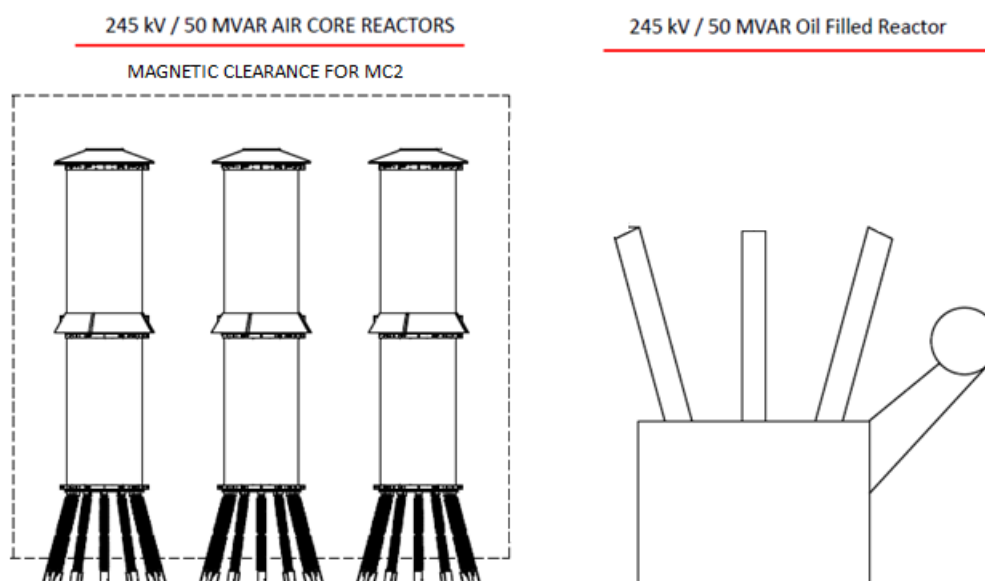


Figure 27 - Overall dimensions comparison between ACR and OIR [image of GE ownership].

A summary with the most advantageous situation to each technology, in terms of installation is presented in Table 10.

Table 10 - Advantages of each technology in terms of installation

Advantages	OIR	ACR
Lower mass and simplified foundation (no need of oil retention base)	X	✓
No need of fire wall	X	✓
Simpler and faster erection & commissioning	X	✓
Lower noise levels	X	✓
Safety for personnel ^a	✓	✓
Installation area ^b	✓	✓
Lower magnetic field lines spread on area surrounding the equipment and reduced distance from the reactor to occupational and general public ^c	✓	X
Possibility to approach the equipment for visual inspection when energized	✓	X
No need of access control fences (live parts not accessible)	✓	X
Availability of tertiary windings for auxiliary services available under request (no need of extra equipment to this end)	✓	X

^a. Equal since suitable access control is considered for air-core reactors.

^b. Despite installation area is similar to both technologies, when the access control fencing (required to ACR) is included in the comparison, ACR installation area tends to be slightly higher, which may be an issue for substations with very restricted installation area.

^c. In substations where the installation of the reactor is intended to be close to general public sidewalks and/or very close to control room and worker circulation areas, the use of ACR may not be recommended (to be checked case by case), since the spread of magnetic field lines (not existing for OIR), may require this equipment to be installed farther from such areas.

3.7 PROTECTION

In most applications of shunt reactors in High Voltage (HV) and Extra High Voltage (EHV) systems, the star points of the reactors are connected to earth, whereas Medium Voltage (MV) shunt reactors are generally not grounded. This work focuses on HV and EHV reactors, bus and line shunt connections, solidly earthed or earthed throughout an impedance (which is the practice for these systems). Shunt reactors should be equipped with over-current and earth fault protection monitoring the line side current. In cases where the reactors are connected to the tertiary winding of a transformer (Medium Voltage reactors), it is most likely that the reactor feeder is included in the transformer differential protection. Differential protection of the reactor can be achieved by splitting each phase into two legs and monitoring the unbalance current in the star point. This method provides extremely fast and sensitive protection of the reactor windings, especially in terms of inter-

turn faults but requires special design (split-phase reactors), which are not possible for many ratings of HV and EHV shunt reactors.

The main hazards and general protection requirements to be observed when protecting a shunt reactor are [20]:

- Bushing and insulation failures, protecting for internal faults to ground as well as to phase-to-phase faults;
- Turn-to-turn and partial discharge faults;
- Other failures such as low oil, high temperature on oil and winding, loss of cooling, etc), when applicable.

The proposed protection scheme should also [20]:

- Prevent false tripping events during switching and external faults;
- Provide suitable breaker failure and pole discrepancy protection;
- Prevent rupture of the reactor tank (for OIR).

The protection scheme is deeply dependent on the layout of the equipment and its use (for the purpose of this work, whether for line or bus configuration), since many aspects related to this use shall be taken into account when defining the suitable relaying sets [20]. However, this work focuses mainly on general protection aspects, with the main differences for both technologies.

- **Typical Single Line Diagram (SLD) for line/bus shunt reactors with associated Instrument Transformers (ITs)**

Typical SLDs of HV Shunt reactor are presented in Figure 28 and Figure 29, being very similar to both technologies. The main difference is that for standard protection of OIRs, distance protection (relay 21) is not commonly used. Therefore, HV voltage transformer signal is not required to such systems, what could lead to a cost reduction associated to Instrument Transformers. For ACRs, unless the relay manufacture indicates a more suitable function to accomplish with turn-to-turn fault protection in a reliable way, the use of distance relay (requiring therefore the HV voltage transformer signal), is strongly recommended.

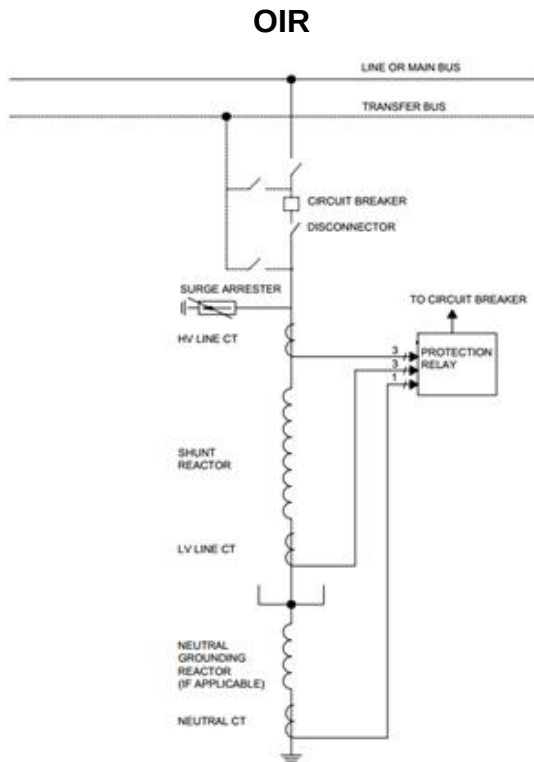


Figure 28 - Typical Single Line Diagram (SLD) for line/bus OIR shunt reactors with associated Instrument Transformers (ITs) [Image of GE ownership].

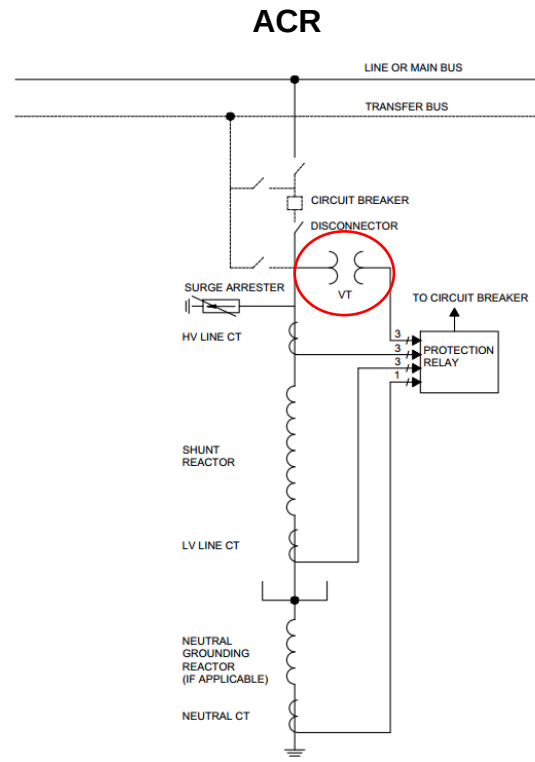


Figure 29 - Typical Single Line Diagram (SLD) for line/bus ACR shunt reactors with associated Instrument Transformers (ITs) [Image of GE ownership].

• Typical protection relays

The protection of oil immersed reactors is similar to the one of power transformers at no load condition. However, the parallel is not so obvious when comparing oil-filled to dry-type equipment. At the same time that the many failure modes are much less likely to occur at the air-core, some protections are not possible on this technology such as turn-to-turn protection using sudden pressure or Buchholz relaying (these devices do not exist in the dry-type) [20].

Whether or not to use redundant or backup protection is a matter of user choice and depends upon factors such as:

- The importance of the particular reactor installation to the electric grid system.
- The cost of the reactor equipment.
- Any special design likely to be more susceptible to certain faults.
- The need to disable the Main 1 (Primary) protection system and maintain full protection on a second protection system while the reactor remains in service.

Most oil-immersed reactors are probably worthy of redundant (Main 1 and Main 2) or at least limited backup protection in addition to a complement of full protection. Many utilities use two

redundant systems to protect their power reactors by having also separate DC supplies, CT windings, and trip coils.

Typical relays used to both technologies are shown in Table 11. Afterwards, a parallel is established, showing the main protection relays used to comply with each failure mode shown in Figure 30.

Table 11 - Main protections to bus/line reactors

ANSI Nr	Name
87R	Reactor phase differential protection
REF, 87N or 67REF	Restricted earth fault protection
50	Instantaneous overcurrent protection
51	Time delayed overcurrent protection
50N	Neutral instantaneous overcurrent protection
51N	Neutral Time delayed overcurrent protection
21	Distance protection
63	Buchholz protection / Sudden pressure relay
49	Thermal overload protection

- **Failure modes of HV and EHV shunt reactors**

The possibilities of faults within a reactor zone can be seen in Figure 30, based on their location. They can be outside the equipment enclosure (between phases and phase-to-ground, “1” and “2” in Figure 30) or inside the enclosure (winding-to-ground near the phase, between phases, winding-to-ground near the neutral and turn-to-turn on individual phases, “3”, “4”, “5” and “6” in Figure 30, respectively) [9].

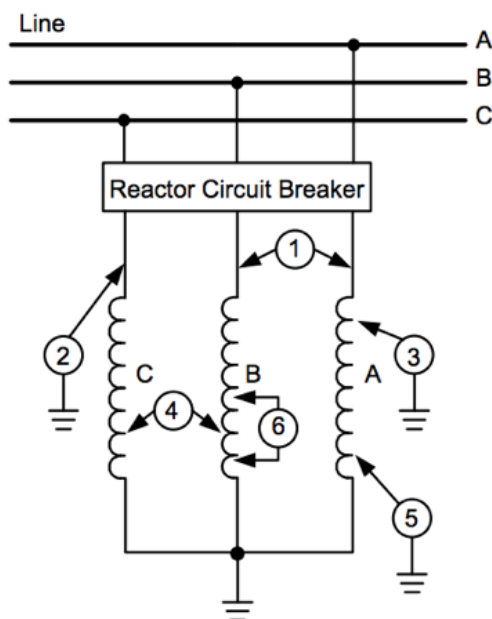


Figure 30 - Failure modes possibilities on shunt reactors [9].

Despite the above-mentioned possibilities of faults in a shunt reactor, the construction technology influences a lot in the probability of incidence of certain faults.

- **Summary of protection relays for typical failure modes of HV and EHV shunt reactors**

A summary of failure modes shown on Figure 30 can be seen in Table 12, with the probability of each mode as well as a comparison of typical protection relays used to both technologies. Notice that most failures are more likely to occur on OIR due to its physical construction.

Table 12 - Failure modes (location and probability)

		OIR Line/Bus				ACR Line/Bus		
Fault		Location	Probability	Main ^f	Backup ^f	Probability	Main ^f	Backup ^f
1	Between phases	Outside enclosure	High	87R	50/51 ^a	Low	87R	50/51 ^a
2	Phase-to-ground	Outside enclosure	High	87R, REF ^b	50/51, 50/51N	Low	87R, REF ^b	50/51, 50/51N
3	Winding-to-ground near the phase	Inside enclosure	High	87R, REF ^b	50/51, 50/51N	Low	87R, REF ^b	50/51, 50/51N

4	Between phases	Inside enclosure	High	87R	50/51 ^a	Low	87R	50/51 ^a
5	Winding-to-ground near the neutral	Inside enclosure	High	REF ^{b c}	50/51N	Low	REF ^{b c}	50/51N
6	Turn-to-turn	Inside enclosure	High	63	51N or 21	High	21	51N
-	Over temperature of insulating oil	Inside enclosure	High	49 ^d	-	N/A	N/A	-
-	Over temperature of windings	Inside enclosure	High	49 ^e	-	High	N/A ^e	-
-	Pressure relief	Inside enclosure	High	63	-	N/A	N/A	-
-	Loss of cooling	Outside enclosure	High	49	-	N/A	N/A	-

a. Distance relay (21) may also be used as backup if voltage signal is available [20].

b. Restricted Ground Fault (REF) function (also known as 87N or 64REF) may also be used to detect internal phase-to-ground faults. It is also based on differential current principle but comparing residual currents between terminal side and in the neutral to ground connection [20].

c. Very low magnitudes of fault such as phase-to-ground near the neutral do not sensitize 87R relay. REF is usually used as a more sensitive protection to this failure mode.

d. Performed by reading the temperature sensor (typically Pt100 Ω at 0 °C), which indicates the temperature locally and remotely through analogue outputs (e.g., 4-20 mA) or through a communication protocol (e.g., DNP3.0 or IEC 61850) [20].

e. Performed by reading the current and using relay 49 at thermal image protection method, where the current is measured and the hot/cold thermal time constant of the equipment is set in the relay. This allows the relay to predict the expected temperature and alarm/trip in case it exceeds. For shunt ACR, it is atypical the use of this function, but could be used as backup of 50/51 functions, specially to protect the equipment against severe turn-to-turn faults, which could lead to a phase-to-phase fault, increasing the current and temperature.

f. Other relays may be used to compose protection scheme.

- **Faults 1 and 4 – Between phases (Outside and Inside the equipment enclosure)**

This fault produces very high fault currents, especially between the circuit breaker and the reactor bushings, being more likely to occur on three-phase oil immersed reactors (typically up to 245 kV). Phase-to-phase faults are not likely to occur in dry-type reactors when the configuration is that of single-phase units arranged with suitable separation between phases [32] (which is usually the case). However, even being unlike to such reactors, with the need of voltage and current signals from HV-side to feed distance relay (21), the use of 87R relay would not require any extra equipment, since the phase CTs on HV side would already be available, not imposing extra costs to the protection solution. Therefore, it is common practice to protect both technologies in the same way.

- **Fault 2, 3 and 5 – Phase-to-ground (Outside and Inside the enclosure)**

The magnitude of this fault depends on its location. In this case, near the phase, the magnitude is generally high (there is less impedance in the circuit to limit the fault current level) [9].

In oil-immersed reactors, this fault is more likely to occur since the ground level on the enclosure is surrounding the equipment, increasing the proximity to the core and tank [20, 33] as well as live part of bushings and tank.

Dry-type reactors are insulated from ground by insulators, which provide very effective and reliable insulation to ground [9]. This fault is therefore unlikely to occur in this type of reactor. This is also reinforced in [32], which states that these support insulators provide standard clearances to ground, being faults to ground unlikely to occur without unusual circumstances such as when an animal bridges the insulation to ground. However, when talking about reactor above 245 kV for example, the insulator height is at least 1900mm (for minimum BIL of 850 kV, according to IEC 60071 and IEC 60273 standards), which decreases the chances to have a short-circuit of this type.

Notice that for fault 5, 87R relay is not listed as main protection. This is because a remarkably high impedance of the reactor before the fault may prevent this relay to be sensitized, being REF (also called 87N or 64REF), a much more sensitive relay to this end.

- **Fault 6 – Turn-to-turn**

Turn-to-turn faults are a challenge to protection Engineers, since faults of this type initially presents a small magnitude, reducing the impedance of the faulted phase and causing a corresponding increase in the phase current. This disrupts the three-phase symmetry of the terminal

currents, resulting in zero-sequence unbalance currents flowing through the neutral to ground. Although the change in phase current can be very small, the current in the faulted turns increases the operating temperature and, in case of oil-immersed reactor, also the pressure inside the tank. This effect can be detected by nonelectrical protection devices such as the Buchholz / pressure relay (63) [9] for OIR or by distance relay (21), being both equivalent in terms of fault detection.

In the past, this type of failure on oil-immersed equipment used to be related to poor quality in the insulating oil available in the market. Nowadays, this is no longer true since there are good oils available with proved reliability. However, factors such as vibration (which causes mechanical fatigue on insulating materials) as well as the excessive presence of water in paper insulation are still a concern to the life of the equipment. This last phenomenon happens because when the temperature increases, so do the water vapor bubbles, reducing dielectric properties on the material of the affected zone. This is more likely to occur when the hotspot temperature is above 140 °C [20].

An equilibrium chart relating water vapor pressure over oil to water concentration in insulation (kraft) paper vs. temperature for oil immersed reactors is shown Figure 31.

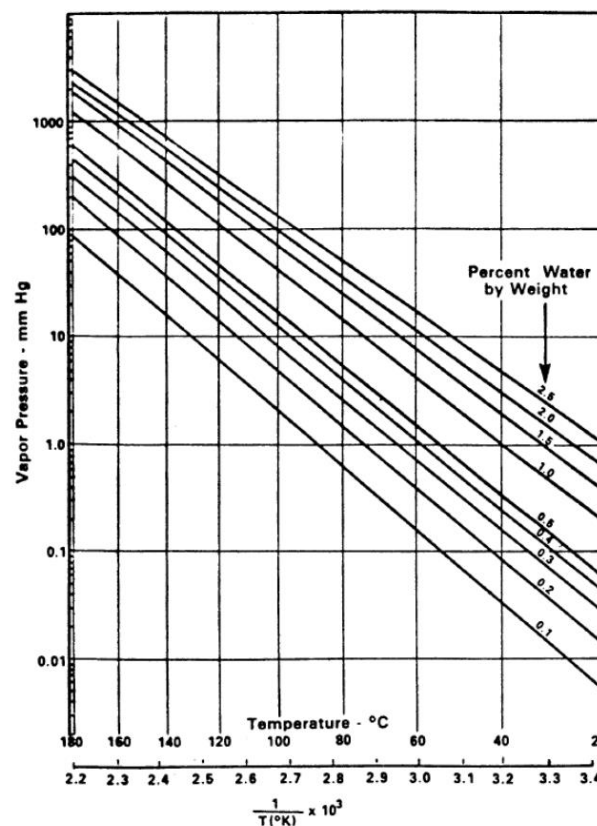


Figure 31 - Equilibrium chart relating water vapor pressure over oil to water concentration in insulation (kraft) paper vs. temperature [20].

Dry-type reactors do not suffer with poor-quality oil, nor excessive vibration or insulation damage risk due to water bubbles, but, unlike OIRs, its winding insulation (especially the first 10% of winding near the high-voltage terminals) is imposed to very steep and high-magnitude impulse waves, when submitted to a lightning strike and during switching events. This occurs due to the presence of stray capacitances, which makes the voltage drop over the windings to be non-linear, making the first windings of the coil (connected near the incoming terminal), to experience higher voltages. These first windings are also where there is more probability to the fault to occur.

The representation of stray capacitances of ACR and concentrated dielectric stress on the first 10% of windings can be seen in Figure 32.

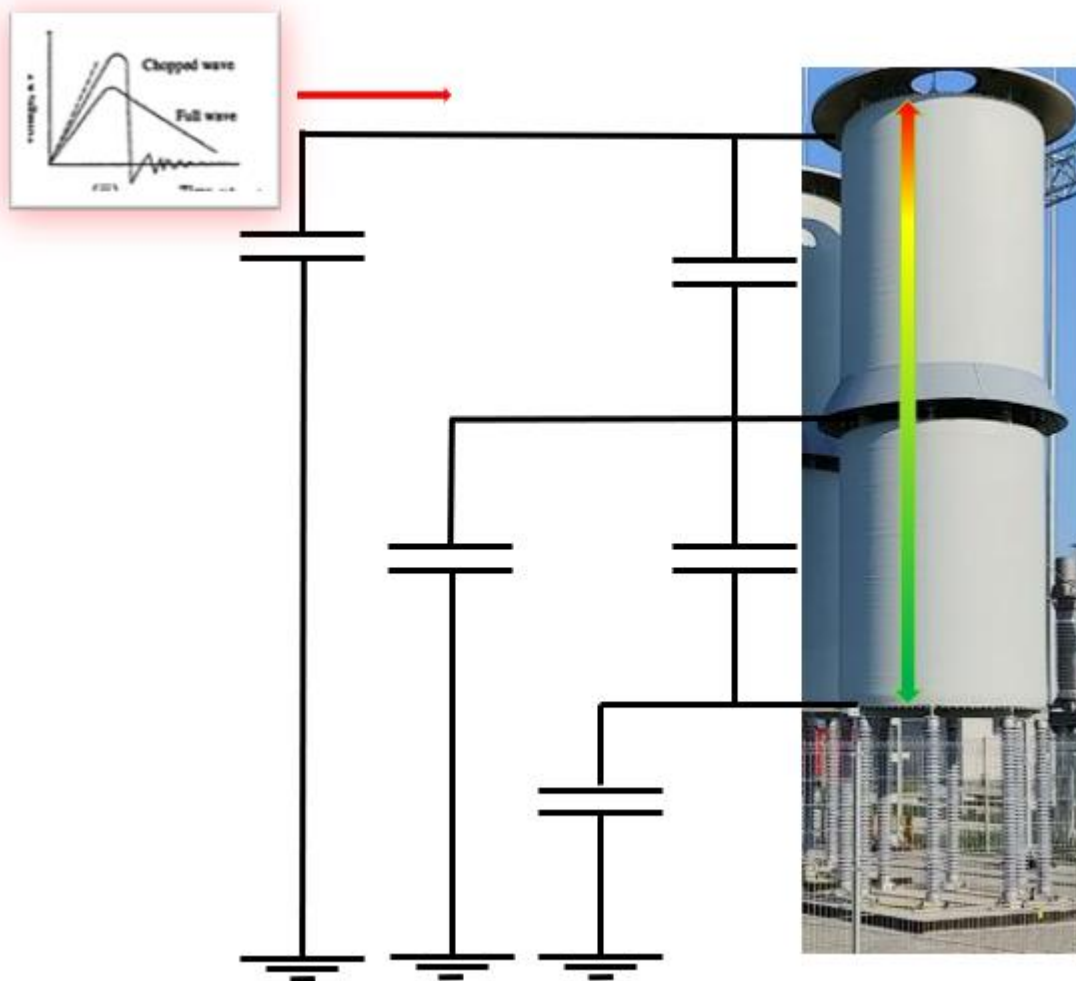


Figure 32 - Representation of stray capacitances of ACR and concentrated dielectric stress on first 10% of windings [image of GE ownership].

When such transient overvoltage exceeds the dielectric withstand capacity of the insulating material between turns, it can deteriorate, damage the insulation, and eventually result in a turn-to-

turn fault. A turn-to-turn fault, if not detected and interrupted quickly, can evolve into a fault between phases or a winding-to-ground fault [9].

The facts above lead to the conclusion that the temperature is more critical to OIR than to ACR, due to the possibility of failures caused by the presence of water in the insulating oil and kraft paper, which do not exist to ACR. Therefore, it is not needed in the ACR specification to require a very low temperature rise limit (below the one indicated in the standard to the thermal class to be adopted), as commonly requested to OIR. However, it was also noticed that dielectric aspects are more critical to ACR than to OIR, due to the presence of capacitance-to-ground values in different levels from bottom to top part of the ACR equipment, which results in non-linearity on transient waves, stressing more the first 10% of the windings. This concentrated overstress does not tend to be an issue, when analyzed by the ACR manufacturer in a proper way.

- **Other faults and monitoring**

Unlike ACR, Oil-immersed equipment need additional protection for temperature monitoring, pressure of insulating fluid, low level of oil, etc, requiring a more complex protection and monitoring system.

A summary with the most advantageous situation to each technology, in terms of protection is presented Table 13 presents.

Table 13 - Advantages of each technology in terms of protection

Advantages	OIR	ACR
No need of voltage signal for protection (no need of VT or CVT if signal is not available)	✓	X
No risk of bushing failures (reducing risk of failure modes do ground)	X	✓
No need of extra safety margin on temperature rise to reduce the risk of turn-to-turn failures	X	✓
No need of special care on insulation by reactor manufacturer, due to the concentration of transient waves on first 10 % of windings	✓	X

3.8 TYPICAL ARRANGEMENTS OF SHUNT REACTOR BANKS

- **Oil-immersed Iron-core reactors (OIR)**

Iron core oil-filled shunt reactors typically present two different configurations depending on the system voltage.

3.8.1 OIR Arrangement 1: Oil-immersed three-phase Reactors

Typically, for systems up to 245 kV OIR reactors are three-phase constructed. It means that they are constructed with the three phases inside the same metallic cage (example in Figure 33).



Figure 33 - Example of three-phase shunt reactor [34].

3.8.2 OIR Arrangement 2: Oil-immersed single-phase Reactors

For systems above 245 kV, typically oil-immersed shunt reactors are constructed with the phases physically separated in different metallic cages, placed side-by-side in the substation. This is mainly linked with the need of a higher electrical insulation, which becomes more complicated to be achieved with the three phases sharing the same physical space. Example of single-phase reactors can be observed in Figure 34.



Figure 34 - Example of single-phase shunt reactor [31].

- **Dry-type Air core reactor (ACR)**

The physical arrangement of air-core reactors depends on several aspects such as manufacturing limits for each coil (specially the maximum height per coil that can be manufactured), the design criteria of the manufacturer (the maximum voltage stress allowed, generally expressed in V/mm) and the ratings of the equipment (specially the inductance, which dictates the number of turns for a certain diameter of the coil and hence, impacting in the required height to accommodate these turns).

Therefore, when comparing two equipment with the same operating voltage and same average diameter, the equipment with a lower power, requires more inductance, as a consequence, more turns requiring therefore, a higher height. Depending on manufacturing limitations, for very low power reactors, manufacturer might even be obligated to increase the number of coils per phase, resulting in a more expensive equipment.

Along with the sentence above, the absence of an iron-core reduces the coupling effect which helps to increase the inductance with the same number of turns. This fact (along with the fact of the previous sentence) leads to the conclusion that **the higher the power, more competitive is the air-core reactor when compared to the oil-immersed technology**, especially for projects with losses limitation (the higher the number of turns, the higher the ohmic losses, increased with the increase on wires length as effect of aluminum resistivity).

In general, for typical power of reactor banks, air-core reactor banks for systems up to 275 kV, each phase is composed by two coils in series. For systems between 275 kV and 420 kV, each

phase is composed by three coils in series and between 420 and 550 kV, of four coils in series per phase.

For systems above 550 kV, air-core reactors are still unusual, but in theory they are possible by adding more coils in series per phase. However, a very special care should be taken by the manufacturer, mainly in dielectric voltage withstanding, since the lightning impulse voltage wave tends to concentrate in the first turns where it is applied (due to the huge height of the coils and the variation on capacitance-to-ground values). For these Ultra High Voltage (UHV) systems, the Basic Insulation Level (BIL) is so huge that this lightning could lead the turn-to-turn insulation of the first coil (near the phase) to fail in such event. Special care related to transient recovery voltage (TRV) should also be taken in this case, for the choice of the suitable circuit-breaker and also the turn-to-turn insulation withstanding for switching-off overvoltage transients, due to switching before natural zero-crossing current and reignition. The use of surge arrester or of a circuit breaker with synchronizer, should be evaluated after the analysis of TRV studies by the manufacturer.

The possibilities of physical arrangements for this technology are presented in 4 subtypes below.

3.8.3 ACR Arrangement 1: One coil per phase (one coil in one tower)

In general, for typical power of banks, air-core reactor banks for systems below 72.5 kV present this configuration.

An example of air-core shunt reactor in one coil per phase is shown in Figure 35. Most banks with this arrangement are insulated. Therefore, full insulation should be guaranteed by base insulators. For this configuration, for grounded banks it is recommended top terminal to be the phase-side terminal so as the base insulators are not required to present full system insulation (only neutral voltage withstand level insulation).

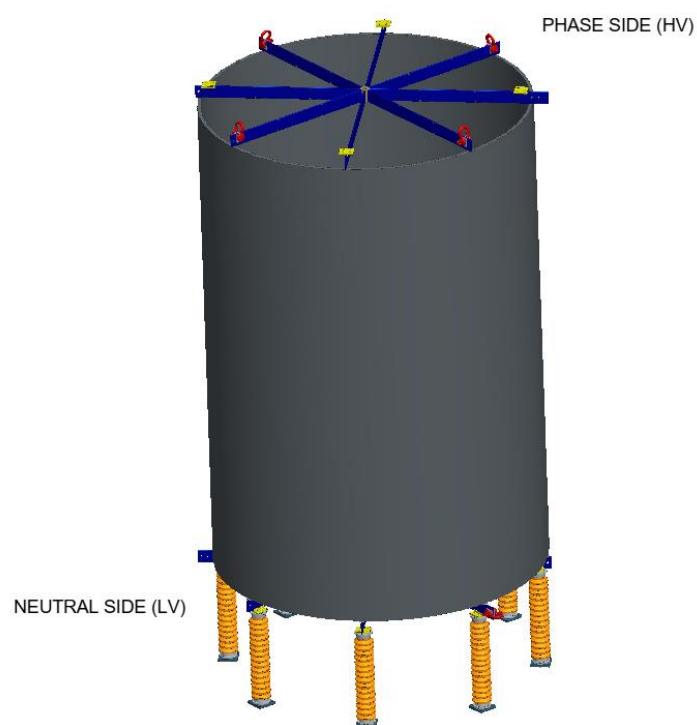


Figure 35 - ACR Arrangement 1 - 1 coil per phase (1 tower) [Image of GE ownership].

3.8.4 ACR Arrangement 2: Two coils per phase (double-stacked coils in one tower)

In general, for typical power of banks, air-core reactor banks for systems up to 275 kV present this configuration presented on Figure 36.

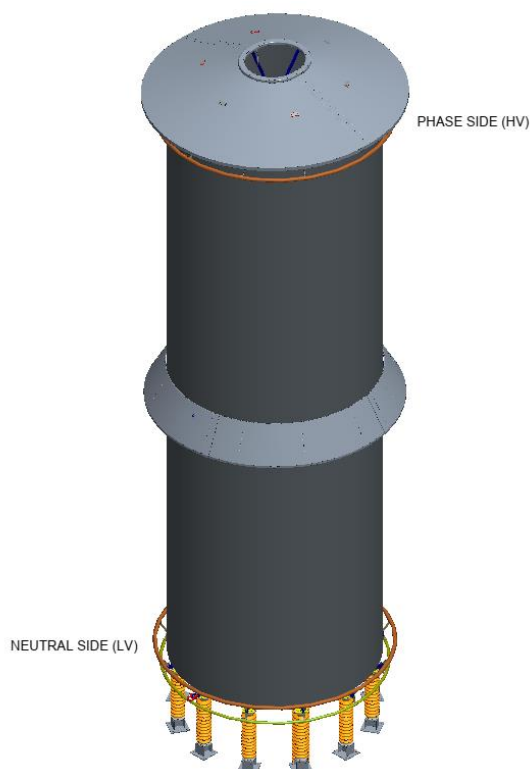


Figure 36 - ACR Arrangement 2 - 2 coils per phase (1 tower) [Image of GE ownership].

Insulation aspects concerning this arrangement is explained in the following sections.

3.8.5 ACR Arrangement 3: Three coils per phase (three-stacked coils in one tower and double-stacked + single coil in two towers)

In general, for typical power of banks, air-core reactors for systems between 275 kV and 420 kV present this layout.

This is the preferred configuration for three-coils arrangement since it presents a lower overall cost (reduces the number of insulators and reduces the number of turns due to coupling effects, when compared to the arrangement of Figure 38).

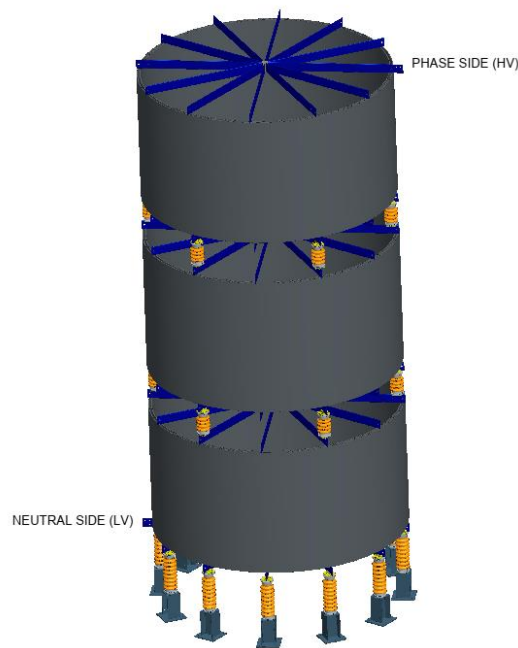


Figure 37 - ACR Arrangement 3 - 3 coils per phase (1 tower) [Image of GE ownership].

For substations with high wind speed and/or seismic levels or with limitation in height, the assembling of Figure 37 may not be suitable, since it tends to present higher overall height, increasing the mechanical stresses on base insulators, which could lead them to be above acceptable limits. For these cases, arrangement in two towers (as per Figure 38) may be the most advised solution.

In substations where installation area is a concern, even if you have high wind speed and seismicity, special insulators (with very high mechanical ratings) combined with their inclination in angles typically from 15 to 25 degrees, may be a viable approach.

The arrangement of Figure 38 presents a greater number of turns for the same inductance of Figure 37 (reduced magnetic coupling), imposing a bit more losses. It also tends to be costly, due to the need to increase the number of insulators. However, this arrangement may be indicated to some substations with limitation in height or with very special mechanical requirements – very high wind speed and/or high seismic levels, etc (which would require very special mechanical ratings for base insulators, in case of arrangement with three coils in one tower).

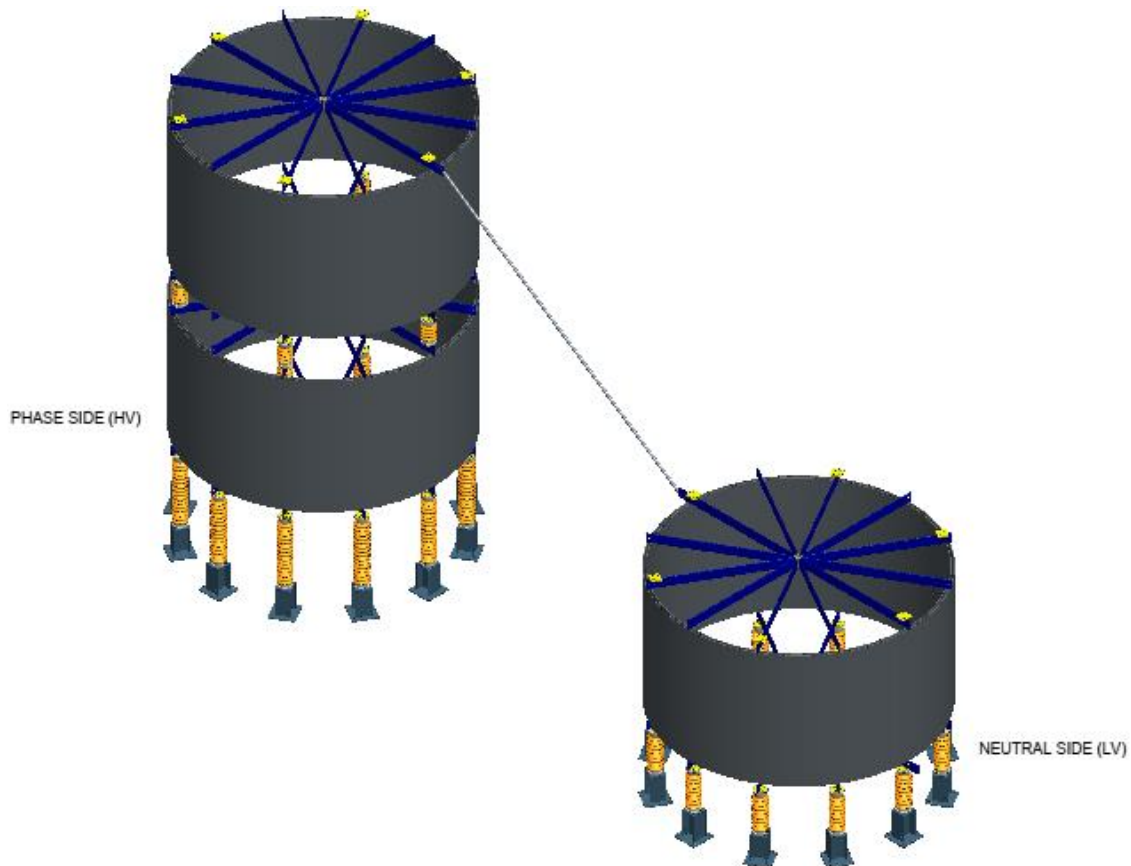


Figure 38 - ACR Arrangement 3 - 3 coil per phase (2 towers) [Image of GE ownership].

3.8.6 ACR Arrangement 4: Four coils per phase (two double-stacked coils per phase)

In general, for typical power of banks, air-core reactors for systems between 420 kV and 550 kV present this configuration.

The most common practice to this arrangement is shown in Figure 39, where both incoming and outgoing connections are done in bottom terminals. This allows to reduce the insulation on neutral-side terminal (lower BIL for insulators), reducing costs with base insulators for the neutral-side tower. It also makes easier to connect instrument transformers (IT) to neutral terminals, since neutral terminals are nearer the ground.

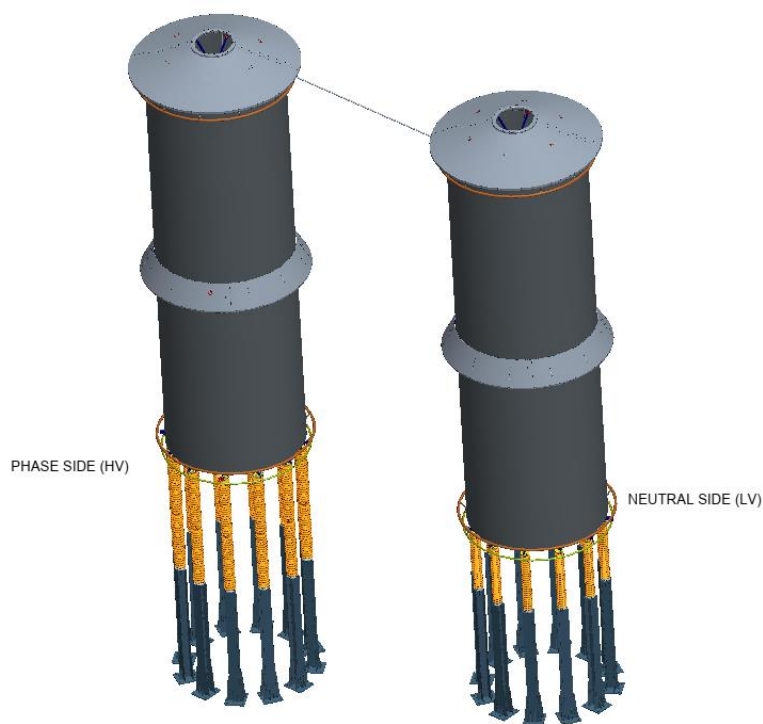


Figure 39 - ACR Arrangement 4 example - 4 coils per phase (2 towers) - bottom connection [Image of GE ownership].

The second possibility for banks with four coils in series per phase, assembled in two side-by-side towers is presented in Figure 40. This connection is indicated where it is needed to have phase-side terminal at a higher position, i.e., when there are constraints to elevate phase-side connection from bottom terminal to the line, respecting safety electrical clearances from the coil. In this case, ITs (Instrument Transformers) connections may be impacted, since they would to be done on top terminals as well.

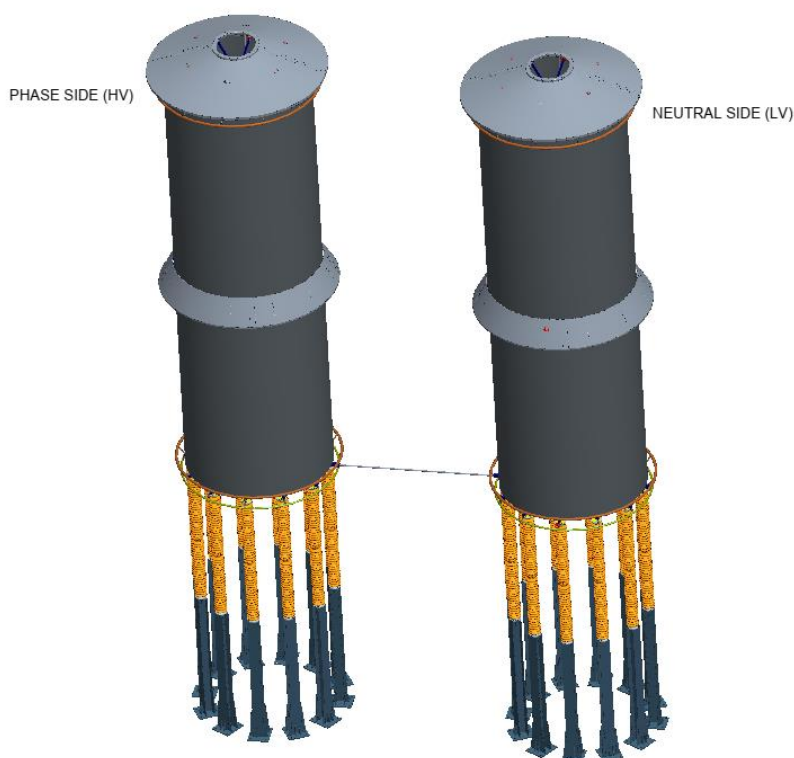


Figure 40 - ACR Arrangement 4 example - 4 coils per phase (2 towers) - top connection [Image of GE ownership].

3.9 INSULATION LEVEL ASPECTS

The insulation level of shunt reactors depends on the voltage level, the standard to follow (IEC, IEEE, ABNT, etc) as well as on the grounding of the neutral. Neutral insulation level depends on the arrangement and grounding of the equipment.

For medium-voltage and higher voltage levels, shunt reactors are usually connected in “wye”. The first group (typically up to 72.5 kV) is insulated-wye and the second one, grounded-wye (typically above 72.5 kV).

Notice that unlike oil-immersed reactors, which have all insulations done by bushings, ACRs uses their coils to guarantee a part of the insulation. The summary matching the grounding scheme and required insulation to phase-side and neutral terminals is presented in Table 14. This is valid for both ACR and OIR.

Table 14 - Insulation summary for air-core reactor

Connection	Phase-side insulation (HV terminal)	Neutral-side insulation (LV terminal)
Insulated single-wye	Full insulation	Full insulation as per standard
Solidly grounded single-wye (without NGR)	Full insulation	BIL above or equal to 110 kV [35]
Grounded single-wye (with NGR)	Full insulation	As per studies

Some remarks regarding insulation aspects may be observed below for each ACR arrangement.

- **Insulation of ACR arrangement 1**

A typical single-phase 72.5kV ACR is presented in Figure 35, built in with one coil per phase. The connection is usually made on upper terminal. This approach, for grounded banks, reduces the BIL required for base insulators. For ungrounded banks (the majority with this arrangement), regardless the connection point it is required to ensure full BIL on base insulators. However, in normal conditions, a voltage close to zero (floating neutral) is imposed on base insulators. This avoids short circuit if case an animal climbs the insulator, for example, bringing more safety and reliability to the installation.

- **Insulation of ACR arrangement 2**

A typical single-phase 245 kV ACR is shown in Figure 36, built in with two stacked coils in series. If the line connection is placed at top terminal, the HV insulation is guaranteed by the coil structure. The neutral Low Voltage (LV) insulation is guaranteed by base insulators. This is the most common connection, since BIL of base insulators can be reduced (respecting remarks of Table 14) and neutral connections are closer to the ground. This makes easier to install and to connect auxiliary equipment, such as current transformers (CT) and neutral busbar, for example.

- **Insulation of ACR arrangement 3**

Most common practice for three coils per phase arrangement is presented in Figure 37. For this case, base insulators can have the same insulation level required to the neutral, reducing overall height and costs. Notice that the coils perform the HV to LV insulation (what is done by bushing at OIR technology).

The second possibility to this arrangement is shown in Figure 38. In this case, base insulators of first stack, needs to have full BIL of the system, increasing the overall costs of the solution.

- **Insulation of ACR arrangement 4**

A typical single-phase 550 kV ACR is presented in Figure 39, built in with four coils in series (two stacks with two coils each). If the line (HV) connection is placed at bottom terminal of first stack, the HV insulation is guaranteed by the base insulator of this first stack. The neutral (LV) insulation is at the bottom of the second stack. Neutral insulation is guaranteed by base insulators of the second stack. This is the most common connection for four coils per phase, since BIL of base insulators of the second stack can be reduced and neutral connections are closer to the ground. This makes easier to install and to connect auxiliary equipment, such as CTs and neutral busbar, for example.

The second possibility for banks with four coils in series per phase is presented in Figure 40, assembled in two side-by-side towers. Due to stray capacitances (which causes non-linearity on distribution of electrical waves on the windings), when this connection is done, it is not easy to ensure which is the suitable insulation ratings to the base insulators (since they are placed between phase-side and neutral-side). Therefore, it is recommended to have full BIL to both stacks, which increase the costs when compared to Figure 39 connection.

3.9.1 Single-phase auto-reclosing and the use of neutral grounding reactors

When a single-phase to ground fault occurs and the faulted phase is isolated from both ends by their single-pole breakers, some voltage is induced in the isolated phase due to capacitive and inductive couplings among the healthy and faulted phases. In spite of the breaker opening at both ends of the faulted phase, the induced voltage feeds current through arc in the faulted point causing its consistency. This current, called secondary arc current, may be high enough to stop arc extinction

after breaker opening. The voltage induced in the faulted phase due to capacitive and inductive coupling is known as secondary arc voltage [36, 37].

As the arc shall be extinguished before the auto-reclosure attempt of the failed phase, if secondary arc time is higher than expected for its auto-reclosure, a fourth reactor, called Neutral Grounding Reactor, can be installed between the neutral and the earth of the shunt reactor bank connected to the line. This reactor creates a LC resonance in the circuit so as the parallel circuits among the phase conductors have high impedance when seen externally. In other words, the inductive currents among the healthy phases of shunt reactors configuration, shall be the same value of capacitive currents, but with opposite polarities.

As a consequence of using a neutral grounding reactor (NGR), the neutral insulation shall be increased (from minimum BIL of 110 kV as per recommendation of the Institute of Electrical and Electronics Engineers – IEEE – C37.21:2008 [35]) to the level equivalent to the maximum voltage across the NGR terminals, when submitted to a line-to-earth fault.

The need of a NGR as well as its impedance shall be determined by single-phase auto-reclosure studies.

- **Oil-immersed Iron-core reactors (OIR)**

The insulation for both line and neutral terminals is guaranteed by reactor bushings, which shall be able to guarantee insulation to the tank (grounded).

- **Dry-type Air core reactor (ACR)**

The insulation of the air-core reactor depends on the arrangement, where the phase and neutral terminals are connected as well as on the presence of neutral grounding reactor.

The summary with the comparison between both technologies in terms of insulation is presented in

Table 15. Notice that unlike OIRs, ACRs use their coils as part of insulation. This explains the fact that they are considered as energized (or live) parts. Therefore, their height is very important to guarantee suitable insulation (commonly measured in V/mm – volts per millimeter – of coil).

Table 15 – Insulation summary depending on arrangement and line connection

			Insulation^{a b}		
	Arrangement	Line (HV) connection	HV-to-ground	LV-to-ground	HV-to-LV (between terminals)
ACR	1	top terminal	coil 1 + LV insulator	LV insulator	coil 1
ACR	2	top terminal	coil 1 + coil 2 + LV insulator	LV insulator	coil 1 + coil 2
ACR	3	top terminal	coil 1 + coil 2 + coil 3 + LV insulator	LV insulator	coil 1 + coil 2 + coil 3
ACR	4	bottom terminal	HV insulator + coil 1 + coil 2 + coil 3 + coil 4 + LV insulator	LV insulator	coil 1 + coil 2 + coil 3 + coil 4
ACR	4	top terminal	coil 1 + coil 2 + HV insulator + LV insulator	coil 3 + coil 4 + LV insulator	coil 1 + coil 2 + coil 3 + coil 4
OIR	-	-	HV bushing	LV bushing	HV + LV bushing

^a. Coil 1 is assumed to be the first coil connected to the line.

^b. HV insulator is assumed to be the stack connected to the line.

4 TRANSIENT ANALYSIS OF SHUNT REACTORS

Transients caused by switching of high voltage shunt reactors are well known. Failures on this equipment during service operations have been receiving significant attention in recent years over numerous technical papers and guides from the power community. The reasons for the shunt reactor failures are now well-understood and physically explained; suitable precautions to avoid such failures or at least reduce the probability of their occurrence are now available [38, 39].

Shunt reactors installed in busbars (not in the power line) are typically switched at least twice a day, and sometimes, even more often depending on the power system loading conditions. Whenever the bus voltage rises to around 4-5 % above the rated voltage, the reactor is then switched-on [38]. Shunt reactors may be kept out of service when the bus voltage is near or below the rated value [38]. Therefore, frequent switching becomes an important matter to this equipment, especially regarding turn-to-turn insulation of reactor windings as well as circuit breaker withstanding (commonly SF6 type, for HV and UHV) [38].

One of the most important aspects to be analyzed regarding switching reactors is current chopping caused by forcing the reactor current to zero before the natural zero crossing, which could result in over-voltages across breaker poles. For vacuum circuit breakers, typically used to switch medium-voltage shunt reactors, the introduction of copper/chromium contact material overcame the problem of high voltages due to switching events [40]. For high-voltage circuit breakers, used to switch reactor banks typically above 38 kV, a special attention on TRV and the Rate of Rise of Recovery Voltage (RRRV) should be taken so that the circuit breaker is adequately rated for the specific application. The oscillation frequency and magnitude are determined by the inductance and stray capacitance associated with the reactor as well as the circuit breaker and network components near the circuit breaker. These capacitances are generally very low, resulting in high frequency switching transients that are especially severe on circuit breaker contact surfaces and reactor windings.

4.1 STRAY CAPACITANCES

The presence of different voltages in the extremity of an insulating material (the air or the winding insulation itself, for example), provides a way for the appearance of stray capacitances. Switching events are high-frequency events where these stray capacitances become significant, imposing specific switching waves that should be carefully analyzed.

The total equivalent stray capacitance tends to be higher to the OIR when compared to the ACR (from some units to some dozens higher). This increases the oscillating frequencies of ACR, which is presented and commented in Section 4. The reactor manufacturer shall disclose this data to the purchaser, so as the TRV studies and the circuit breaker selection can be performed in a proper way.

4.2 TRANSIENT MODELS

Shunt reactors (for both technologies), present very low stray capacitances (typically ACR equivalent capacitances are from some units to some dozen times lower than OIR), which affects high-frequency events during switching-on and switching-off events. Therefore, high-frequency (or transient) model of these equipment shall consider these capacitances. Each technology presents different considerations to be taken into account, as per remarks presented in the following sections.

- **Oil-immersed Iron-core reactors (OIR)**

Oil-immersed reactors transient model can be assumed to be as follows. Notice that there is a resistance to ground, representing the insulation resistance guaranteed by insulating oil and bushings.

Notice that series capacitance is not used, since this parameter for oil-immersed reactors is negligible.

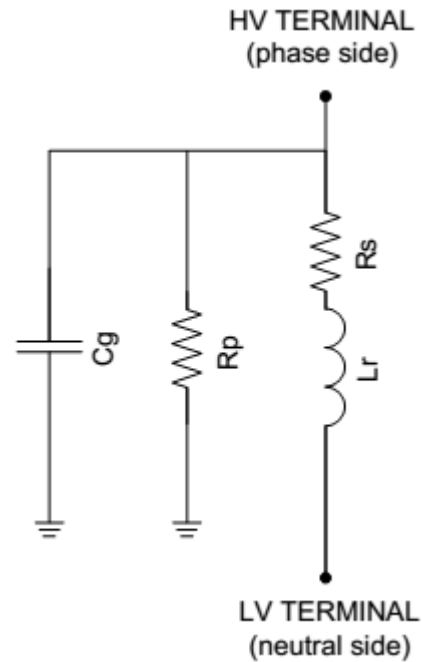
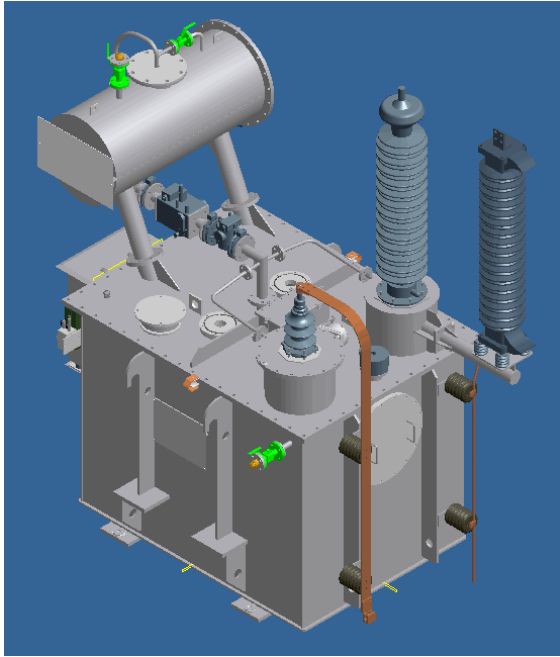


Figure 41 - Transient model of OIR [11].

- **Dry-type Air core reactor (ACR)**

The transient model of air-core reactors is affected by the disposition and the number of coils per phase. The choice for the different types of arrangements is explained in the section 3.8.

The following sections present typical transient models for all voltage ranges up to 550 kV and their arrangement composed by series-capacitance (C_{series} or just C_s) and capacitance-to-ground (C_{ground} or C_g). L_r is the total inductance of the coil; C_s is the capacitance in series of the winding (caused by the cumulative series capacitance due to capacitive effect caused by the turn-to-turn voltage and the insulation among the winding turns); C_g is the capacitance to ground and is caused by the capacitive effect of the voltage of the windings and the ground, where the air is the dielectric material. The R_s is the series resistance of the windings. It is usual to consider the resistance value at power frequency, which is a conservative (since resistance tends to increase with the increase of frequency). All of the values for transient model should be informed by the reactor manufacturer (many available on reactor rating plates).

4.2.1 Transient model for acr arrangement 1

This is the simplest configuration and can be represented by a “pi-model”. Notice that the capacitance to ground is equal to both sides. In reality, for a reactor in standard mounting (vertical

position), the capacitance to ground of bottom terminal (nearer the ground) is higher than the one for top terminal of the coil (farther from the ground). However, this approximation using the whole cumulated capacitance divided in two equal branches, presents negligible divergence on simulation results.

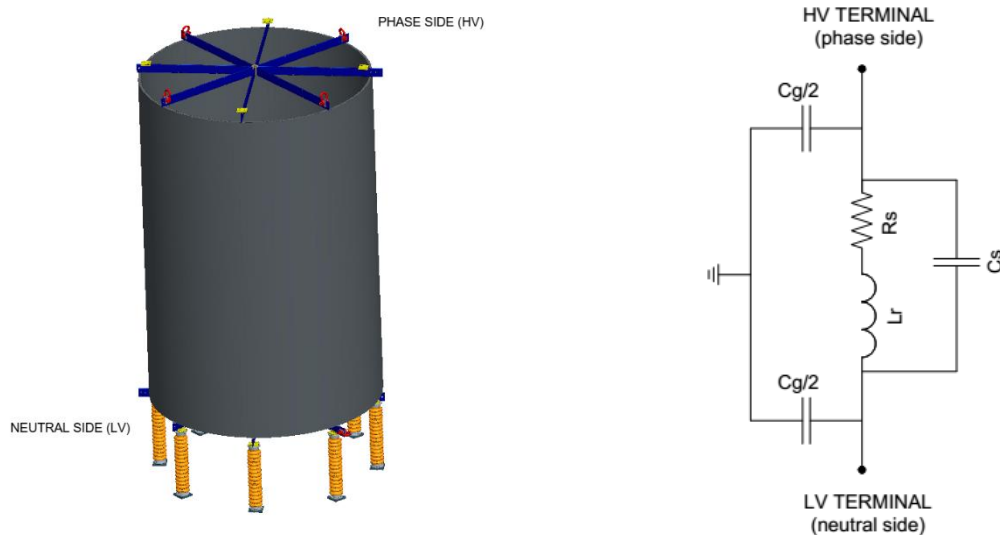


Figure 42 - Transient model of ACR (one coil per phase) [Image of GE ownership].

Since the capacitance-to-ground is assumed to be equal for both ends, regardless which terminal the phase is connected to (whether at top terminal - most common practice for single coil per phase arrangement - or bottom terminal), transient simulations are not affected.

4.2.2 Transient model for ACR arrangement 2

The arrangement of Figure 43 is indicated to reactors with two coils in series per phase. This arrangement is similar to the arrangement with one coil per phase, but other capacitances are included to consider to reflect this mounting.

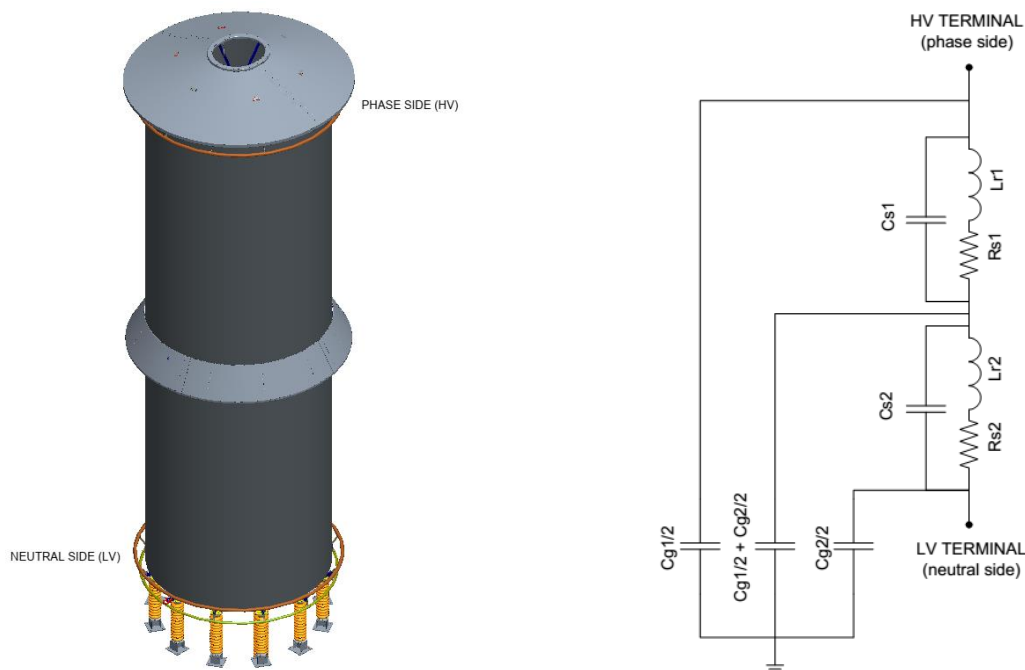


Figure 43 - Transient model of ACR (two coils per phase) [Image of GE ownership].

4.2.3 Transient model for ACR arrangement 3

This arrangement is indicated to reactors with three coils in series per phase. There are two physical possibilities: three-stacked coils in a single tower or two-stacked coils + one single coil assembled side-by-side of the stacked tower. Both use the same transient model, but the capacitance-to-ground values change. For three stacked-coils in a single tower, the highest coil is farer than it would be in the other mounting arrangement, reducing its C_g .

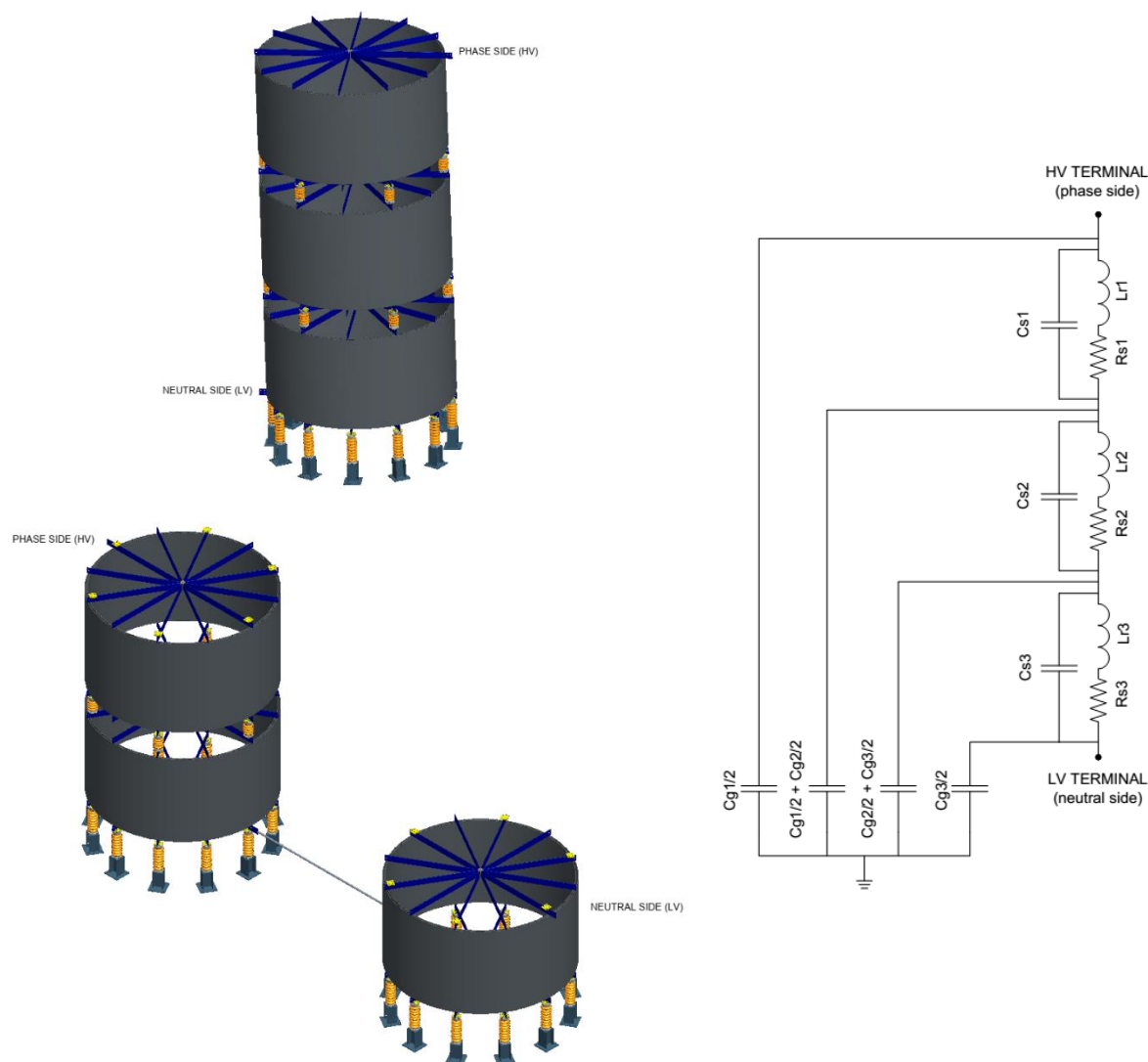


Figure 44 - Transient model of ACR (three coils per phase) [Image of GE ownership].

4.2.4 Transient model for ACR arrangement

This arrangement is indicated to reactors with four coils in series per phase, assembled in two side-by-side towers. Incoming and outgoing connections may be done on top or on bottom terminals. The most common practice is on bottom terminals, so that the insulation on the neutral-side terminal may be reduced, reducing costs with base insulators for the neutral-side tower.

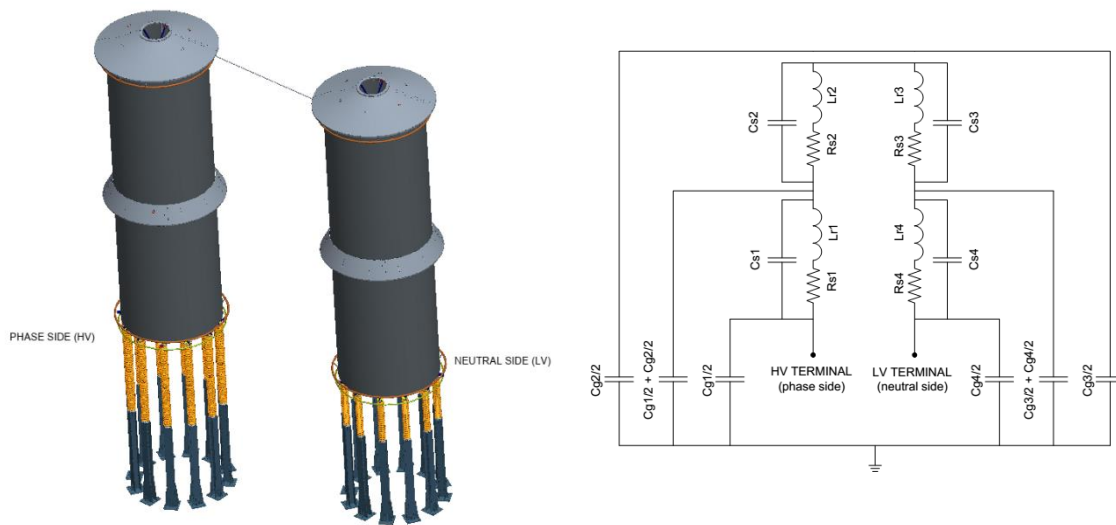


Figure 45 - Transient model of ACR (four coils per phase) – connection at bottom terminals [Image of GE ownership].

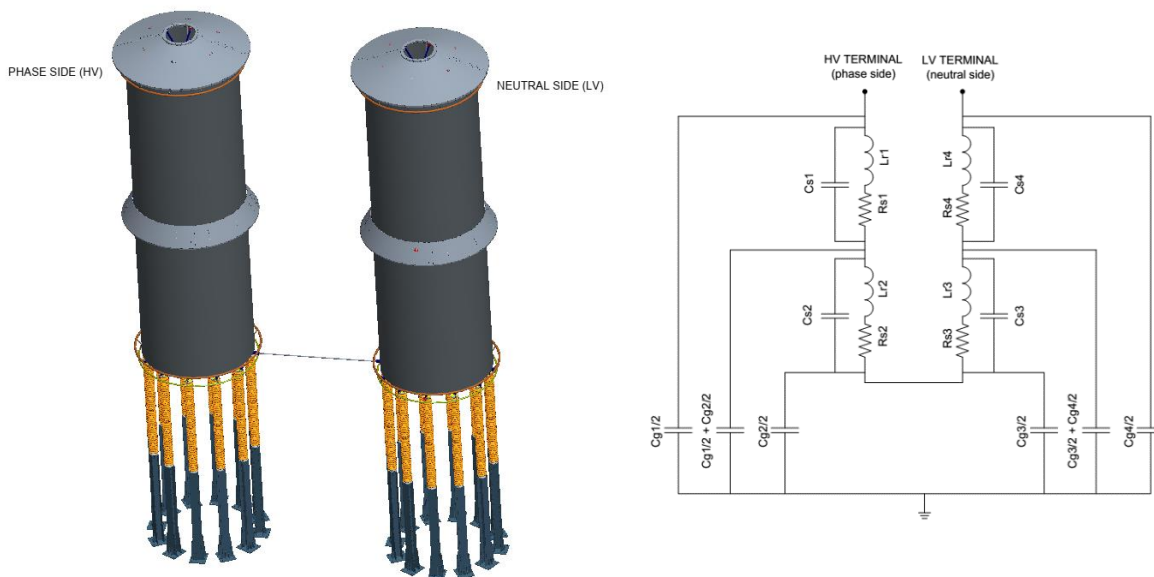


Figure 46 - Transient model of ACR (four coils per phase) – connection at top terminals [Image of GE ownership].

4.3 ENERGIZATION INRUSH CURRENT

The basics behind shunt reactors energizing can be understood as the energization of an L_R circuit. The voltage source E represents the electromotive forces from the power system, the inductance L represents the phase inductance of the shunt reactor and R represents the ohmic resistance of the reactor windings. The system is considered as an infinite busbar, represented by the ideal source [41, 42].

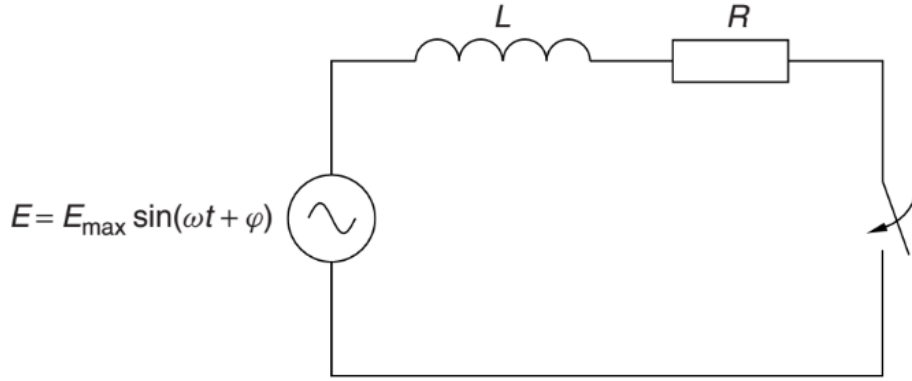


Figure 47 - A sinusoidal voltage source is switched on to an LR series circuit [42].

Applying Kirchhoff's voltage law, the nonhomogeneous differential equation 15 can be obtained.

$$E_{max} \sin(\omega t + \varphi) = Ri + L \frac{di}{dt} \quad (15)$$

The current in the circuit breaker in the moment after the energization is the superposition of a transient current and a steady-state current, since only linear elements are being used in the circuit. The transient component of the current can be obtained by solving the characteristic equation of the homogenous differential equation. The steady-state component of the current is obtained from the particular solution of the nonhomogeneous equation [42].

$$i(t) = i_h(t) + i_p(t) \quad (16)$$

By applying the suitable mathematical operations, the complete solution, which is the sum of the general and the particular solution, can be seen in equation 17 [42].

$$i(t) = e^{-\left(\frac{R}{L}\right)t} \left\{ \frac{-E_{peak}}{\sqrt{R^2 + \omega^2 L^2}} \sin \left[\varphi - \tan^{-1} \left(\frac{\omega L}{R} \right) \right] \right\} + \left\{ \frac{E_{peak}}{\sqrt{R^2 + \omega^2 L^2}} \sin \left[\omega t + \varphi - \tan^{-1} \left(\frac{\omega L}{R} \right) \right] \right\} \quad (17)$$

Where:

i = Current in ampere

R = Resistance of the circuit in ohm

t = Time in second

E_{peak} = Peak value of sinusoidal AC voltage source in volt

L = inductance of shunt reactor in henry.

ω = Angular frequency in radian per second

φ = Phase angle in radian

The first part of the equation 17 represents the transient behavior of inrush current. It contains the exponential term $\exp[-(R/L)t]$, which is called "Direct Current (DC) component" [42]. This term represents the damping of the transients in time, depending on the L/R ratio of the reactor. The term

within the brackets $[\phi - \tan^{-1} (\omega L/R)]$ depends on the instant of the voltage wave at which the energization occurs. Notice that if the energization occurs at 0 V (what happens when the time is 0 or any integer number times π , for a sinusoidal voltage wave), then $\{[\phi - \tan^{-1} (\omega L/R)] = 0\}$. In such case, the first part of the equation is equal to zero ($\sin 0 = 0$) and no transients are observed. If the energization occurs at the peak of the voltage wave (any odd integer number times $\pi/2$ - $\pi/2, 3\pi/2, 5\pi/2$, etc - of a sinusoidal voltage wave), the transients reach the maximum amplitude (as shown in the Figure 48).

The transient term exists to compensate the fact that the current through the inductor does not change instantaneously. It is responsible for producing the asymmetry or DC offset in the energization currents in each phase [42]. The peak inrush current may reach up to $2\sqrt{2}$ times the nominal current due to the DC offset [41].

The minimum asymmetry of DC offset can be guaranteed by ensuring energization near the peak of voltage waves. This is known as synchronized switching or Point-on-Wave (POW) switching.

Ensuring a reduction on unsymmetrical currents is also a way to reduce the chance of activation of zero-sequence current relays, since these may be activated by zero-sequence current flow caused by unsymmetrical currents, especially for solidly grounded neutral [43].

The second part of the equation represents the steady-state behavior of the inrush current. The shape of a transient current in an inductive circuit depends on the instant of switching [42] and can be observed at Figure 48.

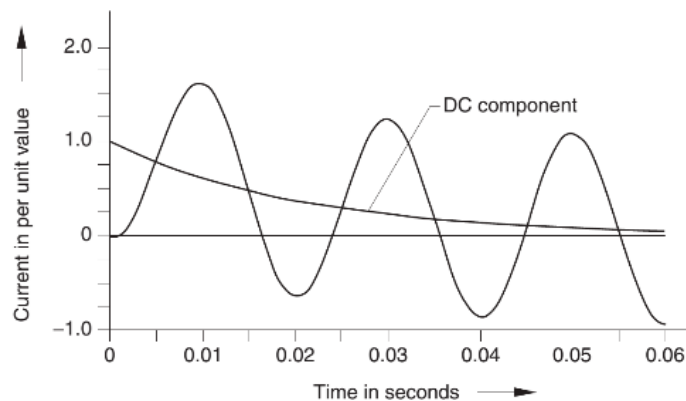


Figure 48 - Transient current in inductive circuit [42].

Current asymmetry becomes smaller if the circuit breaker closes near the maximal value of the power frequency voltage. On the other hand, this causes switching overvoltage. Dielectric stress of reactor insulation caused by the very steep overvoltage, originated from circuit breaker contact gap prestrike immediately before closing, is similar to that caused by the reignition after reactor

deenergizing with voltage across the circuit-breaker interrupter of 1pu. However, it is impossible to obtain reduction of inrush currents and stresses originated from the overvoltage during switching operations at the same time. It remains on the switching studies to find the most acceptable solution [43].

- **Dry-type Air core reactor (ACR)**

Air core reactors are subjected to the inrush currents as per equation 17, containing only the fundamental frequency component with a DC offset [41]. This offset has a long time constant due to typical high L/R ratio (caused by high inductances and low losses, typical for shunt reactors). A longer duration of DC offset present in the circuit can saturate line CTs and cause erroneous operation of protective devices [41].

- **Oil-immersed Iron-core reactors (OIR)**

Oil-immersed reactors are also subjected to the inrush currents as per equation 17 and the DC offset has also a long time constant due to typical high L/R ratio. A longer duration of DC offset can also saturate line CTs and cause erroneous operation of protective devices. However, unlike air core reactors, these ones present rich harmonic content during energizing, and the presence of a magnetic core increases the magnitude of inrush currents to magnetize the iron core. Moreover, unlike air core reactors, an OIR energizing may cause mechanical vibrations and buzzing [43], which are not observed in the same magnitude in ACR.

4.4 DE-ENERGIZING OVERVOLTAGE

Circuit breakers (CB) can easily interrupt currents of shunt reactor banks, when these are switched-off. This happens because CBs are generally designed to interrupt rated currents much higher than the ones of these banks (typically from 4 to 25 times lower). This leads to forcing the current interruption before the natural zero-crossing of current. Hence, when the current is interrupted, there is still energy stored as magnetic field in the reactor windings, causing the phenomenon referred to as current chopping [44].

The energy trapped in the load-side inductances and capacitances (stray capacitances of shunt reactor, its inductance as well as the capacitances in parallel related to other equipment

connected to the busbar), at the instant of chopping, oscillates between the inductance and the parallel capacitances with a typical frequency of the order of 1 kHz to 5 kHz at high voltages and up to 30 kHz for medium-voltage shunt reactors [44].

The oscillation frequency is determined by the interaction of all inductive and capacitive elements between the circuit breaker and the reactor (such as capacitances from disconnectors, surge arresters, busbar insulators and the stray capacitances of the reactor itself).

The first peak of the oscillation has the same polarity as the system voltage at the time of interruption. This overvoltage is referred to commonly as **chopping overvoltage** or the **suppression peak**. The second peak of the oscillation has a polarity opposite to the first peak and is referred to as **recovery voltage peak overvoltage**.

In practice, recovery voltage peak that appears across circuit breaker contacts may lead to a phenomenon named **reignition**. The magnitude of reignition overvoltage depends on the characteristics of the circuit-breaker and the circuit [44].

4.4.1 General circuit for calculation of de-energizing transients

The most general circuit, i.e., considering the neutral grounded through a reactor is presented in Figure 49. The other two types of neutral grounding (directly grounded and ungrounded), can be obtained from this main circuit [44].

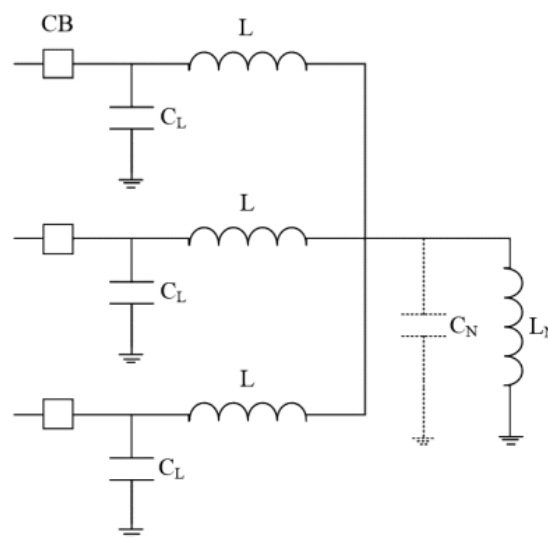


Figure 49 - General case for shunt reactor switching [44].

Where:

CB = circuit breaker

C_L = Load side capacitance

L = Phase inductance of shunt reactor

C_N = Neutral capacitance

L_N = Inductance of neutral reactor

Figure 50 considers the assumption that, at the time of current chopping on the first pole, the second and third poles are assumed to be grounded through an infinite busbar. It is also assumed that the neutral capacitance does not affect the first-pole-to-clear [44]. This is linked to the fact that the only source influence expected is the one from the affected phase being open, since it is assumed the other phases to be completely open during the chopping of the affected phase.

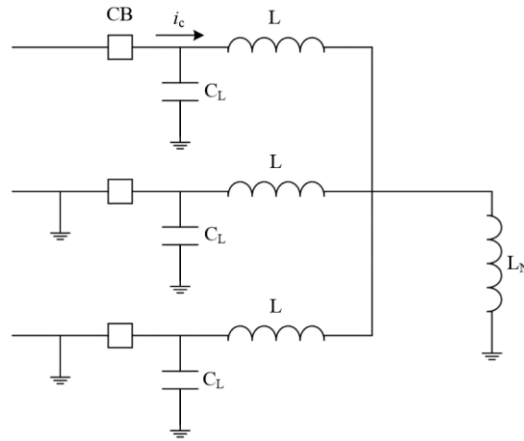


Figure 50 - First-pole-to-clear representation from general circuit [44].

From circuit of Figure 50, the following circuit of Figure 51 can be obtained.

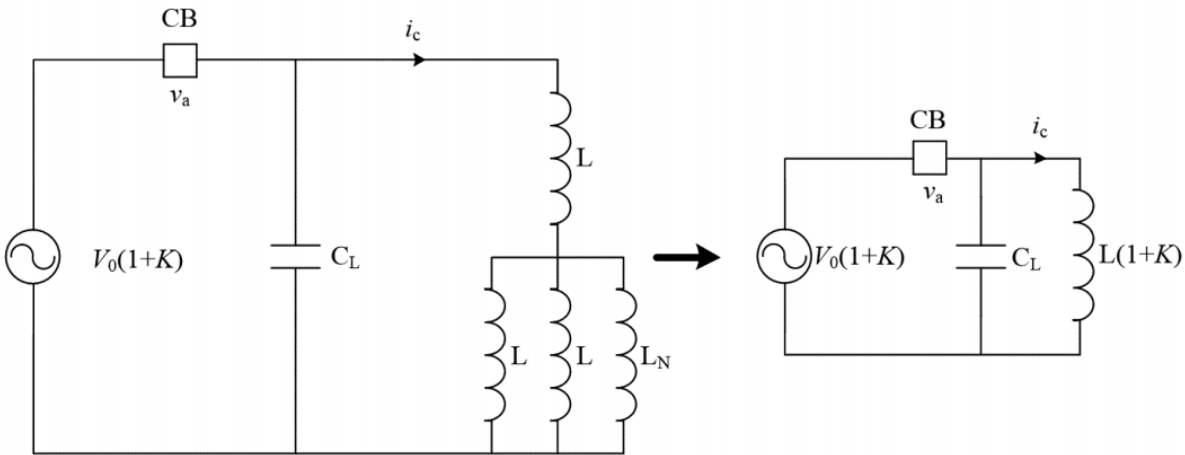


Figure 51 - Single-phase equivalent for the first-pole-to-clear [44].

Where:

V_0 = Power frequency peak voltage to ground at the instant of current interruption

i_c = Chopping current

L = Single-phase shunt reactor inductance

K = Neutral shift factor

v_a = Arc voltage

C_L = Load side capacitance of the shunt reactor

L_N = Inductance of the neutral reactor

CB = Circuit breaker

4.4.2 Overvoltage during reactor de-energizing

The general schematic for chopping and reignition overvoltage can be observed in Figure 52. Just before circuit breaker opening, the neutral voltage is at ground potential, due to system voltage symmetry. However, when the first pole clears, the neutral potential is shifted toward a bias “K” voltage value, due to the appearance of a natural unbalance among the phases. This “K” value depends on the grounding arrangement. The mean neutral voltage “K” decays to zero also depending on grounding arrangement [44].

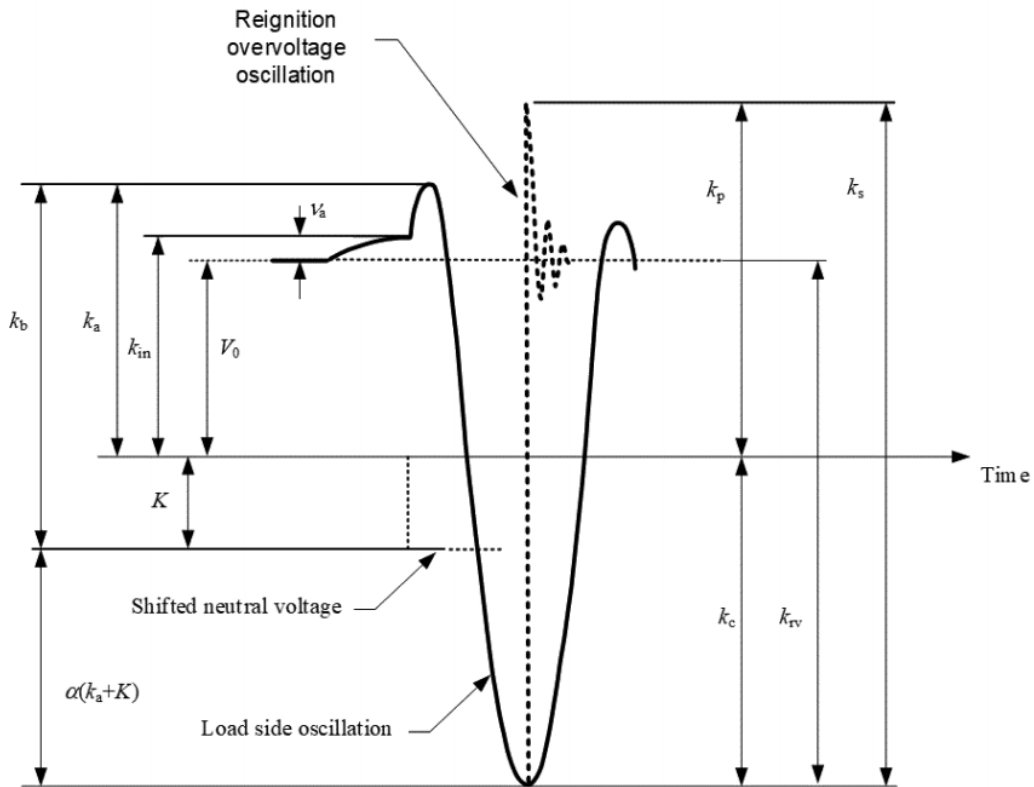


Figure 52 - General schematic for current chopping and reignition overvoltage [44].

The equations related to the parameters shown in Figure 52, can be seen in Table 16.

4.4.3 Equations derived from general circuit

The equations (extracted from [44]) obtained from Figure 49, can be seen in Table 16. These equations present some parameters related to transients, to be better discussed in the following

sections. The particular solutions for ungrounded reactor banks (where $K \sim 0.5$), are not presented, since they are applied to lower voltage levels (systems typically below 72.5 kV), which are not the target for this work.

Table 16 - Summary of main equations for directly grounded and reactor banks grounded through neutral reactor

General Equation	Directly grounded Neutral (3.2)	Grounded through neutral reactor (3.4)
$K = \frac{1}{1 + L/L_N}$	$K = 0$	$K = \frac{1}{1 + L/L_N}$
$k_a = \sqrt{(k_{in} + K)^2 + \left(\frac{i_c}{V_0}\right)^2 \frac{L}{C_L} (1 + K) - K}$	$k_a = \sqrt{k_{in}^2 + \frac{3N\lambda^2}{2\omega Q} \left(1 + \frac{C_p}{C_L}\right)}$	$k_a = (1 + K) \sqrt{1 + \frac{1}{1 + K} \left(\frac{3N\lambda^2}{2\omega Q}\right)} - K$
$k_b = k_a + K$	$k_b = k_a$	$k_b = k_a + K$
$k_c = K + \alpha(k_a + K)$	$k_c = k_a$	$k_c = 2K + k_a$
$k_{rv} = 1 + K + \alpha(k_a + K)$	$k_{rv} = 1 + k_a$	$k_{rv} = 1 + 2K + k_a$
$k_p = 1 + \beta k_{rv} = 1 + \beta[1 + K + \alpha(k_a + K)]$	$k_p = 1 + \beta \left(\frac{C_s}{C_s + C_L} (1 + k_a) \right)$	$k_p = 1 + \beta(1 + 2K + k_a)$
$k_s = (1 + \beta)k_{rv} = (1 + \beta)[1 + K + \alpha(k_a + K)]$	$k_s = (1 + \beta) \left(\frac{C_s}{C_s + C_L} (1 + k_a) \right)$	$k_s = (1 + \beta)(1 + 2K + k_a)$
$f_1 = \frac{1}{2\pi\sqrt{(1 + K)LC_L}}$	$f_1 = \frac{1}{2\pi\sqrt{LC_L}}$	$f_1 = \frac{1}{2\pi\sqrt{(1 + K)LC_L}}$
$RRRV = \frac{V_r\sqrt{2}}{\sqrt{3} \cdot t_3} k_{rv}$	$RRRV = \frac{V_r\sqrt{2}}{\sqrt{3} \cdot t_3} k_{rv}$	$RRRV = \frac{V_r\sqrt{2}}{\sqrt{3} \cdot t_3} k_{rv}$

Where:

K = Neutral shift factor
 L = Single phase inductance of shunt reactor in H
 L_N = Inductance of the neutral reactor
 k_a = Suppression peak overvoltage in per unit
 k_{in} = Voltage across the shunt reactor at the instant of current interruption in per unit
 i_c = Chopping current in Ampere
 V_0 = Power frequency peak voltage to ground at the instant of current interruption
 C_p = Capacitance in Parallel with one breaking chamber in Farad
 C_L = Load side effective capacitance to ground in Farad
 N = Number of series connected breaking chambers of circuit breaker
 λ = Chopping number of one breaking unit in A.F^{-0.5}
 $\omega = 2\pi f$ = Angular rated power system frequency in rad/s
 Q = Three-phase reactive power of reactor bank in VA
 k_b = Suppression peak overvoltage relative to the shifted neutral voltage
 k_c = Recovery voltage peak to ground
 k_{rv} = Recovery voltage peak across the circuit breaker
 k_p = Reignition overvoltage peak to ground

α = Damping factor associated with the chopping overvoltage oscillations ($\alpha = 1$ for a conservative approach. However, some damping effect is expected. Therefore, a value of 0.9 or even lower may also be suitable for a real outcome [44])

β = Damping factor whose value can be assumed to be 0.5

k_s = Reignition overvoltage excursion peak-to-peak

f_1 = Main oscillating frequency of switching transients in Hertz

V_r = Three-phase rated system voltage

4.4.4 Chopping current

The circuit that can be used as base for chopping current calculation is presented in Figure 53 [44].

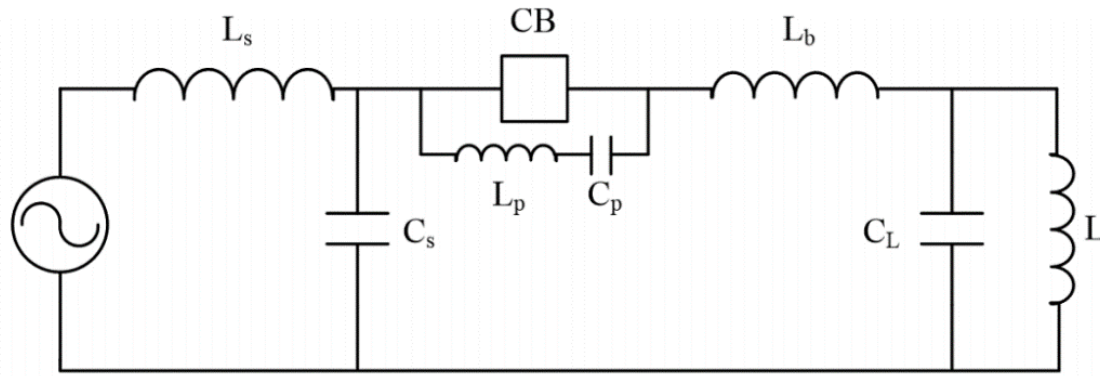


Figure 53 - Basic circuit for chopping current calculation [44].

Where:

L_s = Source side inductance

CB = circuit breaker

C_s = Source side capacitance

L_p = Circuit breaker parallel inductance

C_p = Circuit breaker parallel capacitance (grading capacitance)

L_b = Series inductance of the connection

C_L = Equivalent load capacitance (equivalent stray capacitances from reactor bank + sum of all other capacitances in parallel with the reactor bank)

L = Phase inductance of shunt reactor in Henri

Chopping current value depends on the total capacitance seen by the circuit breaker (C_t) as well as the number of breaker chambers in series per pole (N) and the chopping number of the circuit breaker (λ). Chopping number is obtained by laboratory tests and depend on the type of the breaker [44].

$$i_c = \lambda \sqrt{NC_t} \quad (18)$$

$$C_t = C_p + \frac{C_s C_L}{C_s + C_L} \quad (19)$$

Typical values for chopping numbers of high voltage circuit breakers (this chopping number concept is not applicable to vacuum breakers, where another equation should be used) are presented in Table 17 [44]. Considering that the goal of this work is comprised in the high voltage, where voltage levels are above vacuum switches capabilities, this equation is not presented.

Table 17 - Chopping numbers for circuit breaker types

Circuit breaker type	Chopping number λ [$A \times F^{-0.5}$]
Minimum oil	Between 5.8×10^4 and 10×10^4
Air blast	Between 15×10^4 and 20×10^4
SF ₆ puffer	Between 4×10^4 and 19×10^4
SF ₆ self-blast	Between 3×10^4 and 10×10^4
SF ₆ rotating arc	Between 0.39×10^4 and 0.77×10^4

4.4.5 Oscillation modes

The presence of inductances and capacitances result in different oscillation modes in the circuit. The equations below show the calculation for these main oscillations.

- **Load side oscillation**

The frequency of the load side oscillation for the first-pole-to-clear differs from that of the second and third poles to clear. For the first-pole-to-clear, the frequency of the load side oscillation is given by Equation (20) [44].

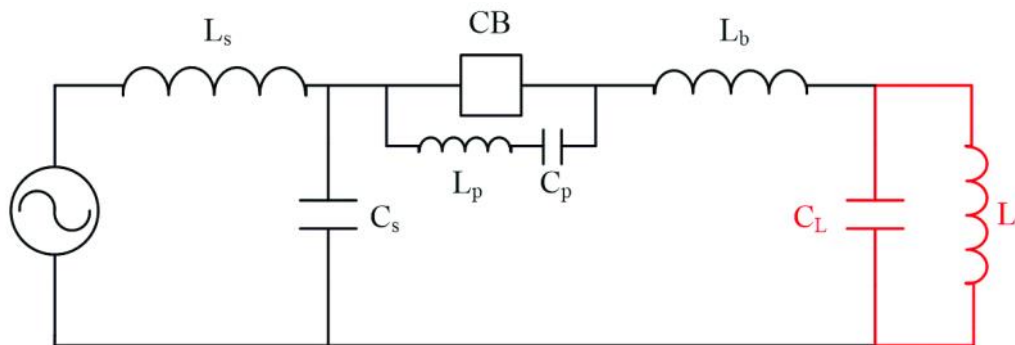


Figure 54 - Circuit of load-side oscillation [44].

$$f_L = \frac{1}{2\pi\sqrt{LC_L}} \quad (20)$$

- **Reignition oscillation**

During de-energizing, the first oscillation occurs when C_p discharges through the circuit breaker, interacting with L_p (refer to Figure X). The frequency of this oscillation is given by Equation (21) [44].

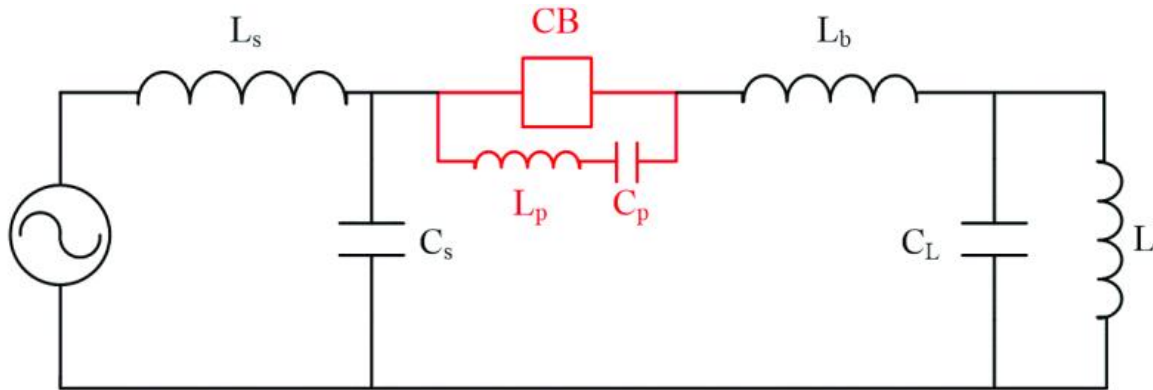


Figure 55 - Circuit of first parallel oscillation [44].

$$f_{p1} = \frac{1}{2\pi\sqrt{L_p C_p}} \quad (21)$$

If the CB is not able to interrupt the current associated to the first oscillation, then a second oscillation (reignition oscillation) occurs, as a result of the voltages on both CB terminals are equalized (voltage across CB equal to zero). If this occurs, oscillation is given by Equation (22) [44].

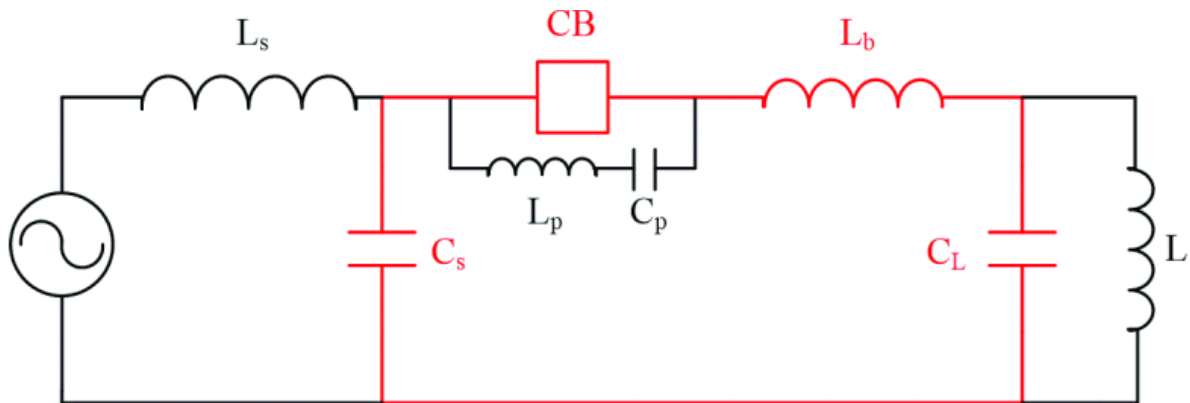


Figure 56 - Circuit of second parallel oscillation [44].

$$f_{p2} = \frac{1}{2\pi} \sqrt{\frac{C_L + C_s}{L_b C_L C_s}} \quad (22)$$

- **Main circuit oscillation**

The CB may or not interrupt the current after second parallel oscillation. If not, a main oscillation would still take place and could be calculated by Equation (23) [44].

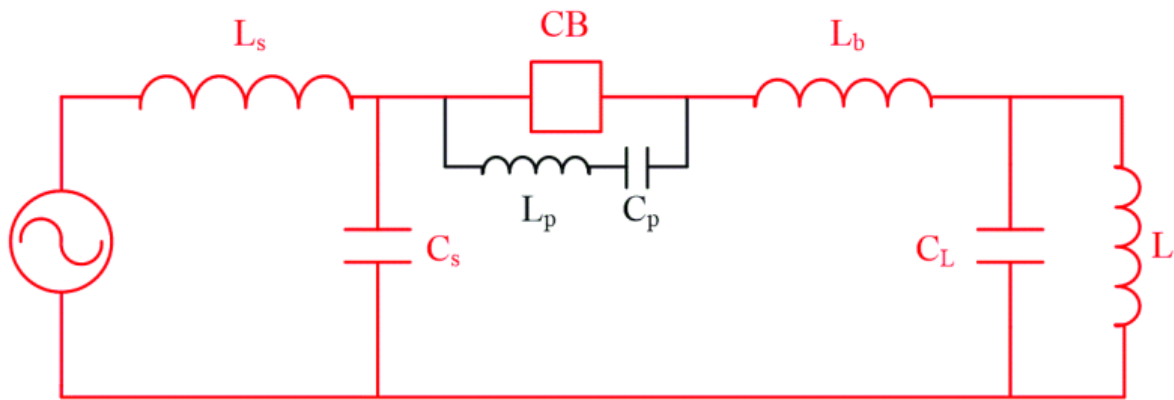


Figure 57 - Circuit of main oscillation (after reignition) [44].

$$f_{p2} = \frac{1}{2\pi} \sqrt{\frac{L_s + L}{L_s L (C_s + C_L)}} \quad (23)$$

4.4.6 Transient recovery voltage trv ('KRV') on the circuit breaker

As presented in section 4.4, when a shunt reactor is switched-off before its natural zero crossing current, the energy stored on its windings appears as an overvoltage on the circuit breaker poles. This voltage is called Transient Recovery Voltage (TRV) and may reach very high values [45].

If TRV is not carefully analyzed, these transients could overcome the limits for a safe operation of the circuit breakers as well as impose a transient above the insulation withstanding of reactor windings. For this reason, in order to comply with TRV from the safe operation of the circuit breaker (avoiding reignition), it may be required to use a circuit breaker of a rated voltage higher than the system voltage [45]. In this context, it becomes crucial to verify whether the circuit breaker is suitable to that specific application and some checks are done in terms of TRV and RRRV.

4.4.7 Rate of rise of recovery voltage (RRRV) on the circuit breaker

The RRRV measures the severity of a circuit breaker operation. Naturally, higher RRRV values are found in systems with higher natural oscillating frequency. The RRRV is a very important factor when selecting a circuit breaker.

4.4.8 Suppression peak or chopping overvoltage ('ka') on reactor insulation

As presented in the previous sections, suppression peak or chopping overvoltage (presented as ' k_a ' parameter) appear on reactor terminals and impose to its winding insulation an overvoltage that should be carefully analyzed by reactor manufacturer.

Typically, HV Shunt reactors present currents below 500 A. When the shunt reactor bank presents very low load currents when compared to rated current of the circuit breaker, the circuit breaker tends to interrupt the circuit faster, hence, with a higher chop current, increasing the k_a parameter and, as a result, the overvoltage transients on reactor terminals [45, 46].

The frequency of k_a is determined by the capacitance seen by the circuit breaker. Air core reactors present the capacitance C_L five or more times lower than for oil-filled reactors. Therefore, the transient frequency tends to be much higher for air-core technology [45].

4.4.9 Reignition overvoltage ('ks') on reactor insulation

When the limits of the circuit breaker is overcome (TRV or RRRV), a reignition occurs. In this moment, the load side voltage rapidly tends toward the source side voltage, producing the reignition overvoltage. The maximum overvoltage possible to be achieved (without damping) for a reignition at the recovery voltage peak is shown in Figure 58 [44]. Current chopping near zero can be observed in Figure 58 (a) and Current chopping with high chopping current value can be seen in Figure 58 (b).

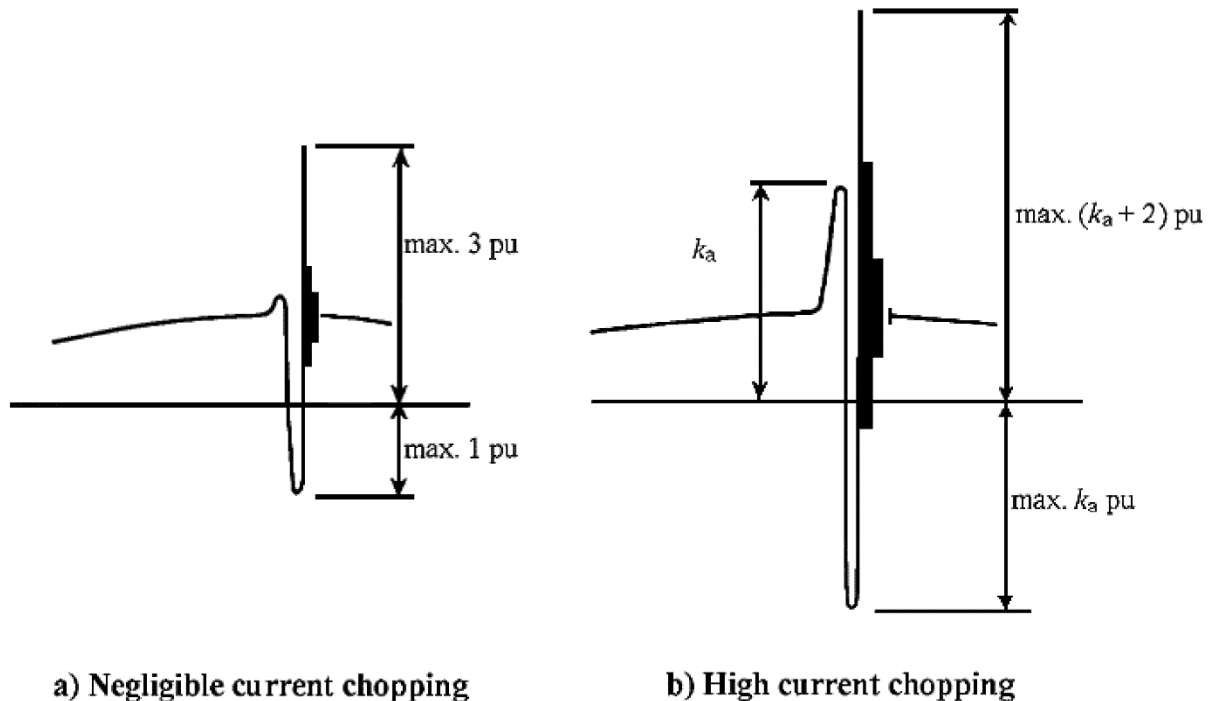


Figure 58 - Maximum reignition overvoltage [44].

Notice that the higher the current chopping (for faster breaker openings), the higher reignition overvoltage. This is the reason why de-energizing transients tends to be higher for reactor banks with lower rated currents (lower rated powers), since the circuit breaker tends to open them more easily. It is worth mentioning that even high-power reactor banks present rated currents much lower the circuit breaker current capabilities. Due to this, when a synchronized switching is not used, transient overvoltage, despite many times within acceptable limits, are never assumed to be negligible.

4.4.10 Circuit breaker selection considering TRV and RRRV

For both technologies, a proper circuit breaker selection, it is advisable to perform the TRV/RRRV studies, comparing the expected results to standardized limits. International Electrotechnical Commission (IEC) 62271-100 standard presents comprehensive guidelines for this selection, which is highly recommended to avoid the occurrence of restrikes. This caution reduces the transients imposed to reactor winding insulation, increasing its lifetime. Reignition should be avoided even if the reactor is designed to withstand these events.

4.5 OVERVOLTAGE MITIGATION ON CB AND REACTOR WINDINGS

Some techniques available to mitigate the overvoltage can be used for both technologies.

4.5.1 Surge arrester

Overvoltage caused by de-energization may cause an insulation breakdown of shunt reactors. To eliminate this risk and protect the insulation, surge arresters may be required to cut voltage at a safe protective level [25, 47]. Regardless the technology to be adopted, this point should be evaluated by the reactor manufacturer based on TRV studies.

4.5.2 Synchronized switching

To avoid the appearance of high inrush and de-energization transients, a controlled switching can be performed, eliminating harmful transients. This kind of switching, reduces significantly the stress for both mechanical and dielectric aspects, on the circuit breaker and the coil, reducing also the possibilities of circuit breaker restrike, which is also a cause of steep overvoltage. [25, 47, 48]. Regardless the technology to be adopted, this point should be evaluated by the reactor systems engineer (or circuit breaker manufacturer) based on TRV studies.

4.6 SWITCHING TRANSIENTS – CALCULATION AND SIMULATION (CASE STUDY)

Shunt Reactors of 150 Mvar, 400 kV, 50 Hz at both oil-immersed and air-core types have been observed. Typical parameters for both equipment technologies were taken into account for the analytical calculations (as per IEEE C37.015) and then, for the simulations using Alternative Transients Program (ATP). Input data for the study case can be observed in the Table 19. Typical parallel capacitances related to circuit breakers, disconnectors, CTs, CVTs and bus support transformers, were also included [43, 25].

The high-voltage 400 kV circuit breaker consists of two breaking chambers, each one with a potential grading capacitor $C = 500 \text{ pF}$ [43, 25]. Both equipment types present the same losses, allowing a direct comparison between them (including in terms of damping and transient duration). The ACR modeling took into account the “ARRANGEMENT 3” scheme, i.e., with three stacked coils per phase, as per Figure 37 and Figure 44. The series resistances were considered at power

frequency (50Hz). This is a conservative approach in terms of damping of switching overvoltage, since it is expected their values to be higher for transient events (high frequency), due to skin effect.

The basic circuit was derived from the circuit presented on Figure 59.

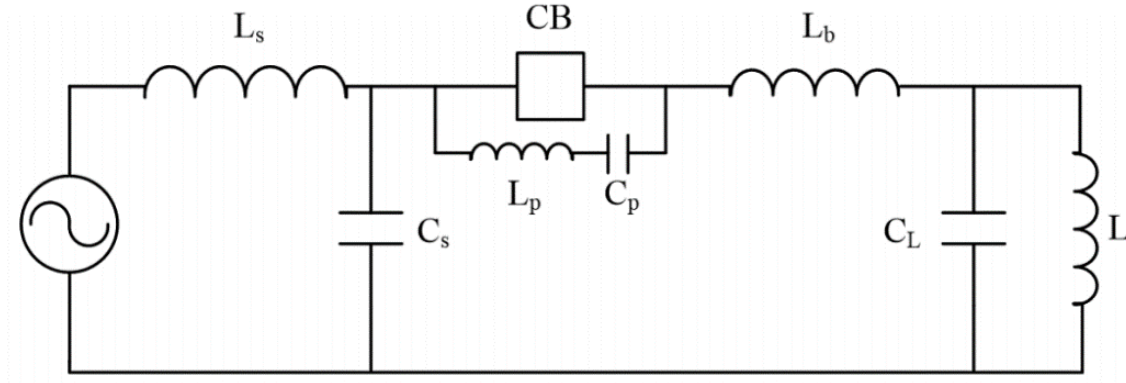


Figure 59 - Basic circuit for switching oscillations [44].

Where:

L_s = Source side inductance

CB = circuit breaker

C_s = Source side capacitance

L_p = Circuit breaker parallel inductance

C_p = Circuit breaker parallel capacitance (grading capacitance)

L_b = Series inductance of the connection

C_L = Equivalent load capacitance (equivalent stray capacitances from reactor bank + sum of all other capacitances in parallel with the reactor bank)

L = Phase inductance of shunt reactor in Henri

The capacitance C_L shall be the sum of the equivalent capacitance-to-ground of the reactor bank transient model (seen from incoming terminals) and the other parallel capacitances from disconnectors, CTs, CVTs, etc (refer to Figure 60).

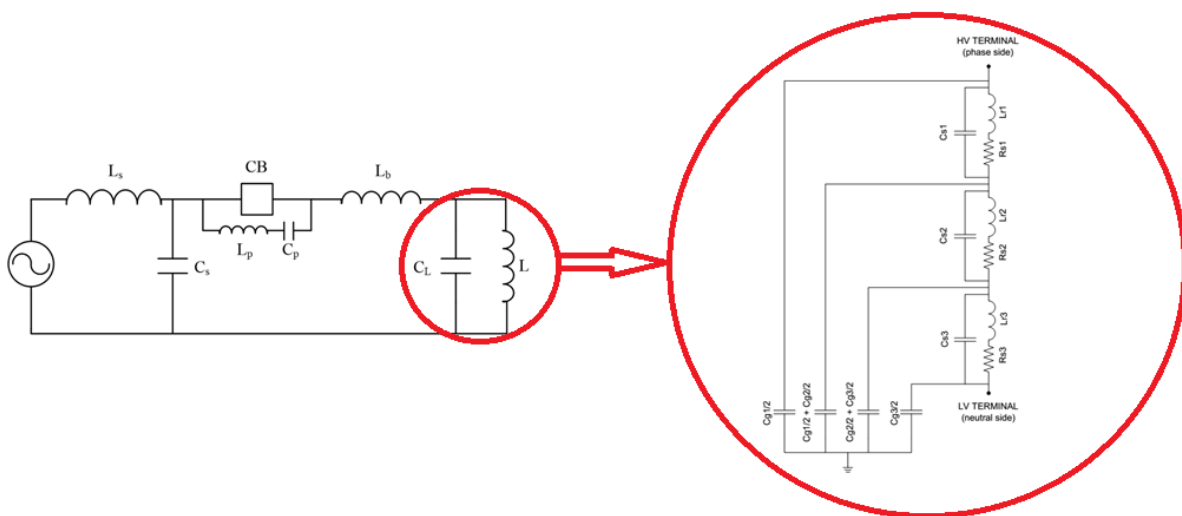


Figure 60 - Basic oscillating circuit adapted to ACR (with 3 coils in series per phase) [44].

C_L of Figure 60 should be calculated with equation (24).

$$C_L = C_{Leq} \text{ (reactor)} + C_L \text{ (busbar)} \quad (24)$$

Stray capacitances of main equipment usually installed at 400kV are presented in Table 18. They compose the total capacitance to ground as per equation (24).

Table 18 - Typical capacitances of main equipment at 400kV busbar

Equipment	Capacitance to ground (nF)
Disconnecter	0.2
CVT	4.4
CT	0.68
Bus support insulator	0.12

All the relevant parameters used for transient calculation and simulation are presented in Table 19.

Table 19 - 150Mvar 400kV 50Hz shunt reactor bank - Input data for case study calculations and simulations

Core type	Air	Iron
Rated Voltage [kV]	400	400
Rated Frequency [Hz]	50	50
Rated Reactive Power [Mvar]	150	150
Rated Current [I_{RMS}]	217	217
Rated Peak Current [I_{PEAK}]	307	307
Total losses @ 400 kV per phase [kW]	80	80
L_s – Source-side inductance [mH] ^a	Refer to ‘a’	Refer to ‘a’
C_s (source side) – Source-side capacitance to ground [nF/phase] ^b	0.44	0.44
L_p – Inductance in parallel with circuit breaker [mH]	Neglected	Neglected
C_p – Grading capacitance in parallel with circuit breaker [nF]	0.5	0.5
L_b – Inductance in parallel with circuit breaker [mH]	Neglected	Neglected
L - Inductance per phase [mH]	3395	3395
Neutral Grounding Reactance [Ω]	200	200
C_L (busbar) – Total parallel capacitance-to-ground of busbar [nF/phase] ^c	5.52	5.52

C_{Leq} (reactor) – Equivalent capacitance-to-ground of winding [nF/phase] ^d	0.23	3.8
R_s – Total series resistance of reactor windings [Ω] ^e	1.7	1.3
R_p – Resistance to ground of reactor windings [M Ω /phase] ^f	N/A	2.7

- ^a. System inductance (source-side) or “surge inductance” depends on the short-circuit level of the busbar. Case studies were based on two different levels (15 kA/s and 30 kA/s).
- ^b. C_s (source side) = disconnector + 2 x bus support insulator = 0.44 nF [25].
- ^c. CL (busbar) = disconnector) + CVT + CT + 2 x bus support insulator = 5.52 nF [25].
- ^d. CL (reactor) is the equivalent stray capacitance from transient model of the reactor bank (seen by incoming terminal of the reactor bank). For OIR, it is usually a concentrated parameter. However, for ACR, CL depends on the mounting arrangement. For this case study, CL (reactor) is based on the stray capacitances $C_{s1}=C_{s2}=C_{s3} = 0.13$ nF and $C_{g1} = 0.28$ nF, $C_{g2} = 0.29$ nF and $C_{g3} = 0.36$ nF.
- ^e. For the ACR, $R_{s1}=R_{s2}=R_{s3} = 0.57 \Omega$.
- ^f. Insulation to ground of air-core reactors is performed by base insulators (usually porcelain or composite). These insulators present a huge impedance to ground, which can be considered infinite for simulation purpose.

Notice that despite the fact that sum of the capacitance-to-ground of OIRs is about 4 times higher than the C_g of ACRs ($C_{g1_{acr}} + C_{g2_{acr}} + C_{g3_{acr}} = 0.93$ nF Vs $C_{g_{oir}} = 3.8$ nF), when the series capacitance of the dry-type reactor windings ($C_{s_{acr}}$) is taken into account, this difference reaches around 16 times ($C_{g_{oir}} = 3.8$ nF Vs $C_{Leq_{acr}} = 0.233$ nF). This difference impacts directly in some transient frequencies and on the RRRV (refer to

Table 23). Therefore, for dry-type reactors, both stray capacitances (C_s and C_g load-side) should be considered. For OIRs, due to the presence of the iron core, a lower number of turns is needed to reach the same inductance of the ACR. This lower number of turns allow the engineer to consider only the capacitance-to-ground value, neglecting the series capacitance on the transient model of the OIR, without major impacts on simulation results.

The saturation characteristics of OIR reactor that were introduced on ATP are presented in Figure 61 [25].

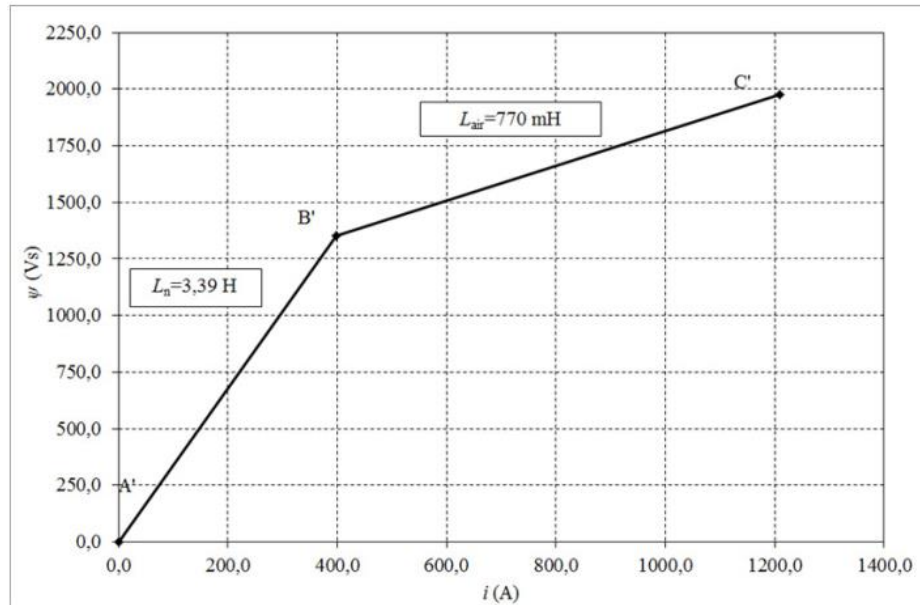


Figure 61 - Instantaneous flux-current saturation curve taken into account to OIR (150 Mvar) [25].

4.6.1 Conditions for calculations and simulations

For the comparison between transients of ACR and OIR, the following study cases were adopted.

- CASE 1: Energization of the Bank at voltage peak on Phase A (minimum inrush current on Phase A) without synchronized switching;
- CASE 2: Energization of the Bank at zero voltage on Phase A (maximum inrush current on Phase A) without synchronized switching;
- CASE 3: Energization of the Bank at voltage peak on three phases (minimum overall inrush current) with synchronized switching;
- CASE 4: De-energization of the Bank without synchronized switching without surge arrester and $I_{k''} = 15\text{kA/s}$;
- CASE 5: De-energization of the Bank without synchronized switching with surge arrester and $I_{k''} = 15\text{kA/s}$;
- CASE 6: De-energization of the Bank with synchronized switching without surge arrester and $I_{k''} = 15\text{kA/s}$;
- CASE 7: De-energization of the Bank without synchronized switching without surge arrester and $I_{k''} = 30\text{kA/s}$;
- CASE 8: De-energization of the Bank without synchronized switching with surge arrester and $I_{k''} = 30\text{kA/s}$;

- CASE 9: De-energization of the Bank with synchronized switching without surge arrester and $I_k'' = 30\text{kA/s}$;

4.6.2 Transient calculations based on IEEE C37.015 guidelines and electrical circuits basics

- **Energizing transients on Reactor terminal (calculations)**

The summary data taken into account for inrush current calculations are presented in Table 20.

The instant of circuit breaker closing is crucial for increasing or decreasing the inrush values. As example, three different closing instants were used: at peak voltage of phase A (case 1), which results in the lower inrush current on that phase; at zero voltage of phase A (case 2), which results in the maximum inrush current on that phase and at peak voltage for all of the three phases (case 3), possible by using synchronized switching, which allows minimum inrush currents for all of the phases.

Table 20 - Energization transients - conditions for calculations and simulations

	Type	Switching time	Type	Short-time current on busbar kA/s	Grading Capacitors	Surge Arrester	Opening time PhA PhB PhC (ms)
CASE 1	OIR	Umax	OIR	15	Yes	No	20 20 20
	ACR	(phase A)	ACR	15	Yes	No	20 20 20
CASE 2	OIR	0V (phase A)	OIR	15	Yes	No	15 15 15
	ACR		ACR	15	Yes	No	15 15 15
CASE 3	OIR	controlled	OIR	15	Yes	No	20 26.7 13.3
	ACR	switching	ACR	15	Yes	No	20 26.7 13.3

In order to simplify the analysis, phase A was set as reference phase for calculations. Inrush current calculation results are presented in Table 21.

Table 21 - Energization transients - calculation results

	Type	E _{peak} (kV)	R _s (ohm)	t (ms) ^a	φ of Phase A (degree)	Inrush Current on Phase A [A (pu)]	Max. Inrush Current (all phases) [A (pu)]
CASE 1	OIR	326.6	1.3	20 (zero V)	-90	305.7 (1.0)	608.0 (2.0)
	ACR	326.6	1.7	20 (zero V)	-90	305.8 (1.0)	608.0 (2.0)
CASE 2	OIR	326.6	1.3	15 (peak V)	-90	608.0 (2.0)	608.0 (2.0)
	ACR	326.6	1.7	15 (peak V)	-90	608.0 (2.0)	608.0 (2.0)
CASE 3	OIR	326.6	1.3	20 (zero V)	-90	305.8 (1.0)	305.8 (1.0)
	ACR	326.6	1.7	20 (zero V)	-90	305.8 (1.0)	305.8 (1.0)

^a Voltage wave at t=0s start at its positive peak value. This is the reason for peak voltage to be at 15ms (and not at 20ms, with power frequency of 50Hz).

Notice that the maximum calculated inrush currents (as per equation 17) are equal to ACR and OIR. This happens because calculations only consider linear components and, unlike ACRs, OIRs present a higher inrush current due to the presence of the iron core, which is saturable from a certain flux value. OIRs may present inrush currents of 5 pu or above (as presented in simulation results).

- **De-energizing transients on Reactor terminal and TRV on circuit breaker (calculations)**

A summary taken into account for switching-off overvoltage calculations is presented in Table 22. Unlike inrush events, the main issue when switching-off a reactor is related to the overvoltage imposed to the circuit breaker and the winding insulation of the reactor bank.

Table 22 - De-energizing transients - conditions for calculations and simulations

	Type	Switching time	Short-time current on busbar kA/s	Grading Capacitors	Controlled Switching	Surge Arrester	Protective level of SA (pu)
CASE 4	OIR	Umax	15	Yes	No	No	-
	ACR	(phase A)	15	Yes	No	No	-
CASE 5	OIR	Umax	15	Yes	No	Yes	1.7
	ACR	(phase A)	15	Yes	No	Yes	1.7
CASE 6	OIR	controlled	15	Yes	Yes	No	-
	ACR	switching	15	Yes	Yes	No	-
CASE 7	OIR	Umax	30	Yes	No	No	-
	ACR	(phase A)	30	Yes	No	No	-
CASE 8	OIR	Umax	30	Yes	No	Yes	1.7
	ACR	(phase A)	30	Yes	No	Yes	1.7
CASE 9	OIR	controlled	30	Yes	Yes	No	-
	ACR	switching	30	Yes	Yes	No	-

Notice that the only difference between cases 7 to 8 and 4 to 6 is the short-circuit current on the busbar.

Table 23 - De-energizing transients - calculation results

	Type	ka (pu)	kc (pu)	krv (pu)	kp (pu)	ks (pu)	fL (kHz)	fp1 (kHz)	fp2 (kHz)	fm (kHz)	lc (A)	tp (μs)	t3 (μs)	RRRV (kV/μs)
CASE 4	OIR	1.30	1.60	2.60	2.30	3.90	0.89	7.12	7.76	7.33	4.29	558.9	486.2	1.7
	ACR	1.31	1.61	2.61	2.30	3.91	1.14	7.12	7.87	9.20	4.26	439.1	382.0	2.2
CASE 5	OIR	1.30	1.60	1.70	1.85	2.55	0.89	7.12	7.76	7.33	4.29	558.9	486.2	1.1
	ACR	1.31	1.61	1.70	1.85	2.55	1.14	7.12	7.87	9.20	4.26	439.1	382.0	1.5
CASE 6	OIR	1.32	1.62	1.70	1.85	2.55	1.40	7.12	8.01	11.12	4.23	356.8	310.5	2.5
	ACR	1.31	1.61	1.70	1.85	2.55	1.16	7.12	7.88	9.38	4.26	430.1	374.2	2.1
CASE 7	OIR	1.30	1.60	2.60	2.30	3.90	0.89	7.12	7.76	10.33	4.29	558.9	486.2	1.7
	ACR	1.31	1.61	2.61	2.30	3.91	1.14	7.12	7.87	12.97	4.26	439.1	382.0	2.2
CASE 8	OIR	1.30	1.60	1.70	1.85	2.55	0.89	7.12	7.76	10.33	4.29	558.9	486.2	1.1
	ACR	1.31	1.61	1.70	1.85	2.55	1.14	7.12	7.87	12.97	4.26	439.1	382.0	1.5
CASE 9	OIR	1.32	1.62	1.70	1.85	2.55	1.40	7.12	8.01	15.67	4.23	356.8	310.5	2.5
	ACR	1.31	1.61	1.70	1.85	2.55	1.16	7.12	7.88	13.22	4.26	430.1	374.2	2.1

4.6.3 Transient simulations on ATP

The case studies informed on Table 20 and Table 22 were simulated on ATP, in order to observe the outcomes and establish a direct comparison between both technologies. Considering that this comparison is the main goal of this work (and not very accurate transients for equipment design), the circuit breaker was represented as an ideal switch with its associated grading capacitances (and not statistic switches, as commonly used on studies of this nature). Moreover, due to the same reason, the source-side circuit is being represented as an ideal source with system reactance and bus capacitances, only (without multiple-bus system, which is the common practice for this kind of simulation).

For the inrush simulations, a ΔT of 10^{-4} seconds and a T_{max} of 3 seconds were considered. For de-energizing transients, these parameters were set as 10^{-6} seconds and 0.5 seconds, respectively.

The equivalent three-phase circuit for OIR is presented in Figure 62, without the use of surge arresters at incoming busbar.

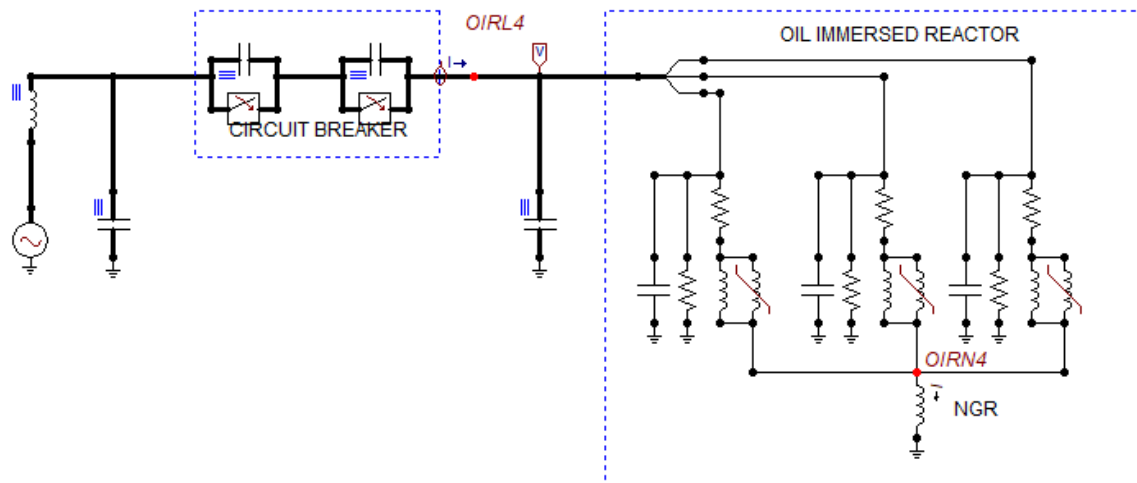


Figure 62 - 400 kV 150 Mvar 50 Hz Oil Immersed shunt reactor bank (w/o surge arrester) [Image of author's ownership].

The equivalent three-phase circuit for OIR is presented in Figure 63, with the use of surge arresters at incoming busbar.

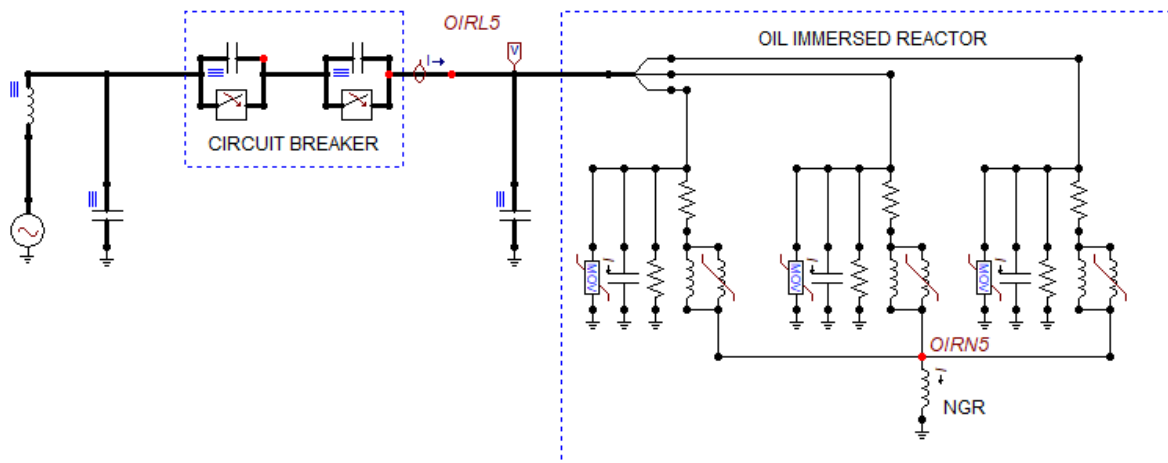


Figure 63 - 400 kV 150 Mvar 50 Hz Oil Immersed shunt reactor bank (with surge arrester) [Image of author's ownership].

The equivalent three-phase circuit for ACR is presented in Figure 64, without the use of surge arresters at incoming busbar.

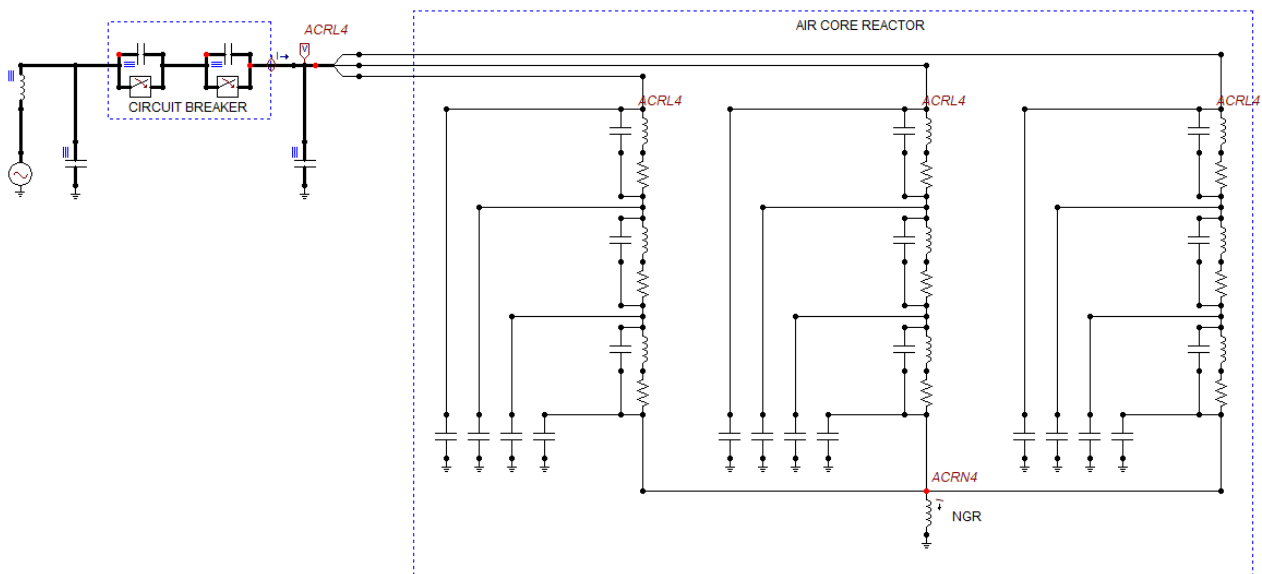


Figure 64 - 400 kV 150 Mvar 50 Hz Air Core shunt reactor bank (w/o surge arrester) [Image of author's ownership].

The equivalent three-phase circuit for ACR is shown in Figure 65, with the use of surge arresters at incoming busbar.

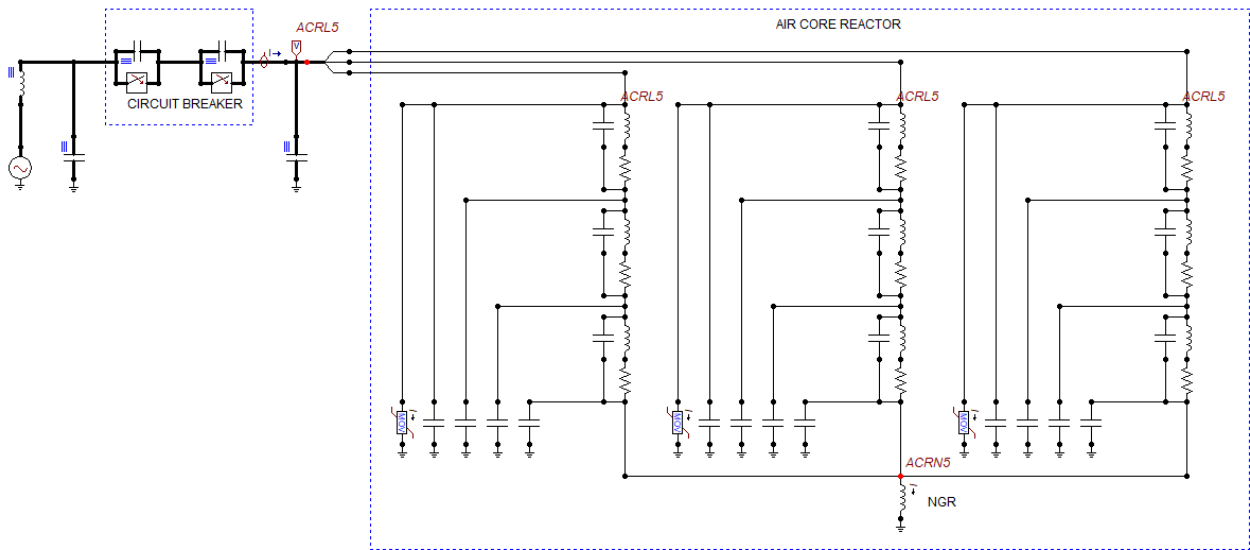


Figure 65 - 400 kV 150 Mvar 50 Hz Air Core shunt reactor bank (with surge arrester) [Image of author's ownership].

The goal of these simulations is to analyze the transient conditions associated to the switching of the circuit breaker. Inrush currents during energizing of the coils as well as transient voltages related to de-energizing switching are analyzed and compared.

The series resistance represented at both ACR and OIR do not affect significantly the peak overvoltage and overcurrent, but introduce damping to the circuit, reducing the requirements in terms of energy and repetitive surges analysis, which tend to be more aggressive to dry-type reactor banks. The frequency at which the resistance is taken is usually the power frequency (50 or 60 Hz), which is a conservative approach. In real situation, the resistance is greater since the transients (high-frequency events), increase the resistance of the coils due to skin effect.

- **Energizing transients on Reactor terminal (simulation results)**

The cases 1, 2 and 3 were simulated. Notice that unlike calculations, inrush currents for OIR are much higher than the one for ACR due to the presence of the iron core, which is saturable from a certain flux value. OIRs may present inrush currents of above 5 pu, which may affect mainly the protection, if not properly adjusted.

Dry-type reactors take advantage on this regard. They do not present any issue related to inrush currents, since 2 pu is considered a low value for this parameter.

The main simulation results of CASE 1 are presented to both reactor types. In the figures showing three-phase simulations, red curves are phase A, green curves are phase B and blue curves are phase C.

The simulation results of the CASE 2 and CASE 3 can be consulted on APPENDIX 2. Source-side voltages can be seen in Figure 66 and Figure 67.

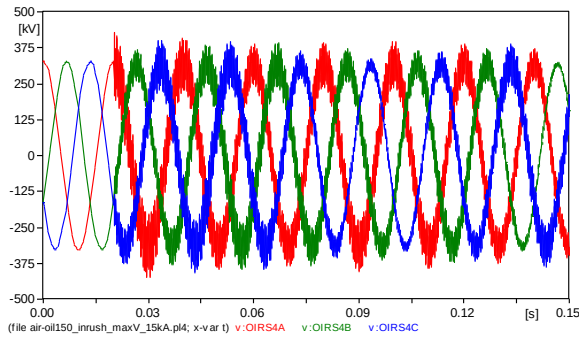


Figure 66 - CASE 1 - Source-side voltages of OIR.

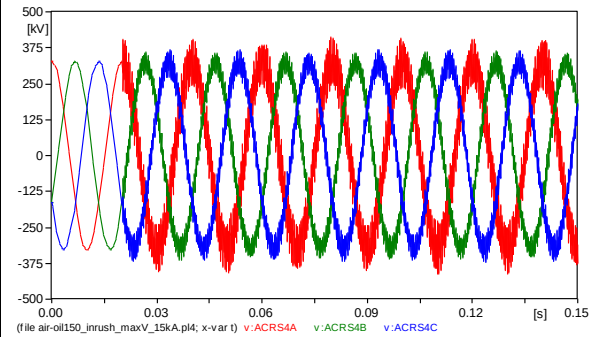


Figure 67 - CASE 1 - Source-side voltages of ACR.

Load-side voltages (on reactor terminals) can be seen in Figure 68 and Figure 69.

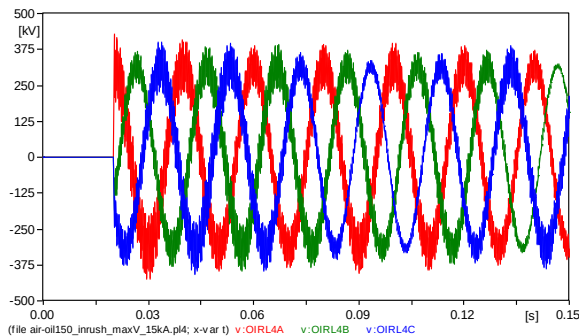


Figure 68 - CASE 1 - Load-side voltages of OIR.

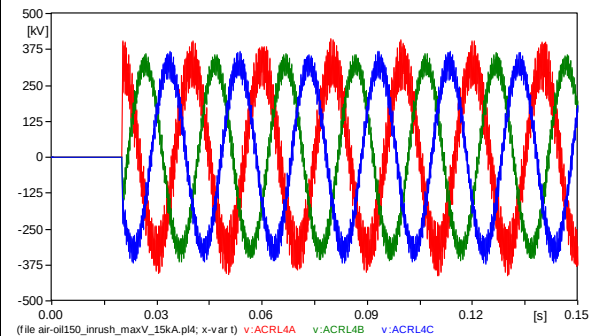


Figure 69 - CASE 1 - Load-side voltages of ACR.

Inrush currents can be seen in Figure 70 and Figure 71.

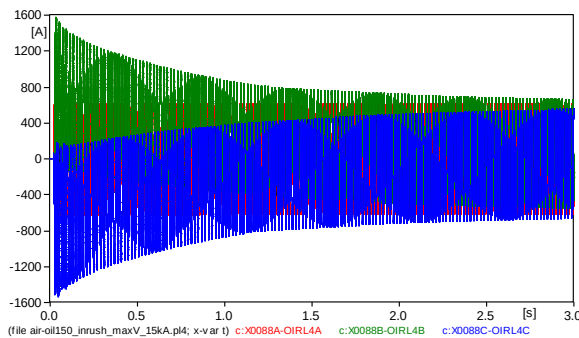


Figure 70 - CASE 1 - Inrush currents of OIR.

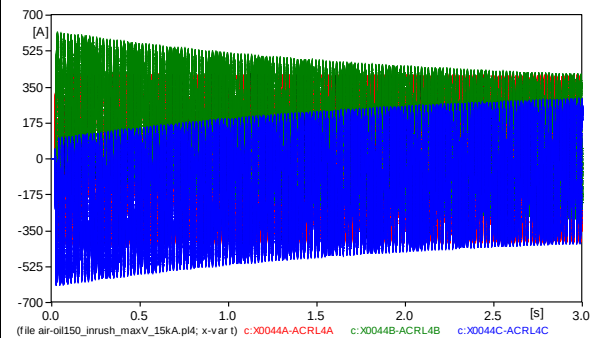


Figure 71 - CASE 1 - Inrush currents of ACR.

Inrush currents can be seen in detail in Figure 72 and Figure 73.

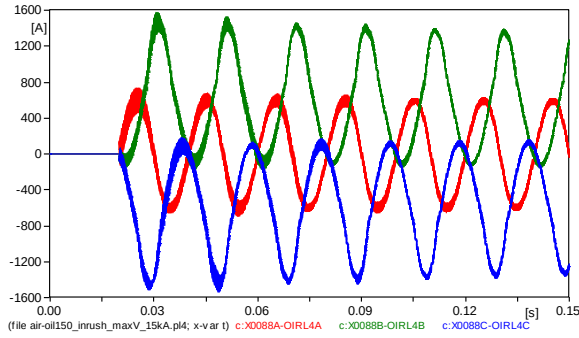


Figure 72 - CASE 1 - Inrush currents of OIR (three-phases).

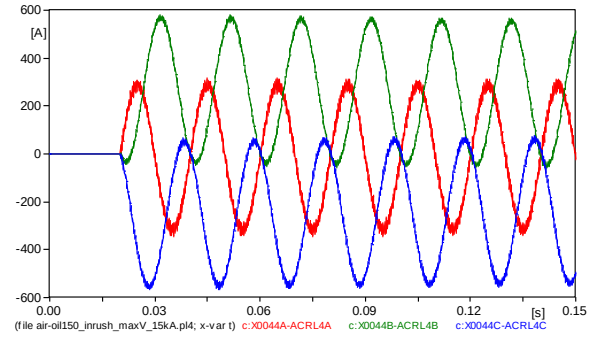


Figure 73 - CASE 1 - Inrush currents of ACR (three-phases).

Neutral currents can be seen in Figure 74 and Figure 75.

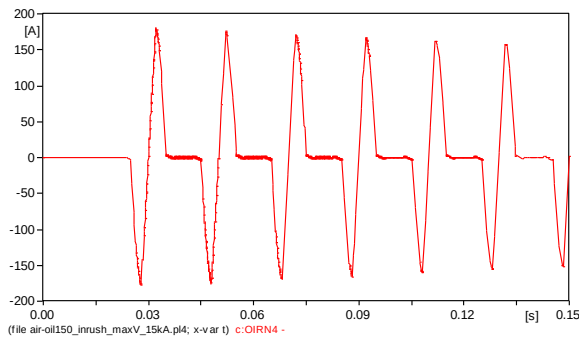


Figure 74 - CASE 1 - Neutral current of OIR.

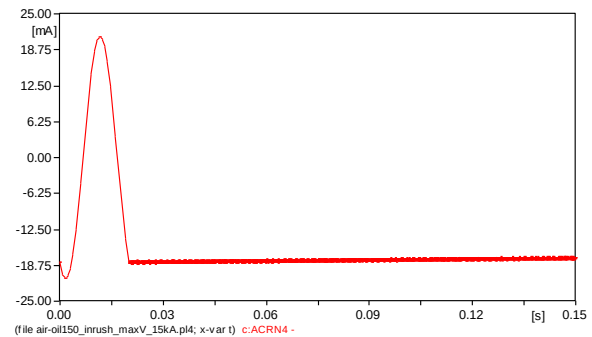


Figure 75 - CASE 1 - Neutral current of ACR.

The summary of the simulation results is presented in Table 24.

Table 24 - Summary of simulation results (inrush currents)

	Type	VL_max [kVp (pu)]	Maximum Inrush Current for all phases [A (pu)]
CASE 1	OIR	429.0 (1.5)	1512 (5.0)
	ACR	403.0 (1.4)	581 (1.9)
CASE 2	OIR	390.0 (1.3)	1572 (5.2)
	ACR	387.0 (1.3)	601 (2.0)
CASE 3	OIR	452.0 (1.5)	656 (2.2)
	ACR	408.0 (1.4)	339 (1.2)

- **De-energizing transients on Reactor terminal and TRV on circuit breaker (simulation results)**

The main simulation results of CASE 4 are presented to both reactor types. In the figures showing three-phase simulations, red curves are phase A, green curves are phase B and blue curves, phase C.

The simulation results of the CASE 5 to CASE 9 can be seen in APPENDIX 2.

Source-side voltages can be seen in Figure 76 to Figure 77

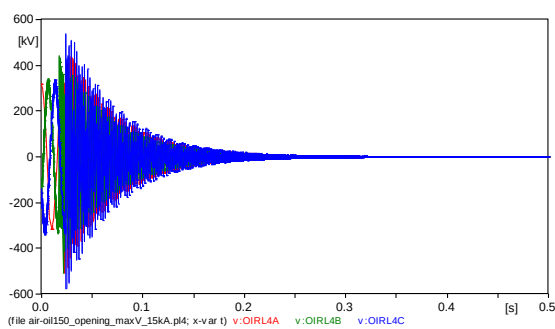


Figure 76 - CASE 4 - Source-side voltages of OIR.

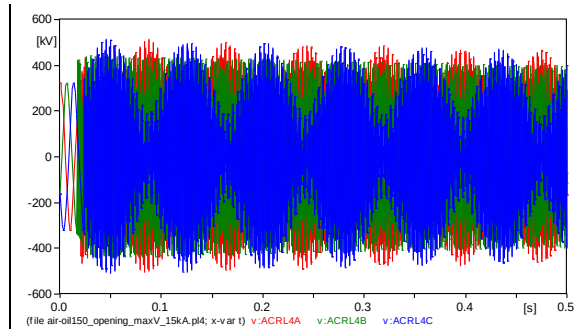


Figure 77 - CASE 4 - Source-side voltages of ACR.

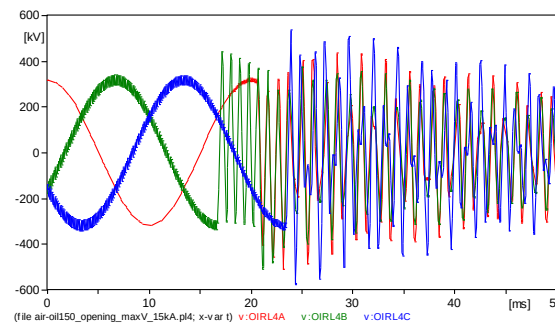


Figure 78 - CASE 4 - Source-side voltages of OIR (three-phases).

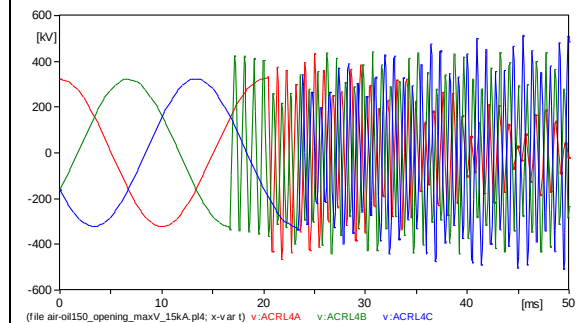


Figure 79 - CASE 4 - Source-side voltages of ACR (three-phases).

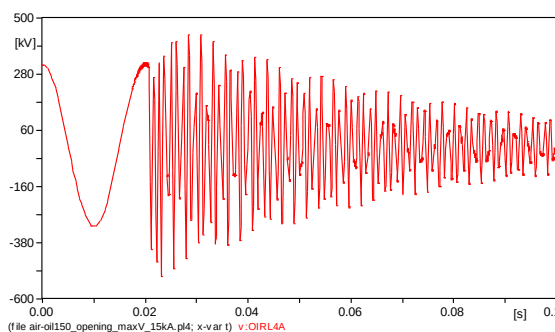


Figure 80 - CASE 4 - Source-side voltages of OIR (Phase A).

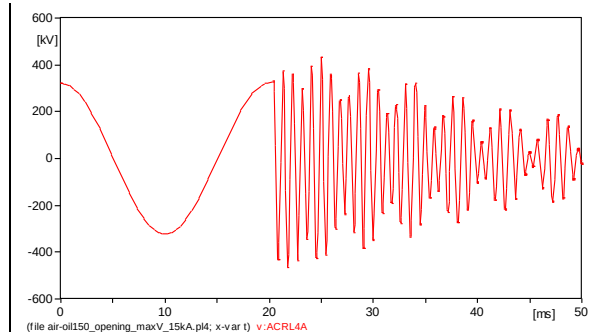


Figure 81 - CASE 4 - Source-side voltages of ACR (Phase A).

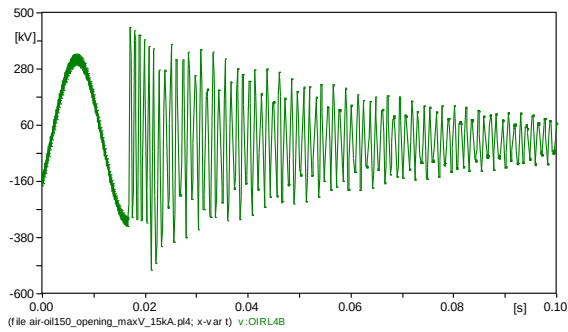


Figure 82 - CASE 4 - Source-side voltages of OIR (Phase B).

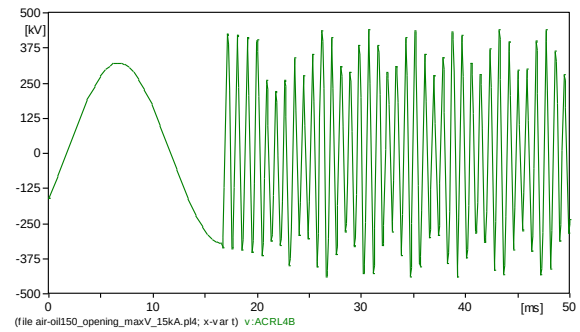


Figure 83 - CASE 4 - Source-side voltages of ACR (Phase B).

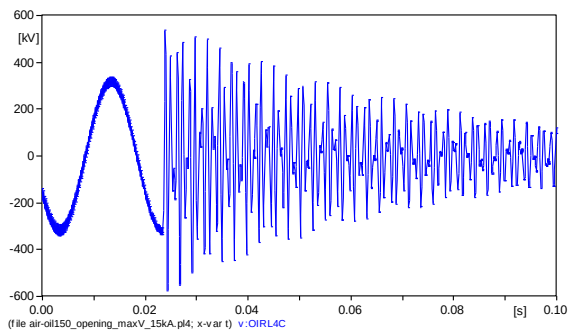


Figure 84 - CASE 4 - Source-side voltages of OIR (Phase C).

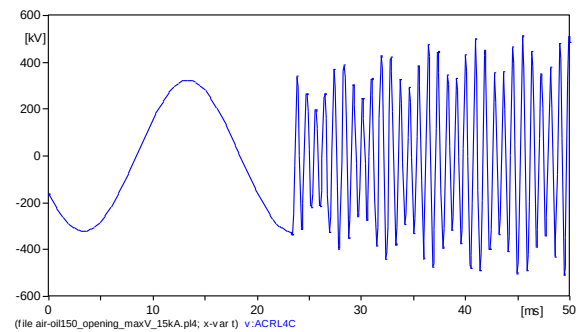


Figure 85 - CASE 4 - Source-side voltages of ACR (Phase C).

• OIR Vs ACR (phase overlap)

In the figures showing phase overlap (Figure 86 to Figure 91), the phases are presented individually at each time, comparing both technologies. For these figures, red curves are to OIR and green ones are to ACR.

To compare directly the transients on both equipment, the phases

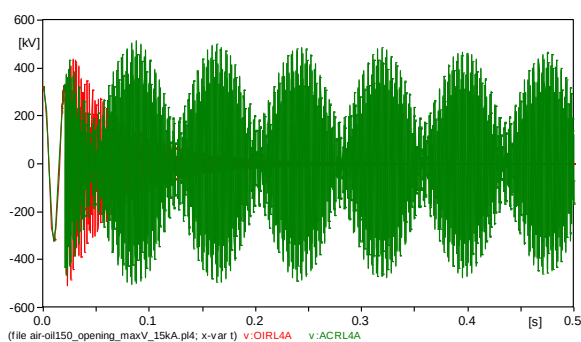


Figure 86 - CASE 4 - Source-side voltages OIR vs ACR overlap - Phase A.

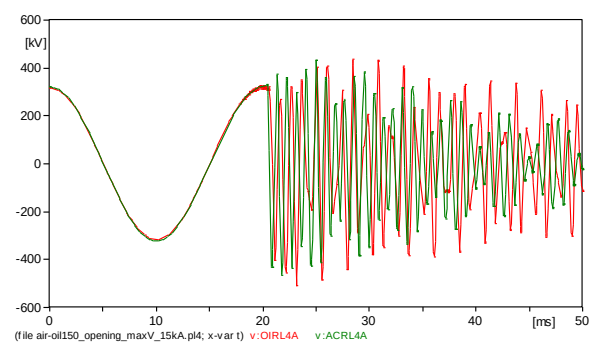


Figure 87 - CASE 4 - Source-side voltages OIR vs ACR overlap - Phase A (detail).

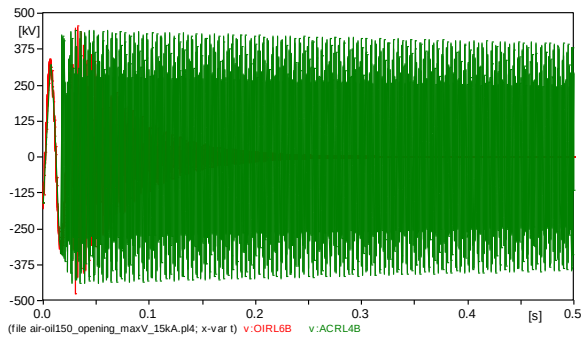


Figure 88 - CASE 4 – Source-side voltages OIR vs ACR overlap – Phase B.

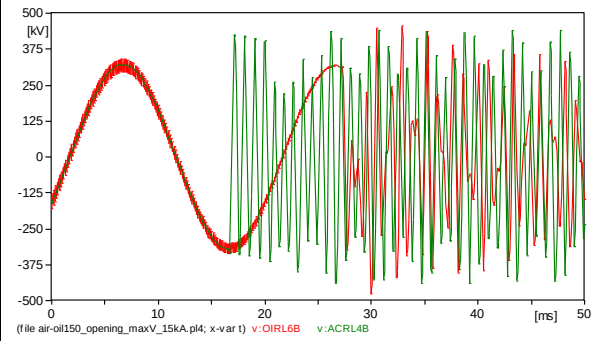


Figure 89 - CASE 4 – Source-side voltages OIR vs ACR overlap – Phase B (detail).

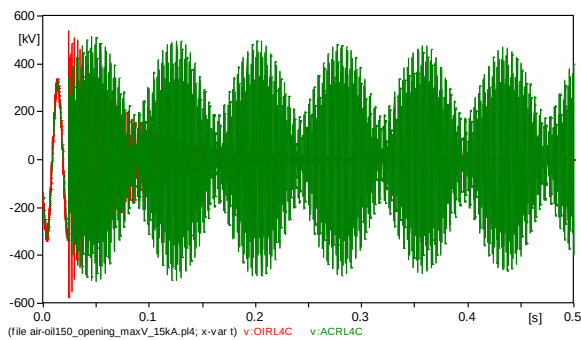


Figure 90 - CASE 4 – Source-side voltages OIR vs ACR overlap – Phase C.

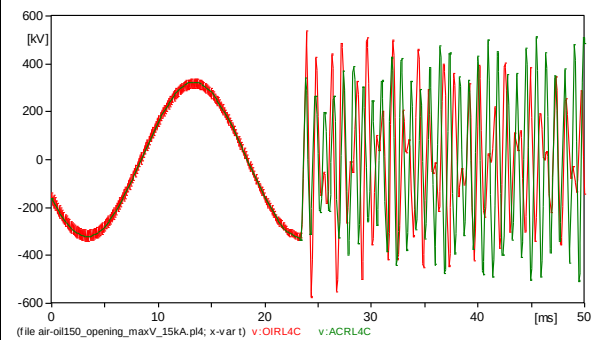


Figure 91 - CASE 4 – Source-side voltages OIR vs ACR overlap – Phase C (detail).

The compilation of results of all the simulated waves (available in APPENDIX 2) are shown in Table 25.

Table 25 - De-energizing transients - simulation results

	Type	ka [kV (pu)]	krv [kV (pu)]	fL (kHz)	RRRV (kV/μs)
CASE 4	OIR	570.0 (1.8)	857.6 (2.7)	1.14	1.7
	ACR	511.0 (1.6)	757.6 (2.4)	1.09	1.7
CASE 5	OIR	455.0 (1.4)	788.6 (2.5)	1.12	1.9
	ACR	417.0 (1.3)	740.6 (2.3)	1.07	1.6
CASE 6	OIR	517.0 (1.6)	781.6 (2.4)	1.22	1.8
	ACR	543.0 (1.7)	787.6 (2.5)	1.15	1.7
CASE 7	OIR	612.0 (1.9)	883.6 (2.8)	1.15	2.0
	ACR	516.0 (1.6)	760.6 (2.4)	1.11	1.7
CASE 8	OIR	460.0 (1.5)	789.6 (2.5)	1.09	1.8
	ACR	415.0 (1.3)	746.6 (2.3)	1.07	1.6
CASE 9	OIR	546.0 (1.7)	801.6 (2.5)	1.20	2.4
	ACR	548.0 (1.7)	790.6 (2.5)	1.12	1.7

4.6.4 Analysis of simulation results and comparison between calculation and simulation

- **Energizing transients on Reactor terminal (simulation results)**

For OIRs, high inrush currents shall be carefully analyzed mainly to avoid trip of the protection for these currents (the same way of power transformers). This is not an issue to ACRs.

The divergences between calculated and simulated results are presented in Table 26. Notice that there is a minor divergence to ACR, but a huge change to OIR. This is due to the fact that calculations only considered linear components and, unlike ACRs, OIRs present a higher inrush current due to the presence of the iron core, which is saturable from a certain flux value. OIRs may present inrush currents of 5 pu or above (in line with simulation results).

Table 26 - Percentage of error between simulations and calculations for inrush currents

	Type	$\Delta I_{\text{inrush sim/calc}} (\%)$
CASE 1	OIR	149 %
	ACR	-4 %
CASE 2	OIR	159 %
	ACR	-1 %
CASE 3	OIR	115 %
	ACR	11 %

The small error to the ACR as well as a higher value to the OIR obtained from simulations (as expected), indicates the accuracy of the models adopted.

- **De-energizing transients on Reactor terminal and TRV on circuit breaker (simulation results)**

Notice that chopping overvoltage (or 'ka' values from simulations), are slightly higher than calculations (refer to

Table 23, Table 25 and Table 27). The main reason is that from simulations, the peak values adopted were assumed to be the higher values, even when the occurrence is only a few "impulse waves" and/or with low duration (yellow marks on Figure 93).

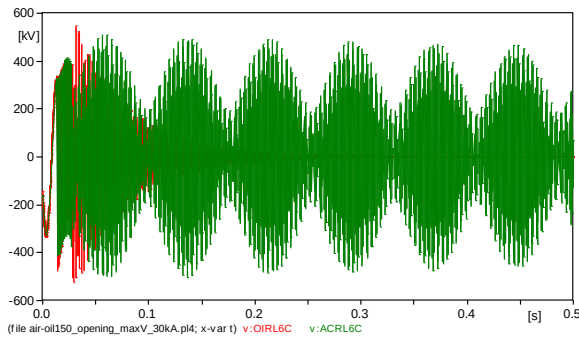


Figure 92 - De-energizing transients - ACR vs OIR surge comparison.

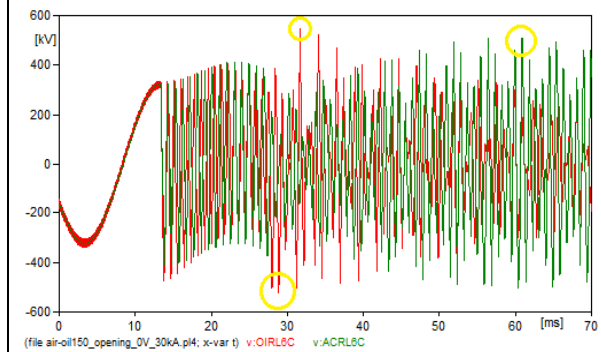


Figure 93 - De-energizing transients - ACR vs OIR surge comparison (zoom).

Notice also that for chopping overvoltage (or 'ka'), the very first transient waves in this example (due to chopping), present a lower peak value than the one to be "felt" by the reactor and circuit breaker afterwards. These first peaks are the only ones that appear on the calculations. This explains the divergence between the calculation and simulation.

Important: from the winding insulation of reactor perspective, having some insulated peaks may not be relevant to reduce its lifespan. However, the incidence of repetitive surges may require, most of the times, the reactor manufacturer to increase the safety margin between the design and actual limits, in terms of dielectric withstanding. Therefore, TRV studies should be disclosed to the manufacturer to guarantee suitable lifespan, specially to dry-type reactor, which tends to present lower damping and more repetitive surges (as seen at green waves of Figure 92, compared to red ones), due to the absence of a resistance to ground on transient model. **However, these surges tend to be much lower than acceptable limits designed to withstand the lightning impulse waves, not presenting, in general, concerns on this regard. The manufacturer is always the best source of information in case of analysis on this regard.**

Load frequency (' f_L ') is very similar between simulations and calculations, since it depends only on the right selection of L and C_L parameters on equivalent circuit used for calculation. Notice that the frequency for ACRs, tends to be slightly higher, due to the reduction on capacitance-to-ground values. This tends to increase the RRRV, which should also be analyzed, specially to guarantee the suitable ratings of the circuit breaker.

A summary with the percentage of error between simulations and calculations, for de-energizing transients is presented in Table 27.

Table 27 - Percentage of error between simulations and calculations for de-energizing transients

	Type	Δk_a sim/calc (%)	Δk_{rv} sim/calc (%)	Δf_L sim/calc (%)	$\Delta RRRV$ sim/calc (%)
CASE 4	OIR	34.6 %	1.1 %	27.0 %	-3.0 %
	ACR	19.9 %	-11.0 %	-4.0 %	-24.0 %
CASE 5	OIR	7.4 %	42.0 %	25.0 %	66.0 %
	ACR	-2.2 %	33.4 %	-6.0 %	10.0 %
CASE 6	OIR	20.2 %	40.8 %	-13.0 %	-27.0 %
	ACR	27.3 %	41.9 %	-1.0 %	-17.0 %
CASE 7	OIR	44.5 %	4.2 %	29.0 %	15.0 %
	ACR	21.0 %	-10.6 %	-3.0 %	-24.0 %
CASE 8	OIR	8.6 %	42.2 %	22.0 %	58.0 %
	ACR	-2.7 %	34.5 %	-6.0 %	10.0 %
CASE 9	OIR	27.0 %	44.4 %	-14.0 %	-3.0 %
	ACR	28.5 %	42.4 %	-4.0 %	-17.0 %

The small error between calculations and simulations, indicates the accuracy of the equations used on calculations as well as of the models adopted on simulations. These facts reinforce the reliability of the data being used on this analysis.

A summary with the most advantageous situation to each technology, in terms of transients is presented in Table 28.

Table 28 - Advantages of each technology in terms of transients

Advantages	OIR	ACR
During energization, lower inrush current amplitudes due to the absence of the iron core	X	✓
During energization, very low influence of short-circuit current (system series inductance) on inrush transients	✓	✓
During switching-off, lower duration for the transients due to reduced resistance to ground value	✓	X
During switching-off, presents lower RRRV values	✓	X
During switching-off, lower oscillating frequency on reactor side	✓	X

5 SUMMARY OF GENERAL ANALYSIS

Based on detailed points of previous sections, a summary of the comparison between Air core and Oil-filled shunt reactors is presented in Table 29, pointing out the most advantageous technology according to each parameter.

Table 29 - Summary of advantages comparing both technologies

Advantage	OIR	ACR
Simpler construction	X	✓
Lower delivery leadtime	X	✓
Cheaper transportation	X	✓
Lower mass and simplified foundation (no need of oil retention base)	X	✓
No need of fire wall	X	✓
Simpler and faster erection & commissioning	X	✓
Low impact of humidity on turn-to-turn insulation failure	X	✓
Cheaper spare parts (no need of full equipment)	X	✓
No risk of bushing failures (reducing risk of failure modes do ground)	X	✓
Lower noise levels	X	✓
Cheaper operation & maintenance	X	✓
Faster and cheaper replacement in case of failure	X	✓
During energization, lower inrush current amplitudes due to the absence of the iron core	X	✓
No need of extra safety margin on temperature rise to reduce the risk of turn-to-turn failures	X	✓
Optimized design for banks with high rated power without losses limitation	✓	✓
Optimized design for banks with low rated power without losses limitation	✓	✓
Optimized design for banks with high rated power with losses limitation	✓	✓
Losses ^a	✓	✓
Safety for personnel ^b	✓	✓
Installation area ^c	✓	✓

During energization, very low influence of short-circuit current (system series inductance) on inrush transients	✓	✓
Low impact on equipment costs with low loss target value	✓	X
Optimized design for banks with low rated power with losses limitation	✓	X
MC1 clearance: no need of calculation and precautions (foundation and metallic parts nearby the reactor)	✓	X
MC2 clearance: no need of calculation and precautions (foundation and metallic parts nearby the reactor)	✓	X
MC3 clearance: no need of calculation and precautions (installation area and fencing for access control)	✓	X
MC4 clearance: no need of calculation and precautions (installation area and fencing for access control)	✓	X
No need of special care on insulation by reactor manufacturer, due to the concentration of transient waves on first 10 % of windings	✓	X
Tertiary windings for auxiliary services available under request	✓	X
Lower magnetic field lines spread on area surrounding the equipment and reduced distance from the reactor to occupational and general public ^d	✓	X
Possibility to approach the equipment for visual inspection when energized	✓	X
No need of access control fences (live parts not accessible)	✓	X
No need of voltage signal for protection (no need of VT or CVT if signal is not available)	✓	X
During switching-off, lower duration for the transients due to reduced resistance to ground value	✓	X
During switching-off, presents lower RRRV values	✓	X
During switching-off, lower oscillating frequency on reactor side	✓	X

^{a.} Despite ACR tend to present higher losses when both are designed in the limit of their thermal class (not a rule, depending on bank ratings), this was considered to be similar, since ACR manufacturer can increase cross section area of windings to have the same losses of OIR.

^{b.} Equal since suitable access control is considered for air-core reactors.

^{c.} Despite installation area is similar to both technologies, when the access control fencing (required to ACR) is included in the comparison, ACR installation area tends to be slightly higher, which may be an issue for substations with very restricted installation area.

^{d.} In substations where the installation of the reactor is intended to be close to general public sidewalks and/or very close to control room and worker circulation areas, the use of ACR may not be recommended (to be checked case by case), since the spread of magnetic field lines (not existing for OIR), may require this equipment to be installed farther from such areas.

6 CONCLUSION

With the advance of manufacturing techniques as well as on the properties of insulation materials used on shunt reactors, it is unquestionable that, nowadays, there is technology and manufacturers ready to offer dry type equipment to be applied at high and extra-high voltage systems, keeping the same reliability and lifespan. The use of such equipment is not only technically possible, but it is also aligned with global trends of sustainability and constant seek for cost reduction (an environmental-friendly and cost-effective product, presenting reduced acquisition, operational and maintenance costs).

In terms of losses, ACR can have similar losses of OIR, based on some conditions and design techniques of ACR, previously discussed on this work. Therefore, for the majority of the cases and for many bank ratings, this is not an issue and the viability of the ACR equipment should be evaluated case by case. Losses are very linked to acquisition costs. The lower the losses target, the higher the ACR acquisition costs, reducing its competitiveness compared to OIR.

In terms of turn-to-turn insulation, it was noticed that the temperature is more critical to OIR than to ACR, due to the possibility of failures caused by the presence of water in the insulating oil and kraft paper, which do not exist to ACR. Therefore, it is not needed in the ACR specification to require a very low temperature rise limit (below the one indicated in the standard to the thermal class to be adopted), as commonly requested to OIR. However, it was also noticed that dielectric aspects are more critical to ACR than to OIR, due to the presence of capacitance-to-ground values in different levels from bottom to top part of the ACR equipment, which results in non-linearity on transient waves, stressing more the first 10% of the windings. This concentrated overstress does not tend to be an issue, when analyzed by the ACR manufacturer in a proper way and/or when some simple techniques are adopted (such as the use of surge arresters in parallel with reactor windings, for example).

In terms of installation, if the precautions to the MC1, MC2, MC3 and MC4 clearances to the ACR, detailed in this work, are adopted, no issues related to magnetic field spread are expected.

In terms of transients, simulation and calculation results showed that both technologies are quite similar for the main aspects (peaks of transient overvoltage and TRV, oscillating frequencies and RRRV) with negligible differences from the application point of view. The apparent disadvantages of ACR such as the incidence of a lower damping (resulting in longer transient duration), for example, tends not to be an issue, since the safety margin between the dielectric properties of the insulating material (designed to withstand the BIL, in general, much more

aggressive in terms of peak withstanding), tend to be enough to ensure suitable lifespan. This point should be evaluated by the ACR manufacturer based on TRV studies, case by case.

On the simulations performed (ACR on “arrangement 3” and OIR on “arrangement 1”), it was also noticed that the inclusion of a resistance to ground to the ACR, equivalent to the resistance to ground of base insulators, do not impose a significant damping, not reducing significantly the transient duration. This is due to the fact that the electrical point of base insulator is “far” from the incoming busbar (there are huge series impedances between the incoming busbar and the resistance to ground on the ACR transient model). Therefore, the same behavior (negligibility of base insulators resistance) is expected to Arrangements 1, 2, 3 and 4 (the last one with connections on top part of the equipment) of ACR. Arrangement 4 with connections on bottom part, tends to present a more important damping.

Despite the advantages of dry-type air core reactors, some aspects may elect oil-immersed equipment the best choice for some cases, for example in substations where the installation of the reactor is intended to be close to general public sidewalks and/or very close to control room and worker circulation areas, since the spread of magnetic field lines (negligible for OIR), may require this equipment to be installed farther from such areas. Moreover, reactors with very low power levels are usually more competitive in oil technology, since the existence of an iron core, allows to reach the same impedance with a lower number of turns in a more “compact” and less costly equipment. Other aspects such as the possibility to have tertiary windings to feed auxiliary services (no need to have extra transformer for this purpose), the absence of need to have fencing to access control, are also examples of advantages of OIR.

The possibility to replace OIR by ACR is something relatively new and major actors of power community, are still unaware about this possibility, without major impacts to the system. However, it is clear that the use of ACRs is the more and more being asked mainly in developed countries, where new technologies and environmental aspects are better accepted and valued. In other countries, however, it is clear that specific standards and codes should be modernized, since their requirements are based exclusively to OIRs. This opens the way for unnecessary and exhaustive technical discussions and alignments, to stablish a parallel between both types, which could be clearly stated in such codes.

International standards for shunt reactors (notably IEEE C57.21 as well as NBR 5356 and IEC 60076 series) should also be reviewed, bringing more specific details specially linked to the design and testing of HV ACRs for this application, since at HV and EHV levels, there are some particularities that did not appear when testing MV equipment (traditional use of ACR shunt reactor).

Today, the gaps on design and testing requirements are being agreed between manufacturer and purchaser, requiring specialized alignment calls.

In Brazil, ONS grid codes should also be reviewed, since the losses limits imposed to reactors are much lower than the worldwide practice. The result of this is an equipment, many times, designed far from its thermal capacity, resulting in a non-optimized equipment, when the dry-type is intended to be adopted.

The objectives of this work were achieved, since it was possible to present the most relevant comparing points related to the use of both reactor types.

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APPENDIX 1 – NAGAOKA TABLE

- **Nagaoka table for self-inductance calculation**

Table 30 presents Nagaoka constant for inductance calculation.

Table 30 - Table for Nagaoka constant (K) for $(2a/b) \leq 1$

2a/b	K	2a/b	K	2a/b	K
0.50	0.818136	0.67	0.768978	0.84	0.725240
0.51	0.815082	0.68	0.766262	0.85	0.722821
0.52	0.812049	0.69	0.763565	0.86	0.720419
0.53	0.809037	0.70	0.760886	0.87	0.718033
0.54	0.806046	0.71	0.758225	0.88	0.715663
0.55	0.803035	0.72	0.755582	0.89	0.713308
0.56	0.800125	0.73	0.752958	0.90	0.710969
0.57	0.797195	0.74	0.750351	0.91	0.708647
0.58	0.794285	0.75	0.747762	0.92	0.706339
0.59	0.791395	0.76	0.745191	0.93	0.704047
0.60	0.788525	0.77	0.742637	0.94	0.701770
0.61	0.785675	0.78	0.740100	0.95	0.699509
0.62	0.782844	0.79	0.737581	0.96	0.697262
0.63	0.780032	0.80	0.735079	0.97	0.695030
0.64	0.777240	0.81	0.732593	0.98	0.692813
0.65	0.774567	0.82	0.730126	0.99	0.690611
0.66	0.771713	0.83	0.727675	1.00	0.688423

a. If the value of 2a/b ratio is within the range of two values of the table, it is needed to obtain actual value by linear interpolation.

APPENDIX 2 – SIMULATION RESULTS

- **Energizing transients on Reactor terminal (simulation results)**

- CASE 1: Energization of the Bank at voltage peak on Phase A (minimum inrush current on Phase A) without controlled switching;

In the figures showing three-phase simulations, red curves are phase A, green curves are phase B and blue curves are phase C.

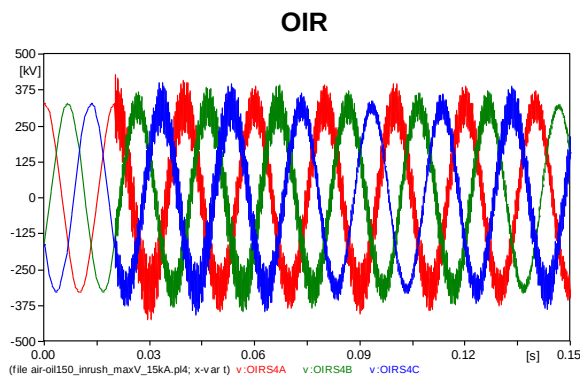


Figure 94 - CASE 1 - Source-side voltages of OIR.

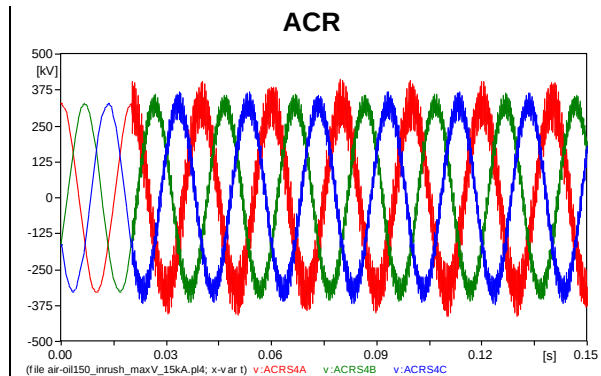


Figure 95 - CASE 1 - Source-side voltages of ACR.

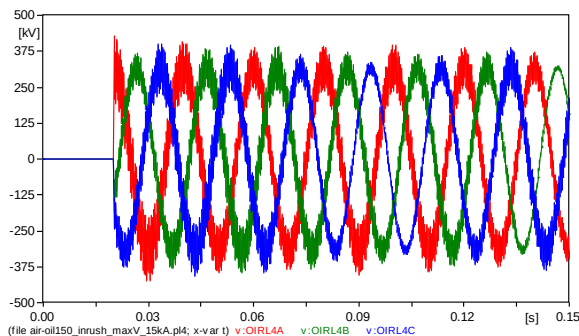


Figure 96 - CASE 1 - Load-side voltages of OIR.

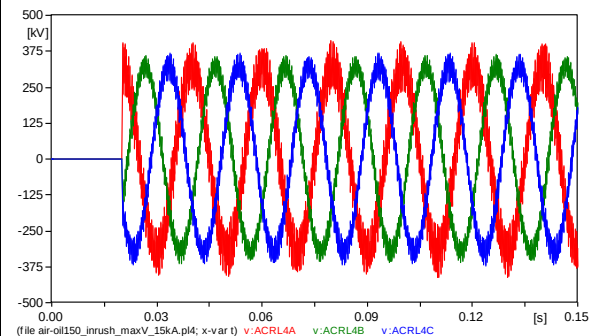


Figure 97 - CASE 1 - Load-side voltages of ACR.

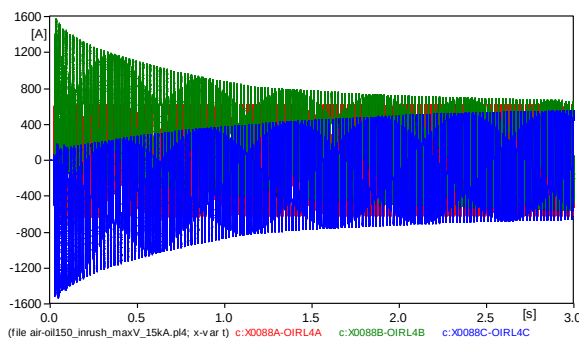


Figure 98 - CASE 1 - Inrush currents of OIR.

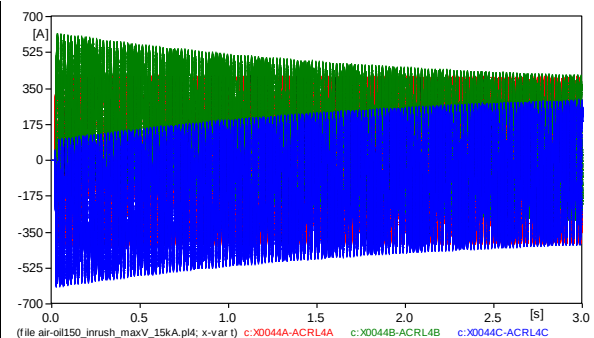


Figure 99 - CASE 1 - Inrush currents of ACR.

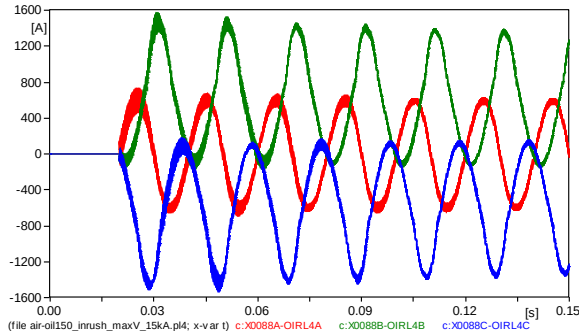


Figure 100 - CASE 1 - Inrush currents of OIR (three-phases).

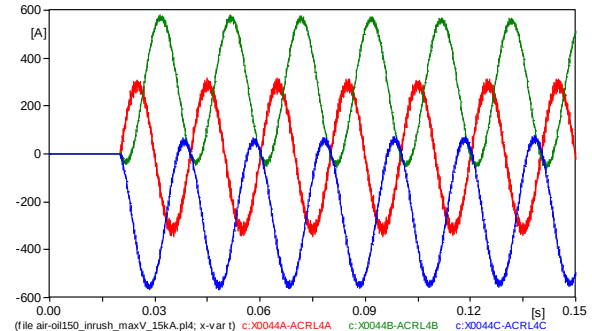


Figure 101 - CASE 1 - Inrush currents of ACR (three-phases).

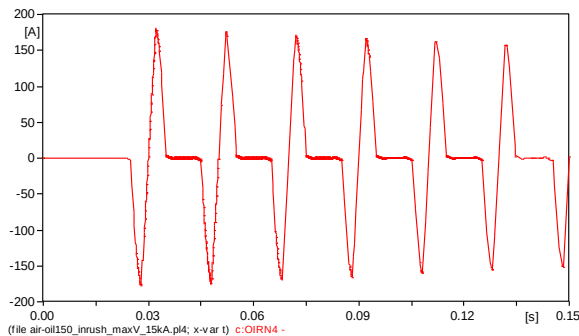


Figure 102 - CASE 1 - Neutral current of OIR.

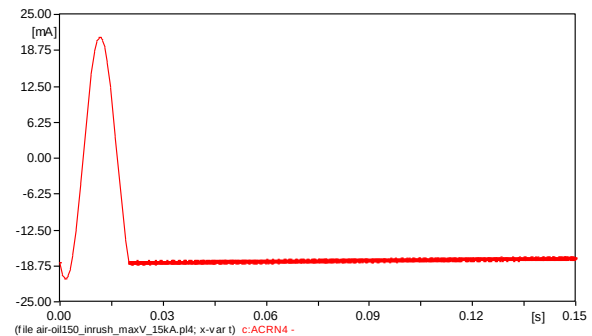


Figure 103 - CASE 1 - Neutral current of ACR.

- CASE 2: Energization of the Bank at zero voltage on Phase A (maximum inrush current on Phase A) without synchronized switching;

In the figures showing three-phase simulations, red curves are phase A, green curves are phase B and blue curves are phase C.

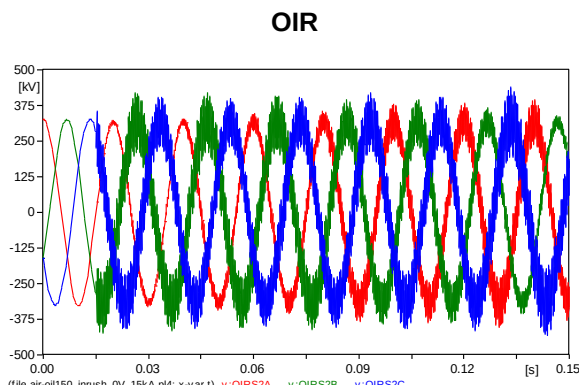


Figure 104 - CASE 2 - Source-side voltages of OIR.

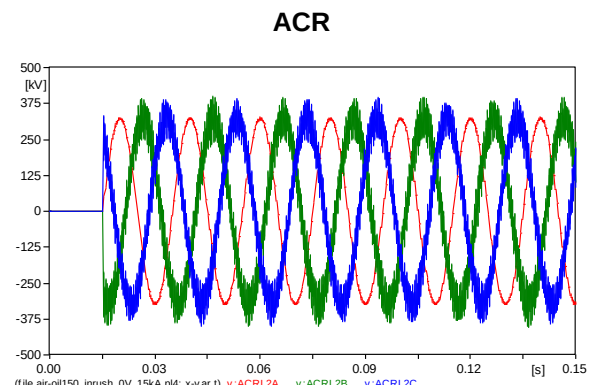


Figure 105 - CASE 2 - Source-side voltages of ACR.

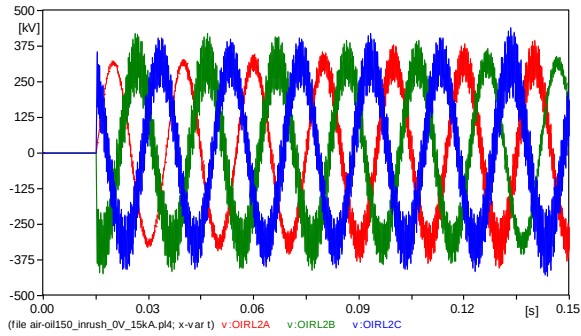


Figure 106 - CASE 2 - Load-side voltages of OIR.

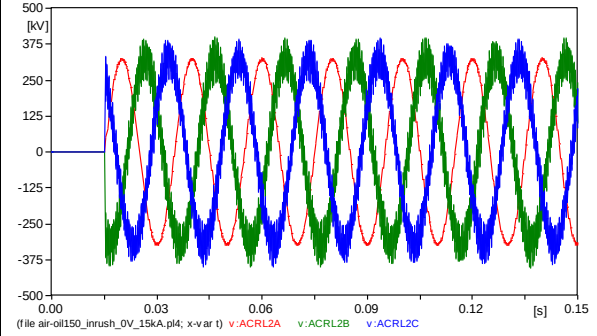


Figure 107 - CASE 2 - Load-side voltages of ACR.

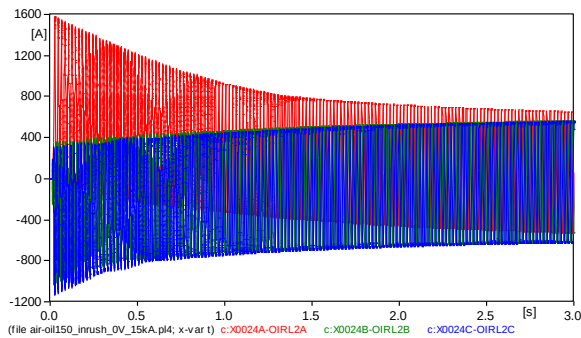


Figure 108 - CASE 2 - Inrush currents of OIR.

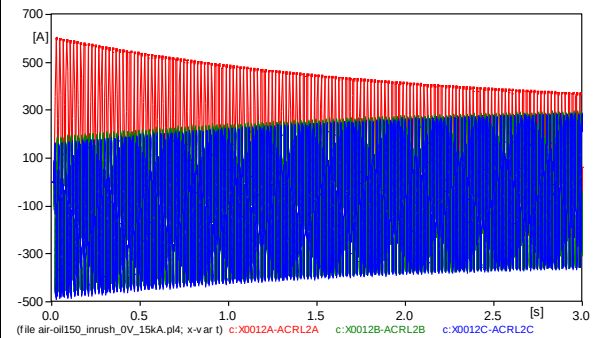


Figure 109 - CASE 2 - Inrush currents of ACR.

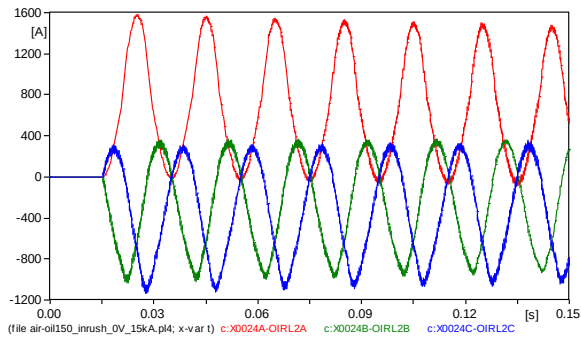


Figure 110 - CASE 2 - Inrush currents of OIR (three-phases).

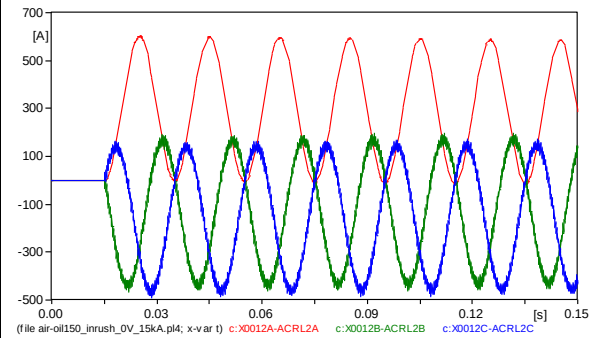


Figure 111 - CASE 2 - Inrush currents of ACR (three-phases).

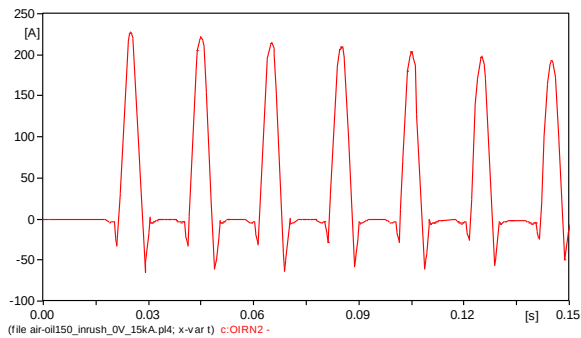


Figure 112 - CASE 2 - Neutral current of OIR.

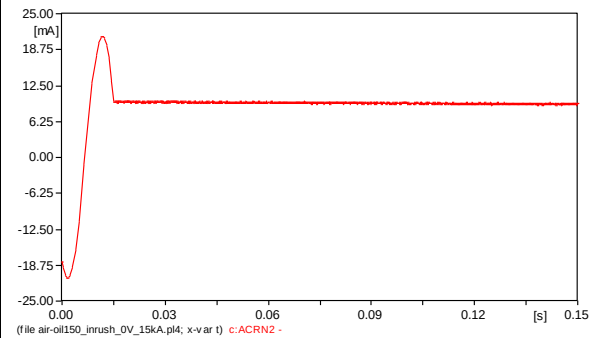


Figure 113 - CASE 2 - Neutral current of ACR.

- CASE 3: Energization of the Bank at voltage peak on three-phase (minimum overall inrush current) with synchronized switching;

In the figures showing three-phase simulations, red curves are phase A, green curves are phase B and blue curves are phase C.

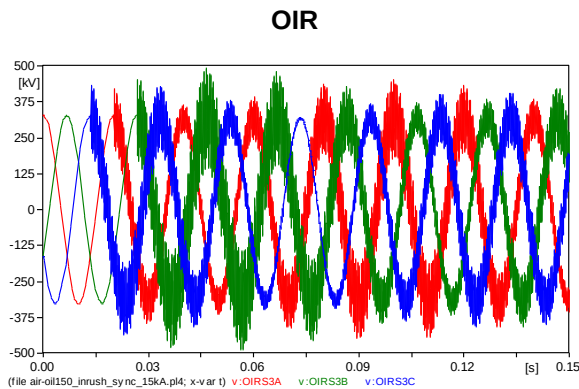


Figure 114 - CASE 3 - Source-side voltages of OIR.

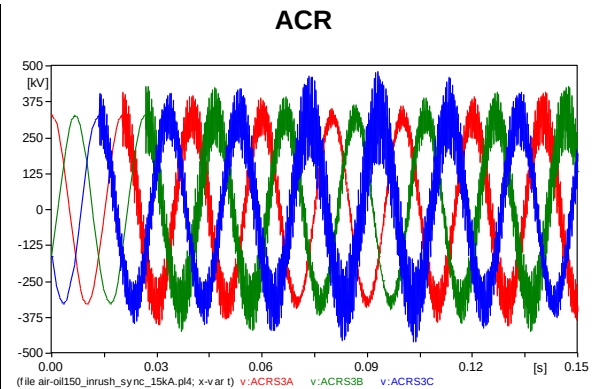


Figure 115 - CASE 3 - Source-side voltages of ACR.

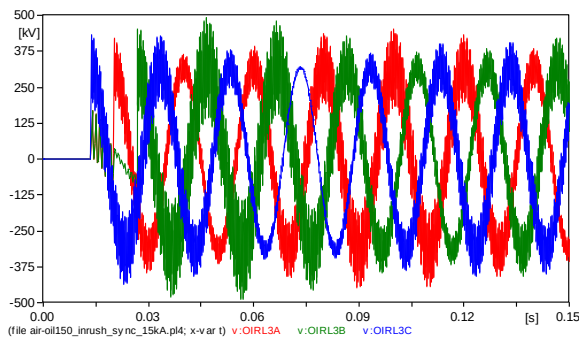


Figure 116 - CASE 3 - Load-side voltages of OIR.

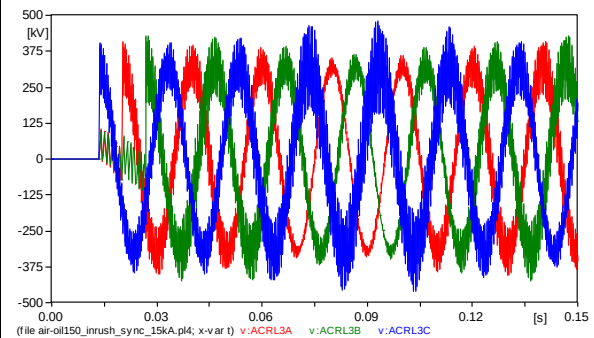


Figure 117 - CASE 3 - Load-side voltages of ACR.

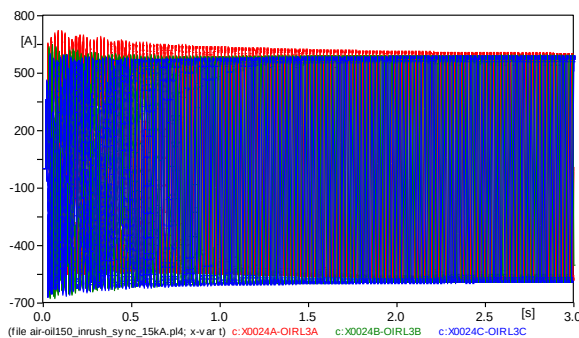


Figure 118 - CASE 3 - Inrush currents of OIR.

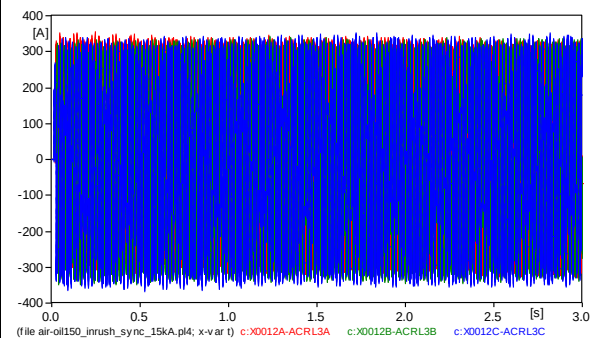


Figure 119 - CASE 3 - Inrush currents of ACR.

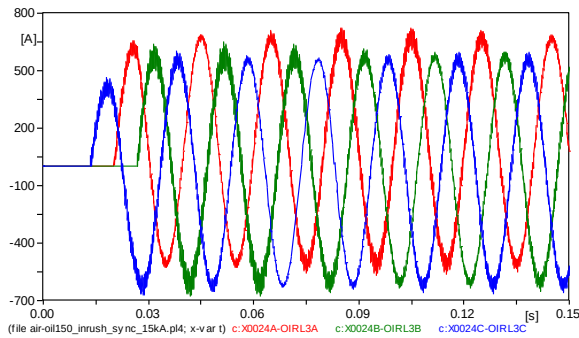


Figure 120 - CASE 3 - Inrush currents of OIR (three-phases).

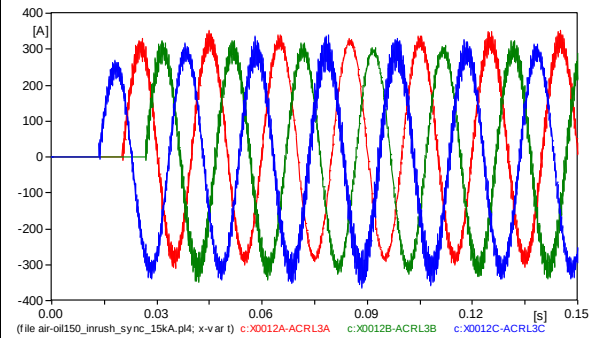


Figure 121 - CASE 3 - Inrush currents of ACR (three-phases).

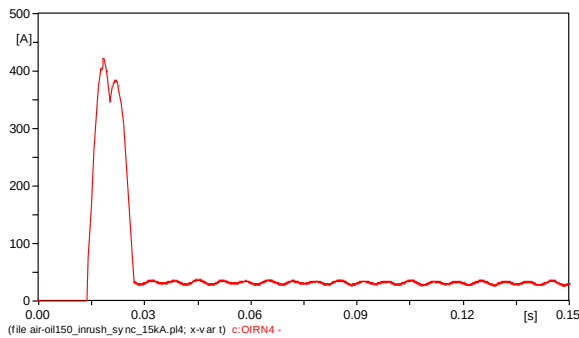


Figure 122 - CASE 3 - Neutral current of OIR.

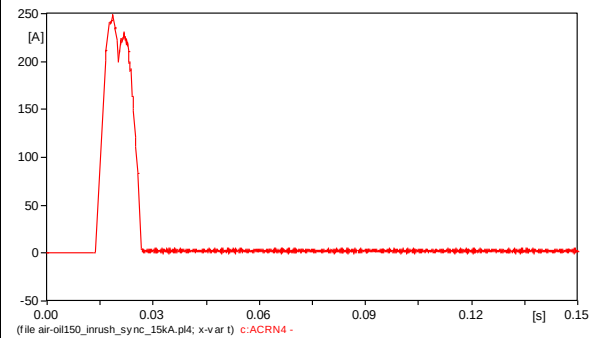


Figure 123 - CASE 3 - Neutral current of ACR.

- **De-energizing transients on Reactor terminal and TRV on circuit breaker (simulation results)**

- CASE 4: De-energization of the Bank without synchronized switching without surge arrester and $I_k'' = 15 \text{ kA/s}$;

In the figures showing three-phase simulations, red curves are phase A, green curves are phase B and blue curves are phase C. In the figures showing phase overlaps, each phase is shown comparing both equipment types, one at a time.

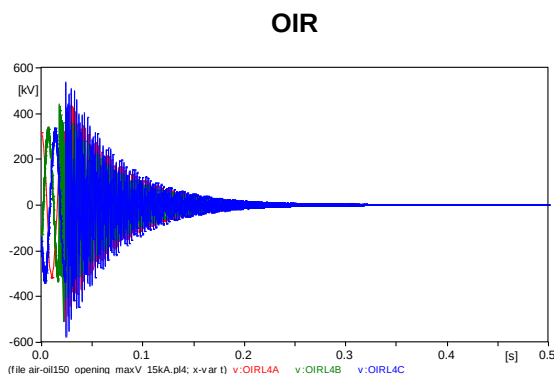


Figure 124 - CASE 4 - Source-side voltages of OIR.

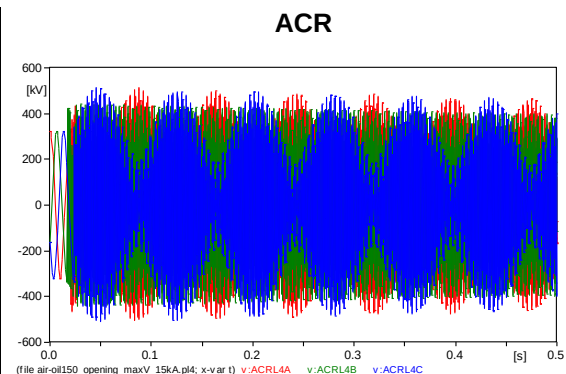


Figure 125 - CASE 4 - Source-side voltages of ACR.

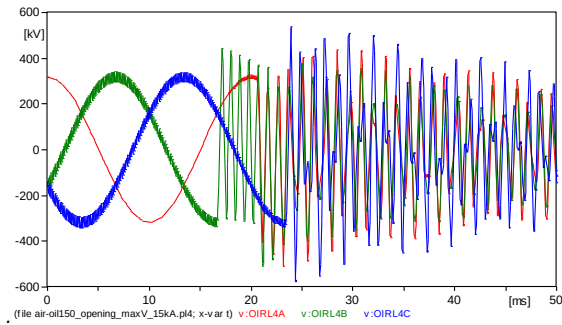


Figure 126 - CASE 4 - Source-side voltages of OIR (three-phases).

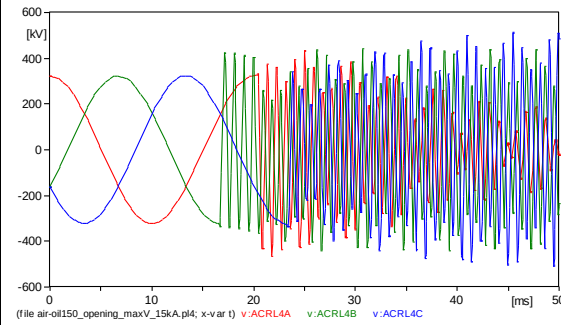


Figure 127 - CASE 4 - Source-side voltages of ACR (three-phases).

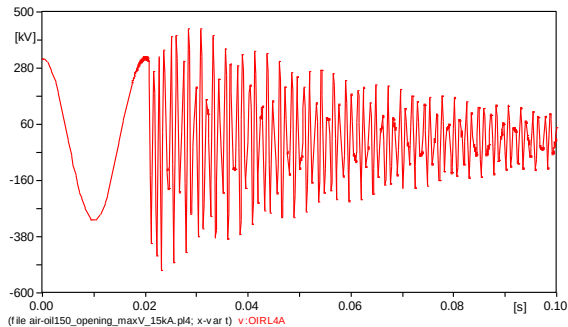


Figure 128 - CASE 4 - Source-side voltages of OIR (Phase A).

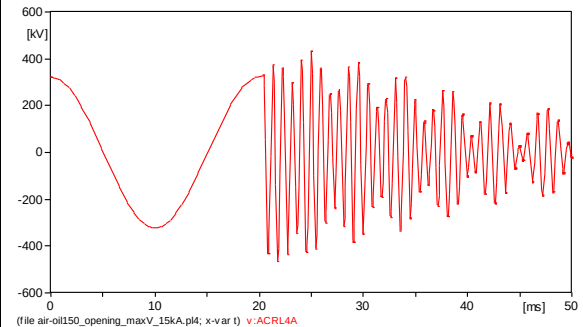


Figure 129 - CASE 4 - Source-side voltages of ACR (Phase A).

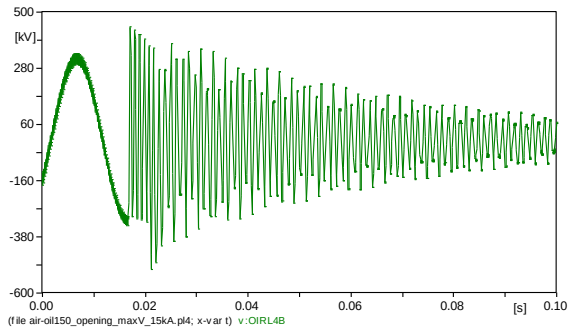


Figure 130 - CASE 4 - Source-side voltages of OIR (Phase B).

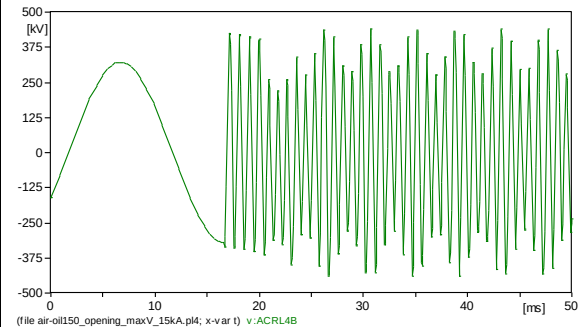


Figure 131 - CASE 4 - Source-side voltages of ACR (Phase B).

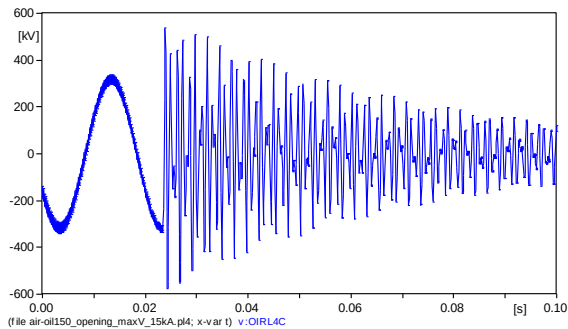


Figure 132 - CASE 4 - Source-side voltages of OIR (Phase C).

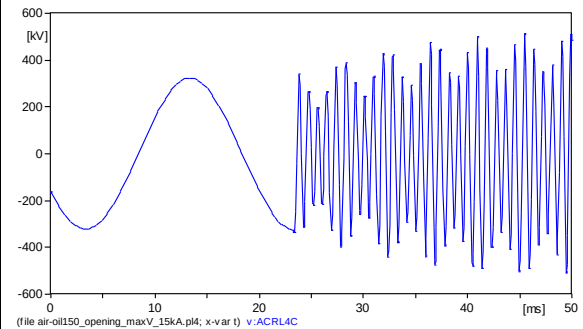


Figure 133 - CASE 4 - Source-side voltages of ACR (Phase C).

OIR Vs ACR (phase overlap)

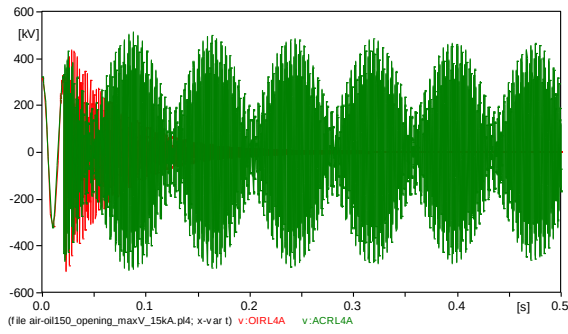


Figure 134 - CASE 4 – Source-side voltages OIR vs ACR overlap – Phase A.

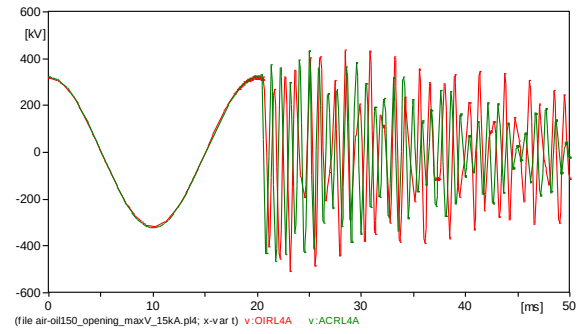


Figure 135 - CASE 4 – Source-side voltages OIR vs ACR overlap – Phase A (detail).

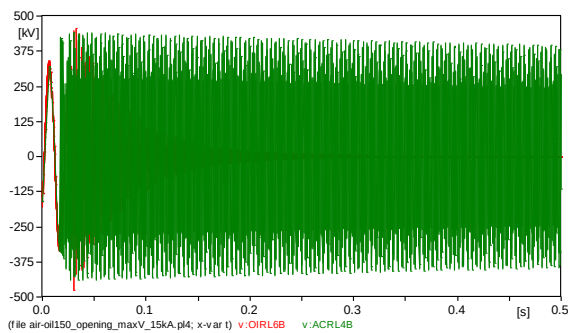


Figure 136 - CASE 4 – Source-side voltages OIR vs ACR overlap – Phase B.

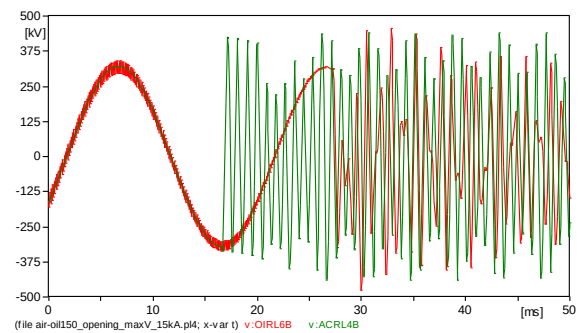


Figure 137 - CASE 4 – Source-side voltages OIR vs ACR overlap – Phase B (detail).

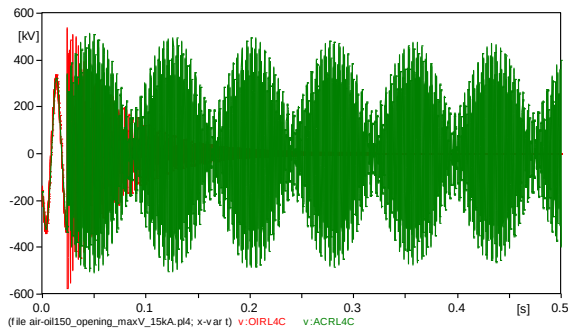


Figure 138 - CASE 4 – Source-side voltages OIR vs ACR overlap – Phase C.

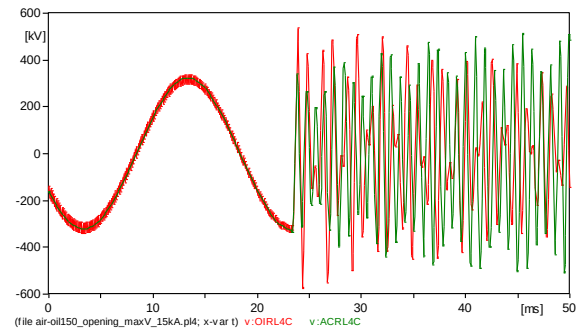


Figure 139 - CASE 4 – Source-side voltages OIR vs ACR overlap – Phase C (detail).

- CASE 5: De-energization of the Bank without synchronized switching with surge arrester and $I_k'' = 15 \text{ kA/s}$;

In the figures showing three-phase simulations, red curves are phase A, green curves are phase B and blue curves are phase C. In the figures showing phase overlaps, each phase is shown comparing both equipment types, one at a time.

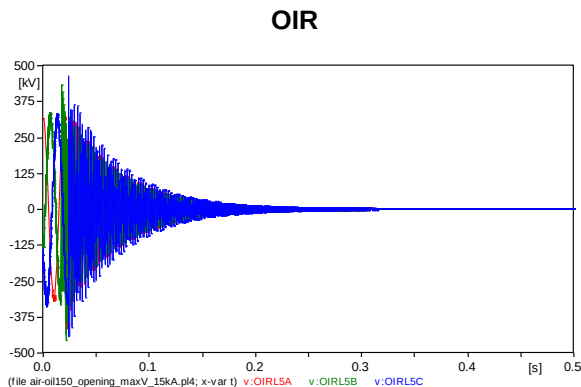


Figure 140 - CASE 5 - Source-side voltages of OIR.

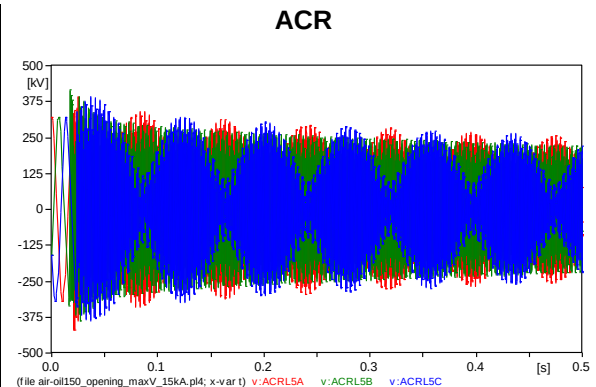


Figure 141 - CASE 5 - Source-side voltages of ACR.

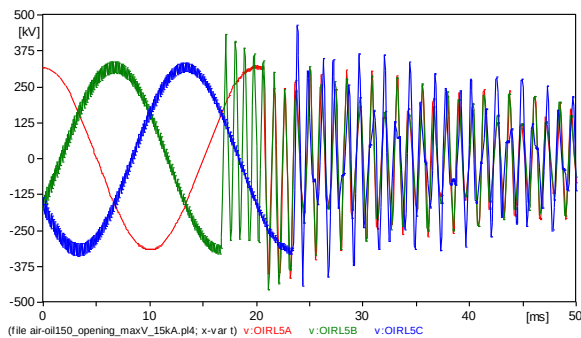


Figure 142 - CASE 5 - Source-side voltages of OIR (three-phases).

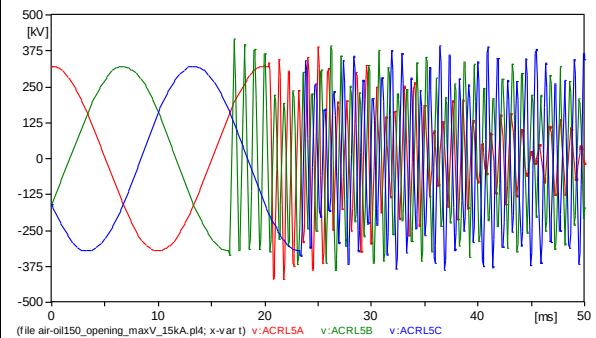


Figure 143 - CASE 5 - Source-side voltages of ACR (three-phases).

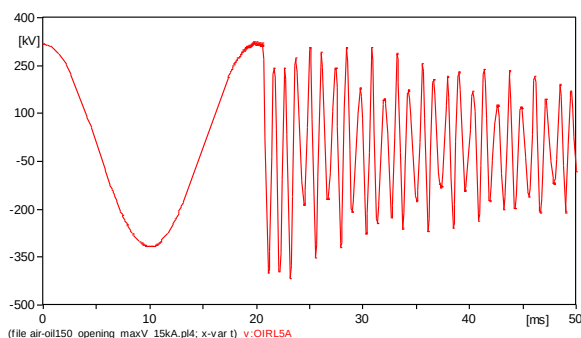


Figure 144 - CASE 5 - Source-side voltages of OIR (Phase A).

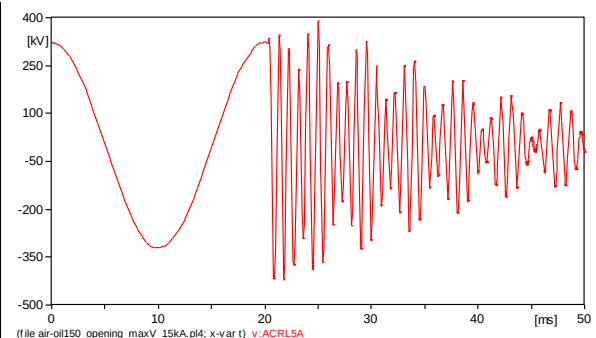


Figure 145 - CASE 5 - Source-side voltages of ACR (Phase A).

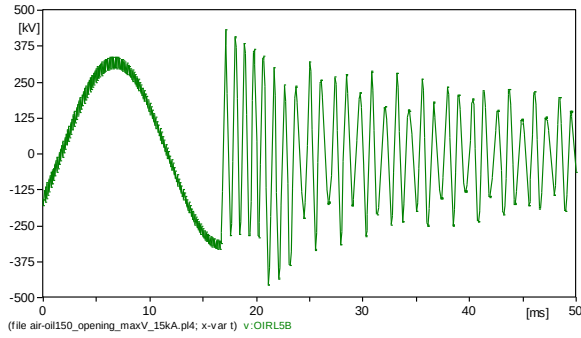


Figure 146 - CASE 5 - Source-side voltages of OIR (Phase B).

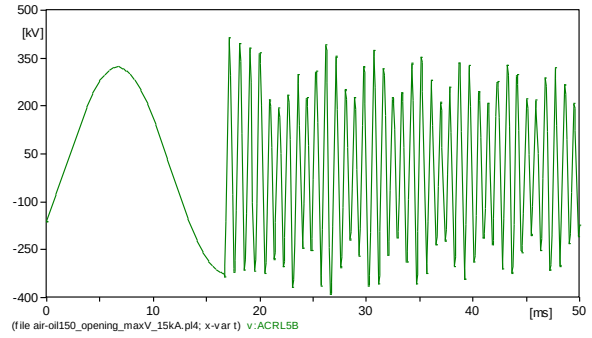


Figure 147 - CASE 5 - Source-side voltages of ACR (Phase B).

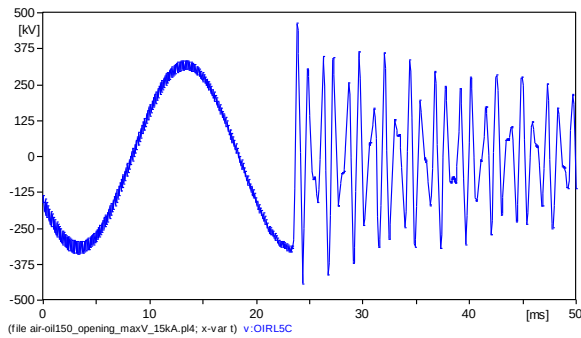


Figure 148 - CASE 5 - Source-side voltages of OIR (Phase C).

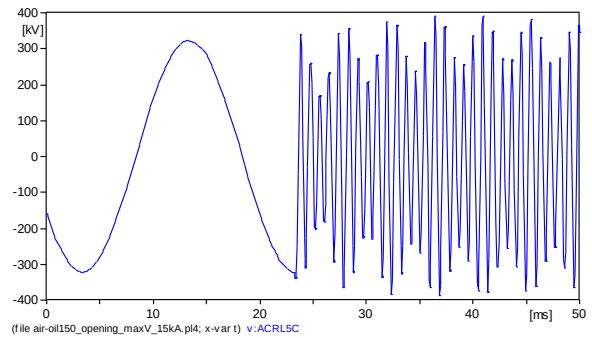


Figure 149 - CASE 5 - Source-side voltages of ACR (Phase C).

OIR Vs ACR (phase overlap)

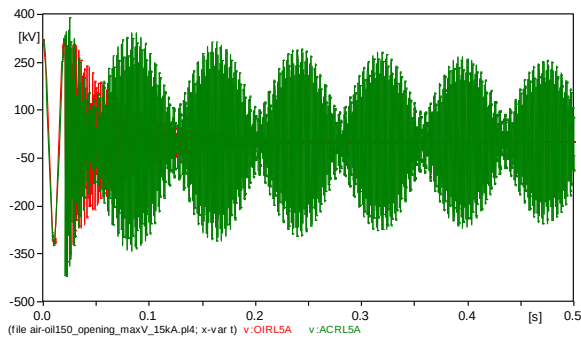


Figure 150 - CASE 5 - Source-side voltages OIR vs ACR overlap - Phase A.

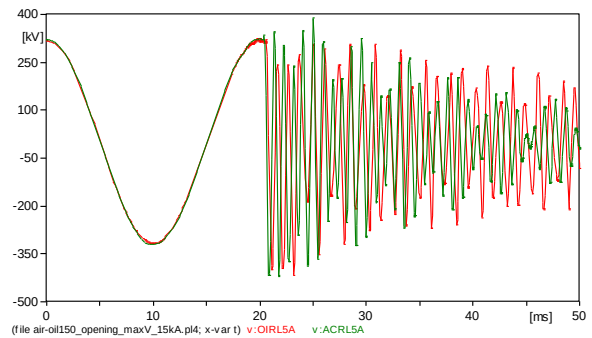


Figure 151 - CASE 5 - Source-side voltages OIR vs ACR overlap - Phase A (detail).

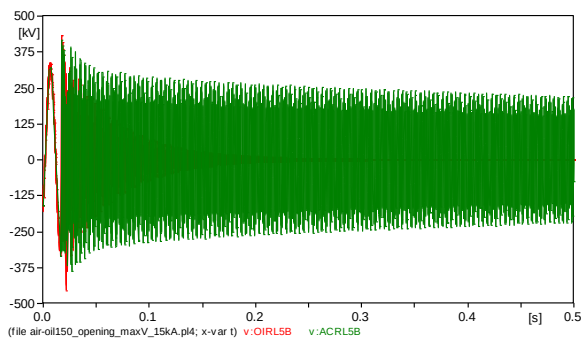


Figure 152 - CASE 5 - Source-side voltages OIR vs ACR overlap - Phase B.

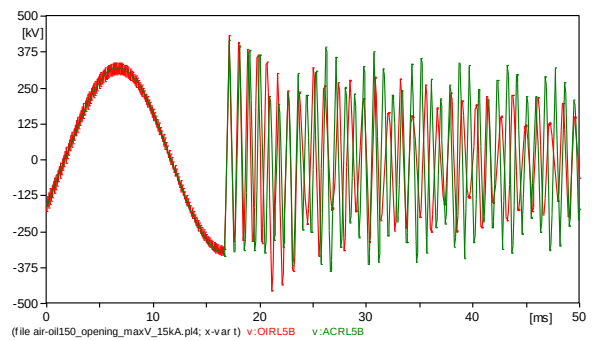


Figure 153 - CASE 5 - Source-side voltages OIR vs ACR overlap - Phase B (detail).

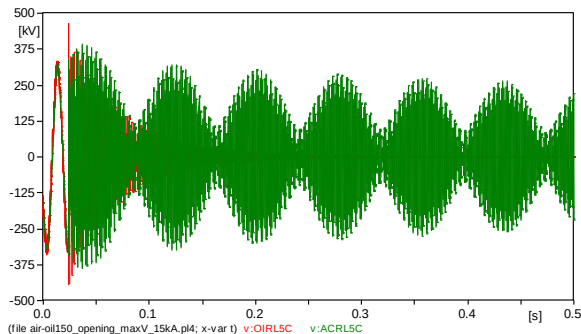


Figure 154 - CASE 5 – Source-side voltages OIR vs ACR overlap – Phase C.

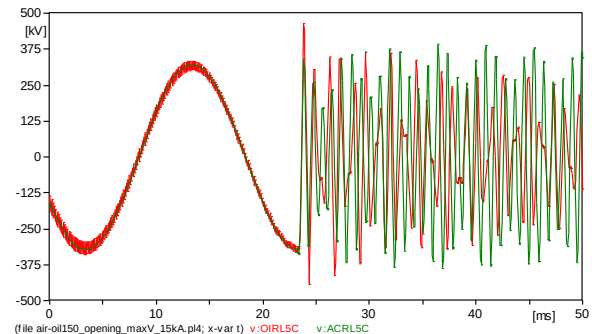


Figure 155 - CASE 5 – Source-side voltages OIR vs ACR overlap – Phase C (detail).

- CASE 6: De-energization of the Bank with synchronized switching without surge arrester and $I_k'' = 15 \text{ kA/s}$;

In the figures showing three-phase simulations, red curves are phase A, green curves are phase B and blue curves are phase C. In the figures showing phase overlaps, each phase is shown comparing both equipment types, one at a time.

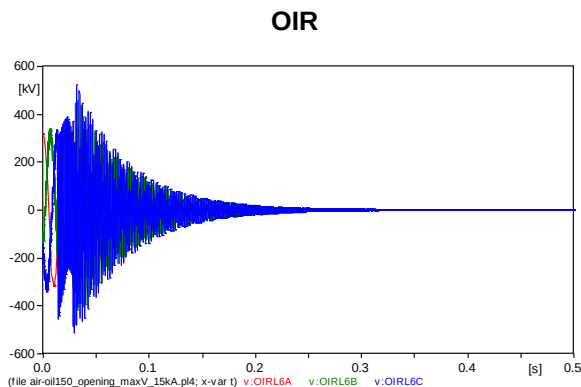


Figure 156 - CASE 6 - Source-side voltages of OIR.

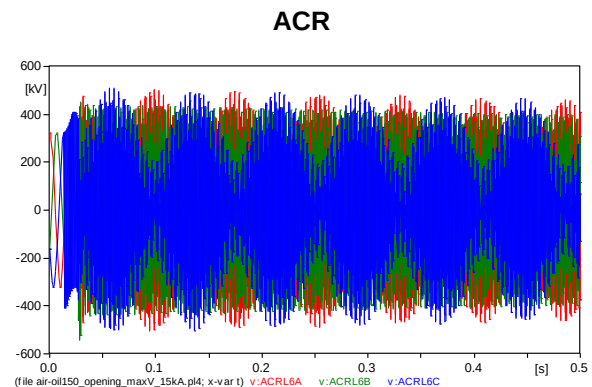


Figure 158 - CASE 6 - Source-side voltages of ACR.

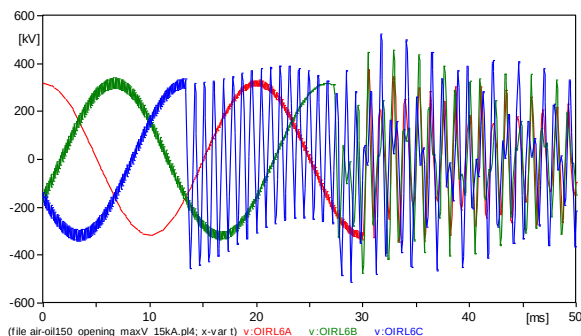


Figure 157 - CASE 6 - Source-side voltages of OIR (three-phases).

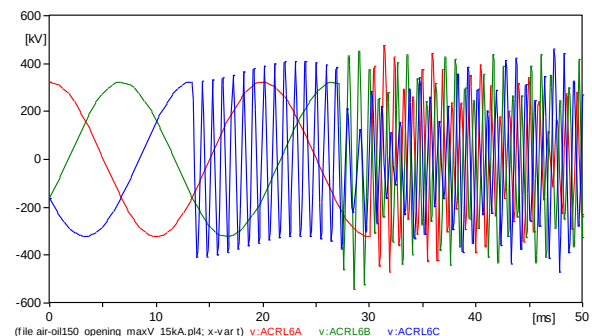


Figure 159 - CASE 6 - Source-side voltages of ACR (three-phases).

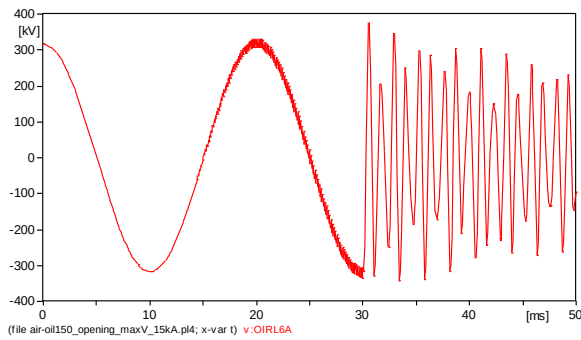


Figure 160 - CASE 6 - Source-side voltages of OIR (Phase A).

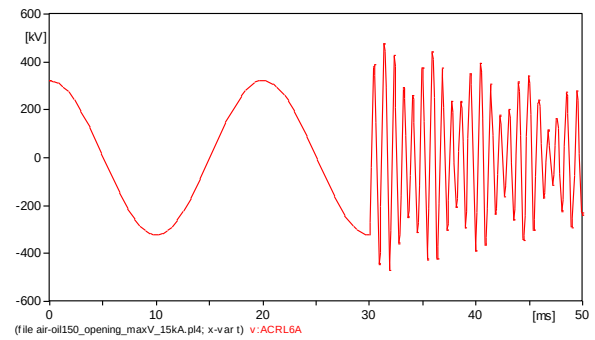


Figure 161 - CASE 6 - Source-side voltages of ACR (Phase A).

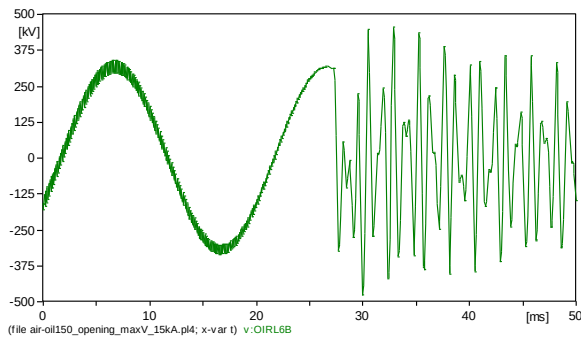


Figure 162 - CASE 6 - Source-side voltages of OIR (Phase B).

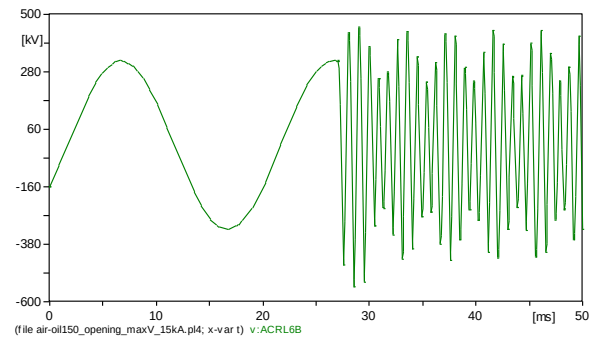


Figure 163 - CASE 6 - Source-side voltages of ACR (Phase B).

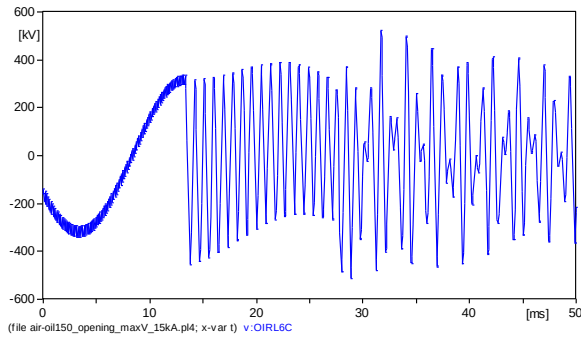


Figure 164 - CASE 6 - Source-side voltages of OIR (Phase C).

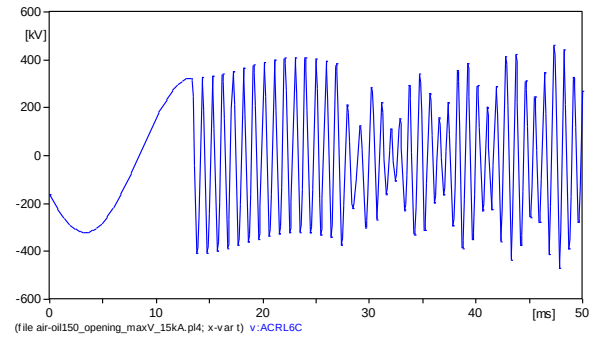


Figure 165 - CASE 6 - Source-side voltages of ACR (Phase C).

OIR Vs ACR (phase overlap)

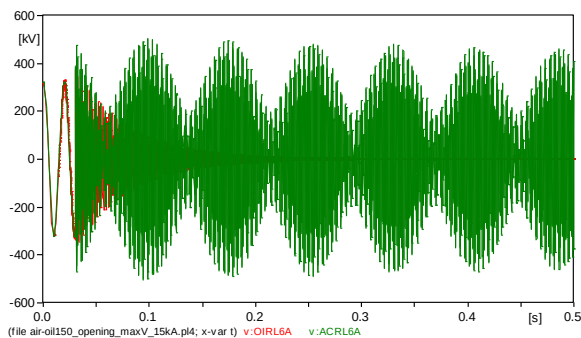


Figure 166 - CASE 6 - Source-side voltages OIR vs ACR overlap - Phase A.

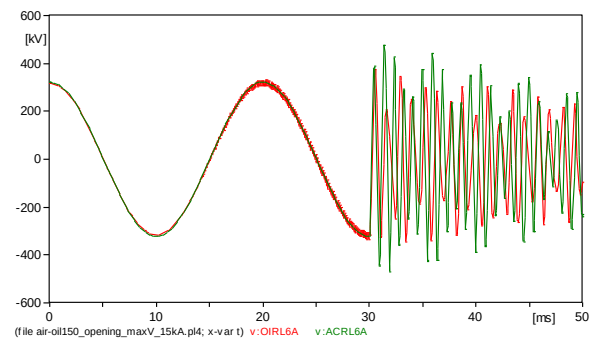


Figure 167 - CASE 6 - Source-side voltages OIR vs ACR overlap - Phase A (detail).

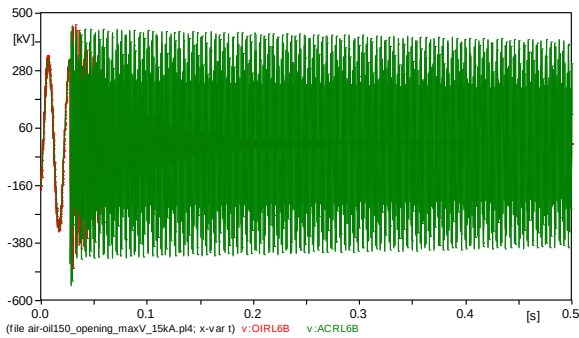


Figure 168 – CASE 6 – Source-side voltages OIR vs ACR overlap – Phase B.

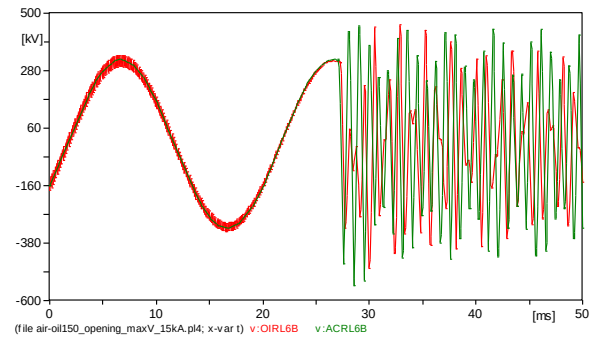


Figure 169 – CASE 6 – Source-side voltages OIR vs ACR overlap – Phase B (detail).

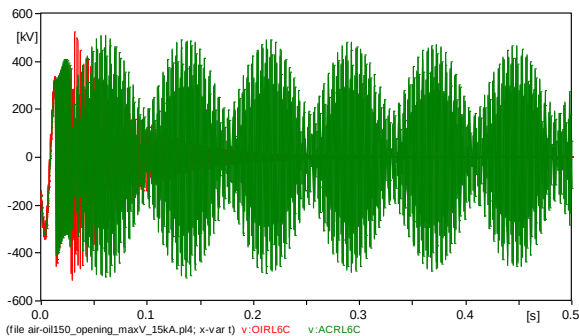


Figure 170 – CASE 6 – Source-side voltages OIR vs ACR overlap – Phase C.

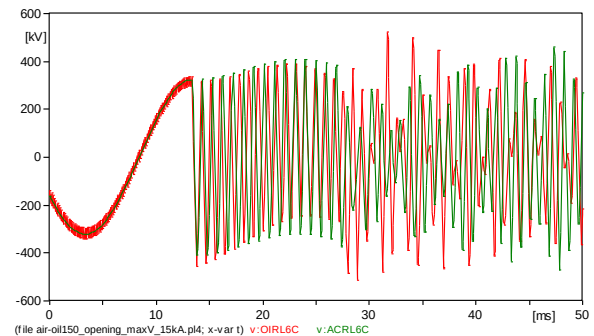


Figure 171 – CASE 6 – Source-side voltages OIR vs ACR overlap – Phase C (detail).

- CASE 7: De-energization of the Bank without synchronized switching without surge arrester and $I_k'' = 30 \text{ kA/s}$;

In the figures showing three-phase simulations, red curves are phase A, green curves are phase B and blue curves are phase C. In the figures showing phase overlaps, each phase is shown comparing both equipment types, one at a time.

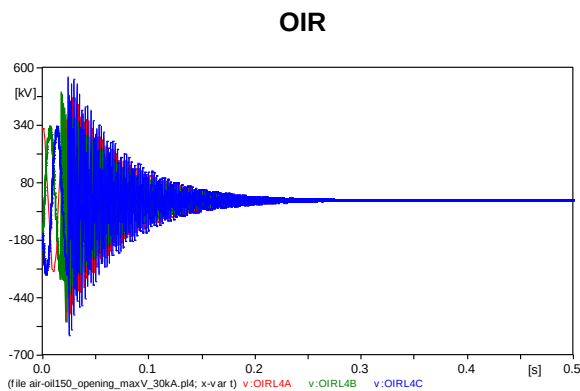


Figure 172 - CASE 7 - Source-side voltages of OIR.

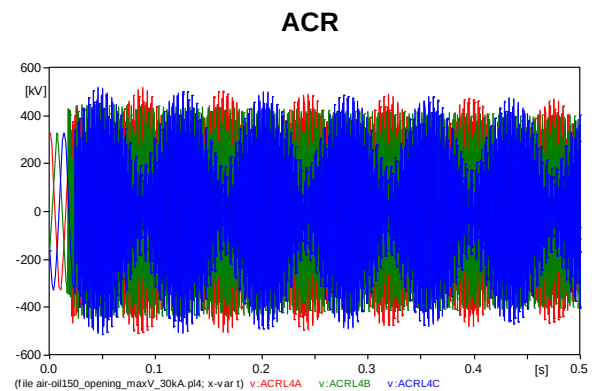


Figure 173 - CASE 7 - Source-side voltages of ACR.

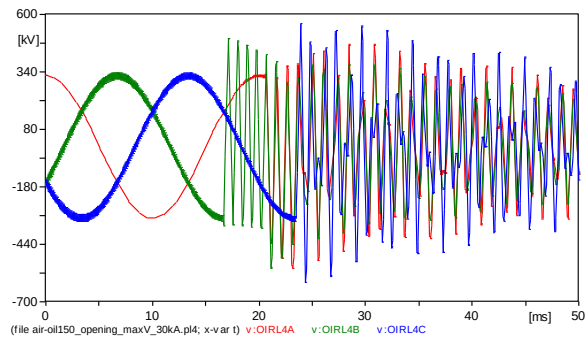


Figure 174 - CASE 7 - Source-side voltages of OIR (three-phases).

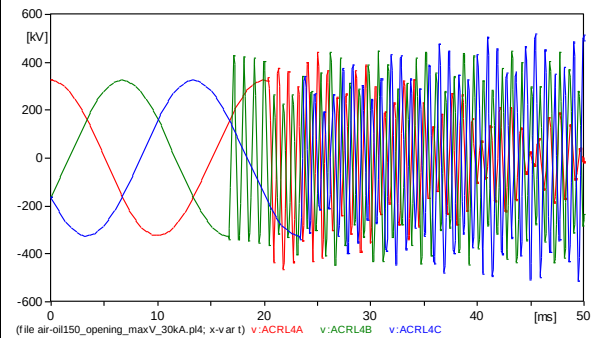


Figure 175 - CASE 7 - Source-side voltages of ACR (three-phases).

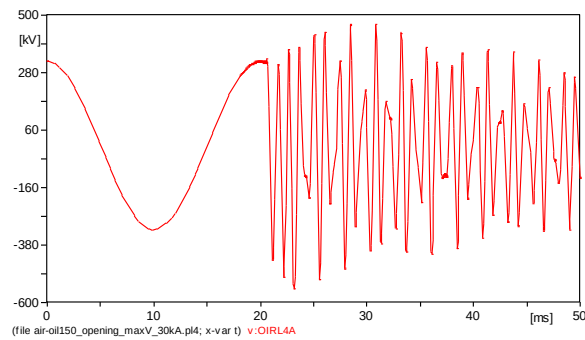


Figure 176 - CASE 7 - Source-side voltages of OIR (Phase A).

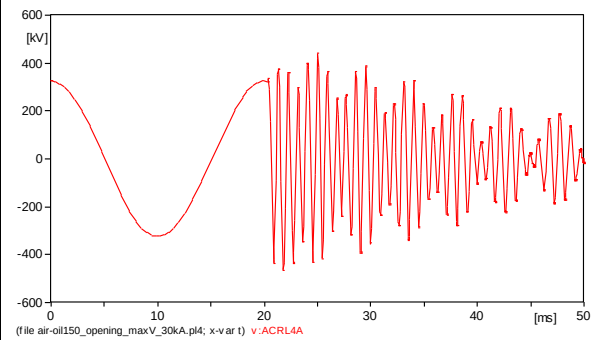


Figure 177 - CASE 7 - Source-side voltages of ACR (Phase A).

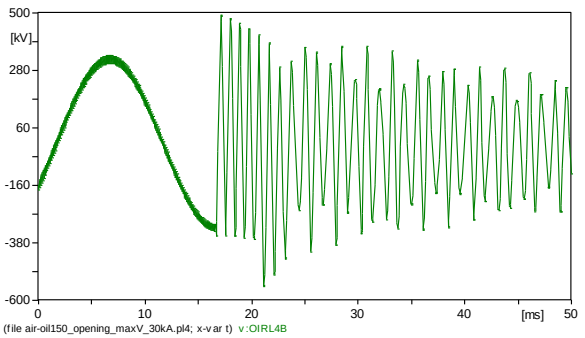


Figure 178 - CASE 7 - Source-side voltages of OIR (Phase B).

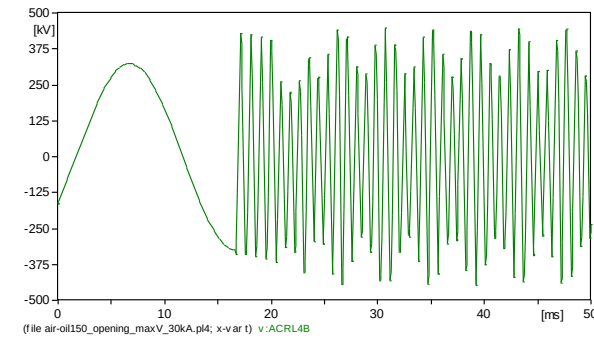


Figure 179 - CASE 7 - Source-side voltages of ACR (Phase B).

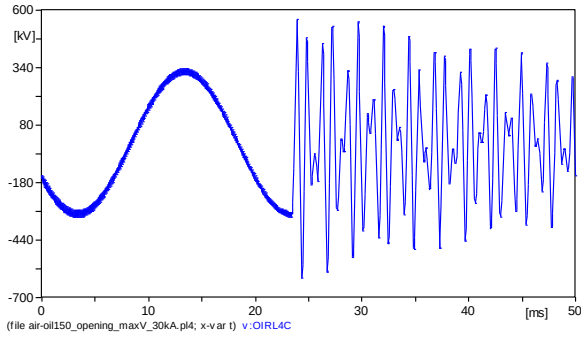


Figure 180 - CASE 7 - Source-side voltages of OIR (Phase C).

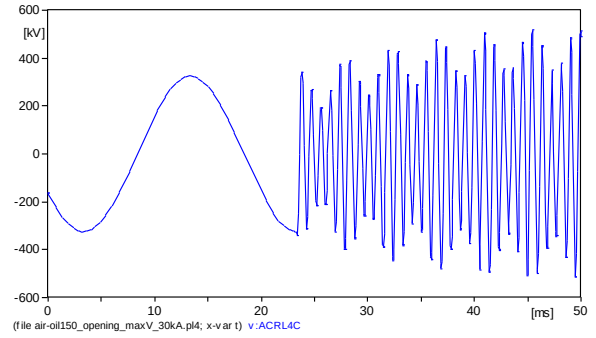


Figure 181 - CASE 7 - Source-side voltages of ACR (Phase C).

OIR Vs ACR (phase overlap)

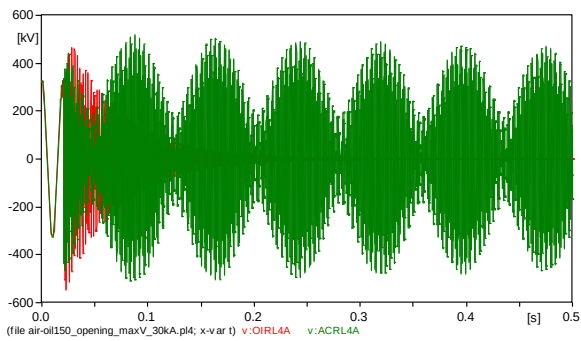


Figure 182 - CASE 7 - Source-side voltages OIR vs ACR overlap - Phase A.

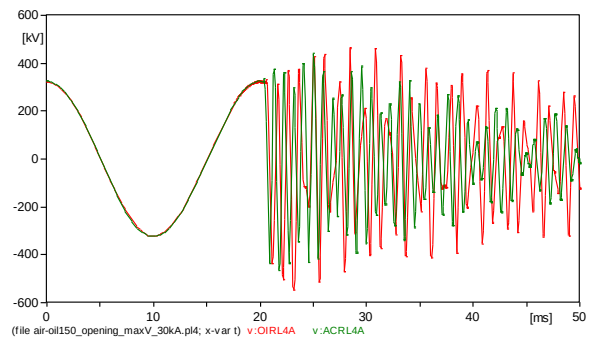


Figure 183 - CASE 7 - Source-side voltages OIR vs ACR overlap - Phase A (detail).

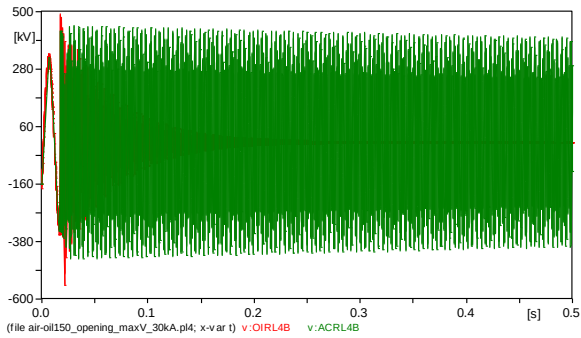


Figure 184 - CASE 7 - Source-side voltages OIR vs ACR overlap - Phase B.

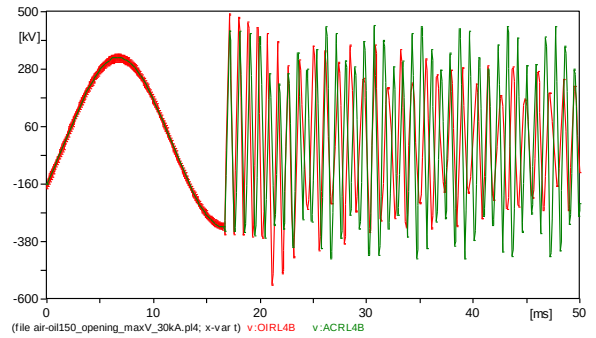


Figure 185 - CASE 7 - Source-side voltages OIR vs ACR overlap - Phase B (detail).

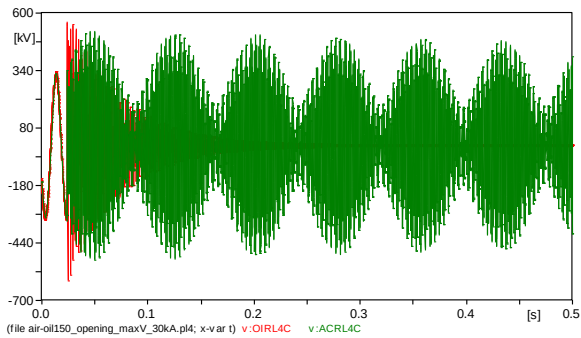


Figure 186 - CASE 7 - Source-side voltages OIR vs ACR overlap - Phase C.

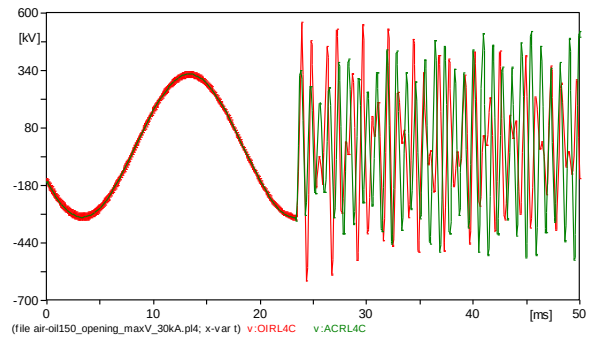


Figure 187 - CASE 7 - Source-side voltages OIR vs ACR overlap - Phase C (detail).

- CASE 8: De-energization of the Bank without synchronized switching with surge arrester and $I_k'' = 30 \text{ kA/s}$;

In the figures showing three-phase simulations, red curves are phase A, green curves are phase B and blue curves are phase C. In the figures showing phase overlaps, each phase is shown comparing both equipment types, one at a time.

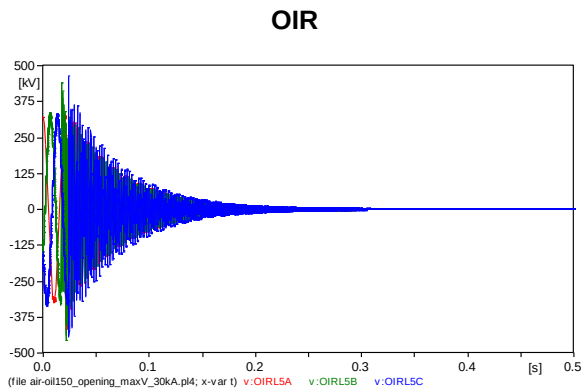


Figure 188 - CASE 8 - Source-side voltages of OIR.

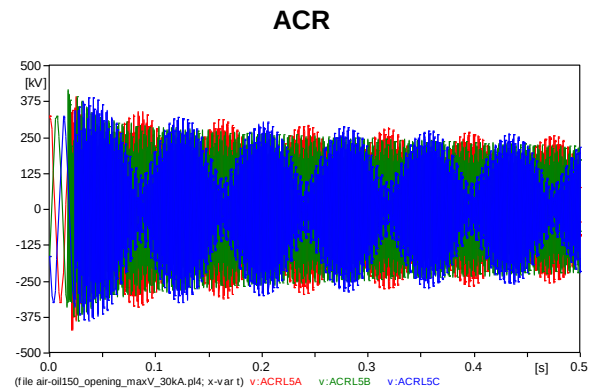


Figure 190 - CASE 8 - Source-side voltages of ACR.

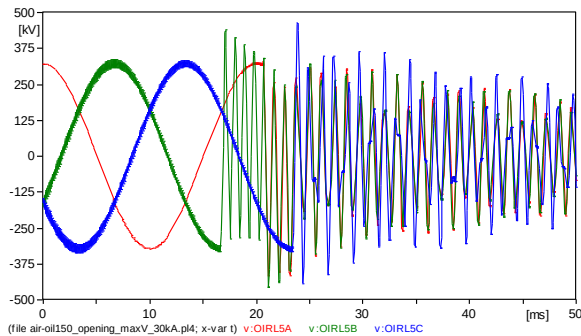


Figure 189 - CASE 8 - Source-side voltages of OIR (three phases).

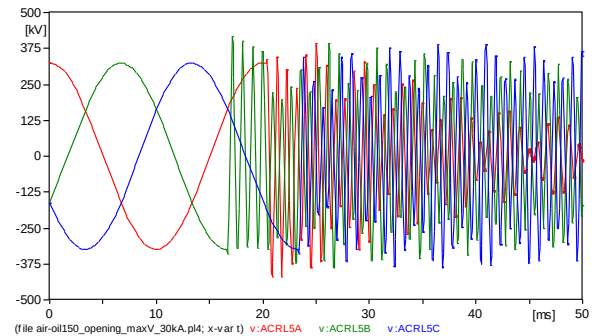


Figure 191 - CASE 8 - Source-side voltages of ACR (three phases).

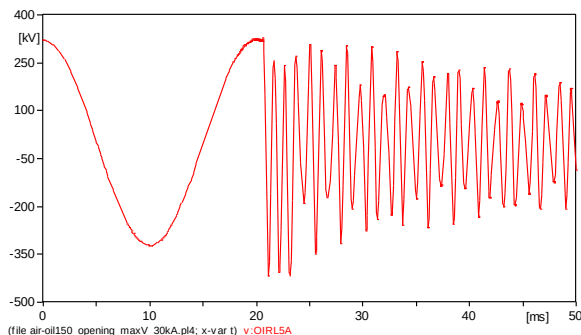


Figure 192 - CASE 8 - Source-side voltages of OIR (Phase A).

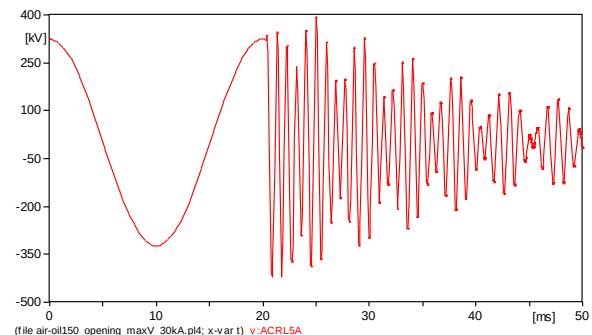


Figure 193 - CASE 8 - Source-side voltages of ACR (Phase A).

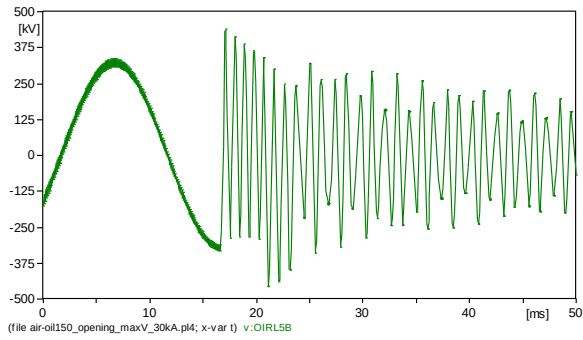


Figure 194 - CASE 8 - Source-side voltages of OIR (Phase B).

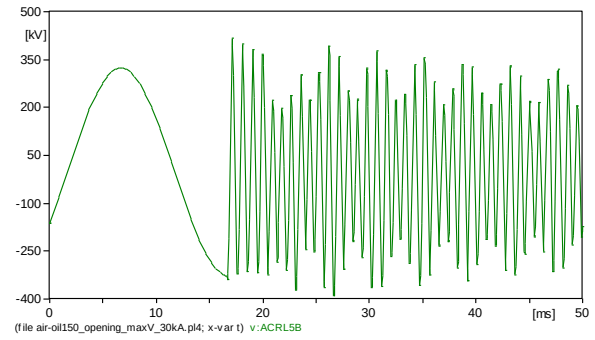


Figure 195 - CASE 8 - Source-side voltages of ACR (Phase B).

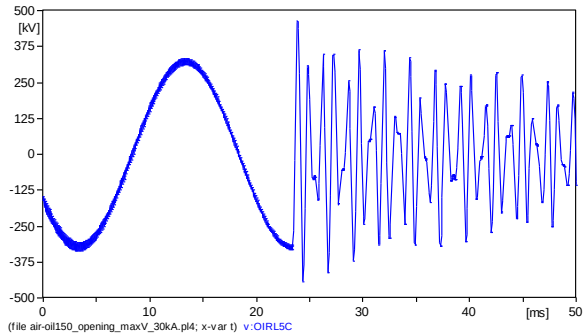


Figure 196 - CASE 8 - Source-side voltages of OIR (Phase C).

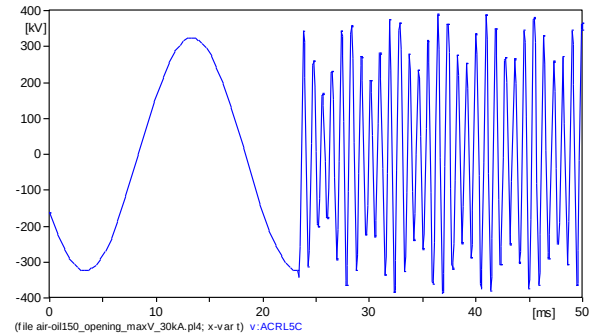


Figure 197 - CASE 8 - Source-side voltages of ACR (Phase C).

OIR Vs ACR (phase overlap)

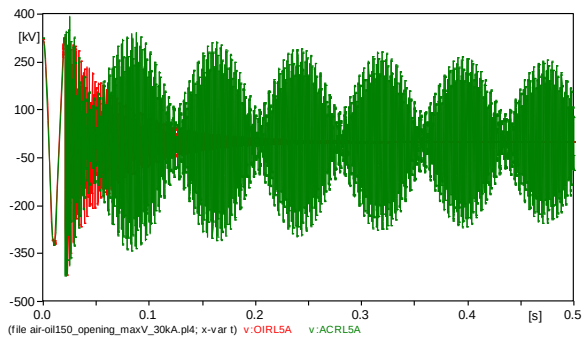


Figure 198 - CASE 8 - Source-side voltages OIR vs ACR overlap - Phase A.

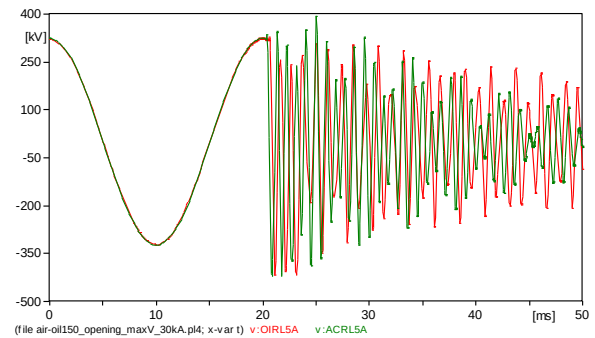


Figure 199 - CASE 8 - Source-side voltages OIR vs ACR overlap - Phase A (detail).

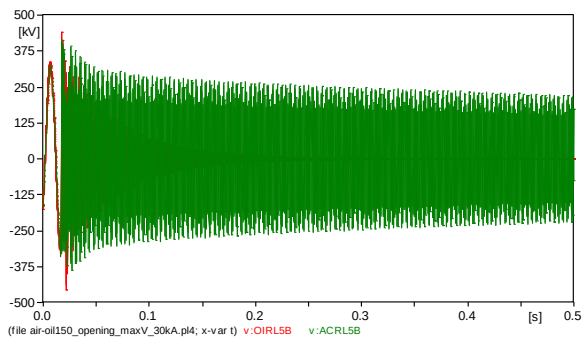


Figure 200 - CASE 8 - Source-side voltages OIR vs ACR overlap - Phase B.

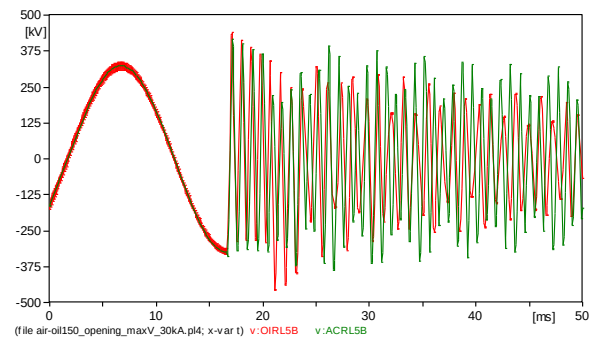


Figure 201 - CASE 8 - Source-side voltages OIR vs ACR overlap - Phase B (detail).

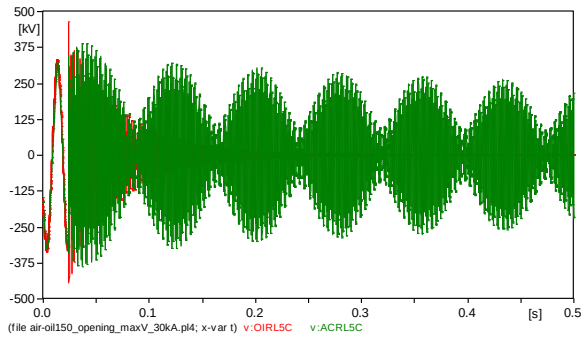


Figure 202 – CASE 8 – Source-side voltages OIR vs ACR overlap – Phase C.

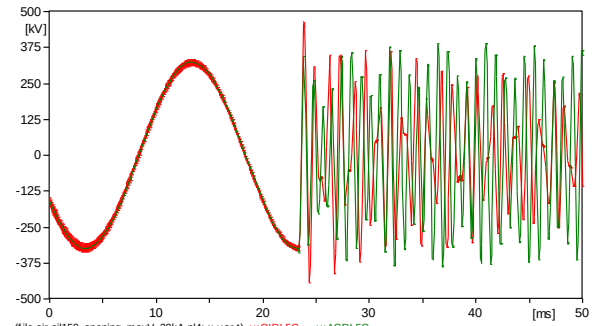


Figure 203 – CASE 8 – Source-side voltages OIR vs ACR overlap – Phase C (detail).

- CASE 9: De-energization of the Bank with synchronized switching without surge arrester and $I_k'' = 30 \text{ kA/s}$;

In the figures showing three-phase simulations, red curves are phase A, green curves are phase B and blue curves are phase C. In the figures showing phase overlaps, each phase is shown comparing both equipment types, one at a time.

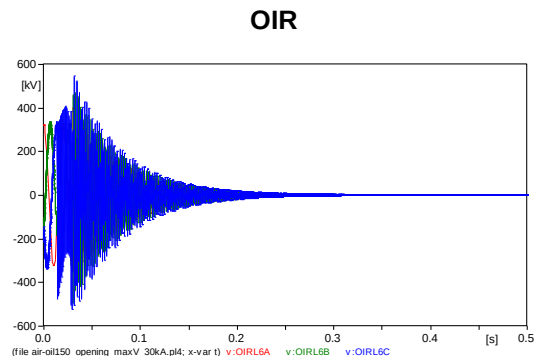


Figure 204 - CASE 9 - Source-side voltages of OIR.

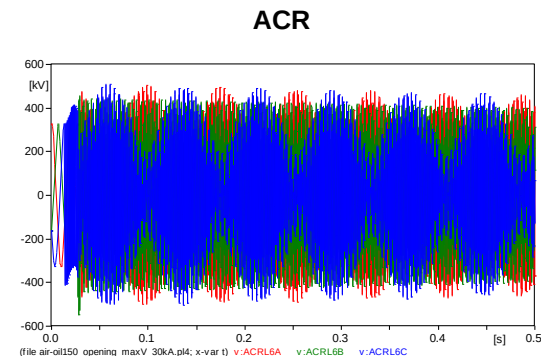


Figure 205 - CASE 9 - Source-side voltages of ACR.

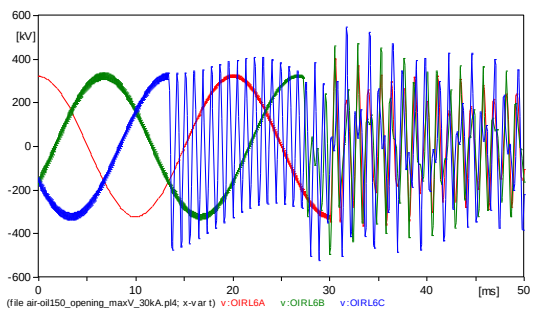


Figure 206 - CASE 9 - Source-side voltages of OIR - (detail of three-phases).

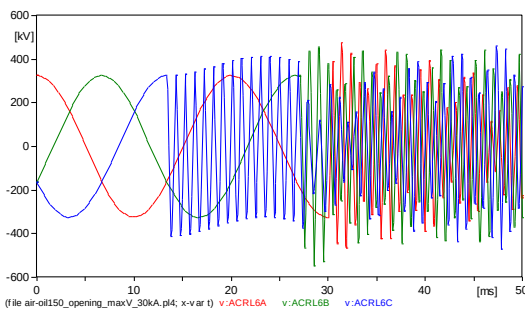


Figure 207 - CASE 9 - Source-side voltages of ACR - (detail of three-phases).

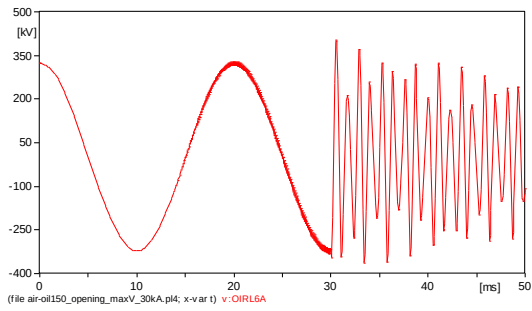


Figure 208 - CASE 9 - Source-side voltages of OIR - (Phase A).

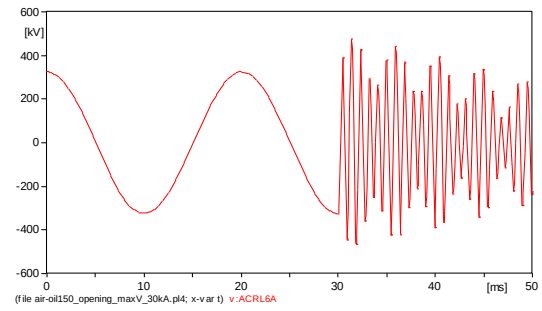


Figure 209 - CASE 9 - Source-side voltages of ACR - (Phase A).

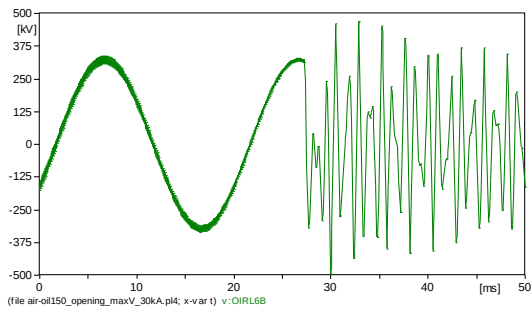


Figure 210 - CASE 9 - Source-side voltages of OIR - (Phase B).

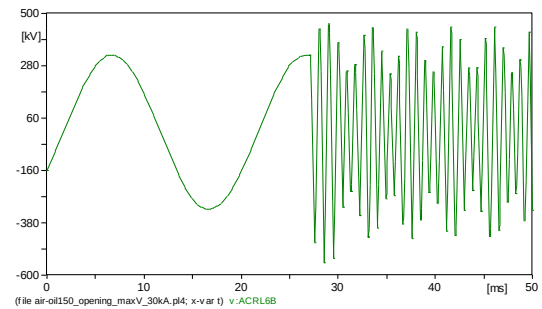


Figure 211 - CASE 9 - Source-side voltages of ACR - (Phase B).

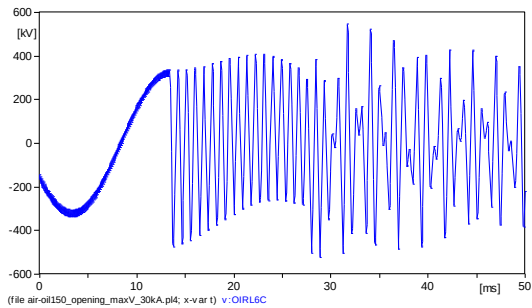


Figure 212 - CASE 9 - Source-side voltages of OIR - (Phase C).

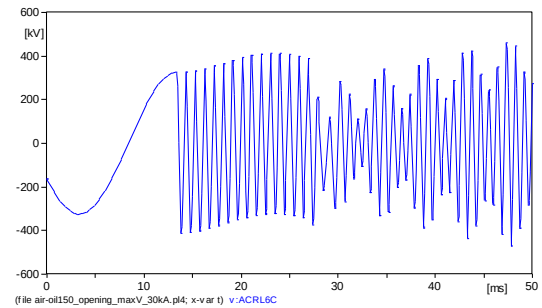


Figure 213 - CASE 9 - Source-side voltages of ACR - (Phase C).

OIR Vs ACR (phase overlap)

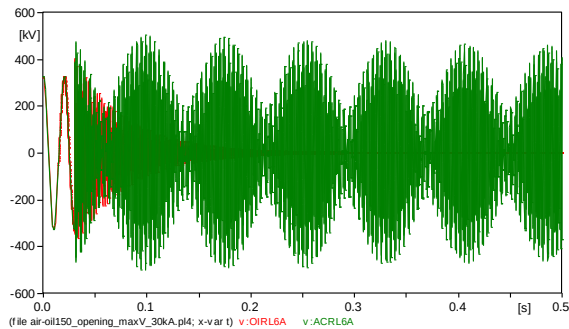


Figure 214 - CASE 9 - Source-side voltages OIR vs ACR overlap - Phase A.

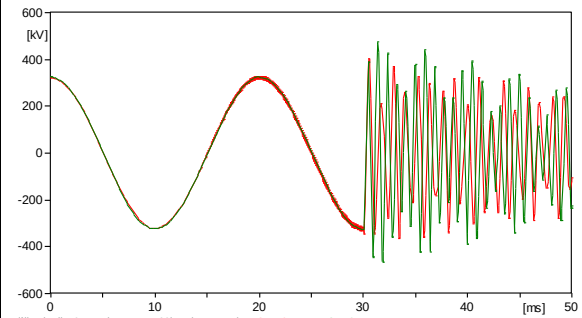


Figure 215 - CASE 9 - Source-side voltages OIR vs ACR overlap - Phase A (detail).

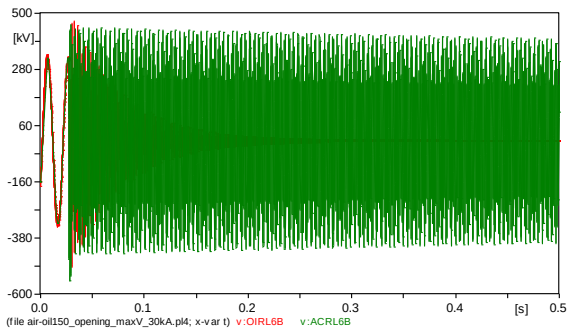


Figure 216 – CASE 9 – Source-side voltages OIR vs ACR overlap – Phase B.

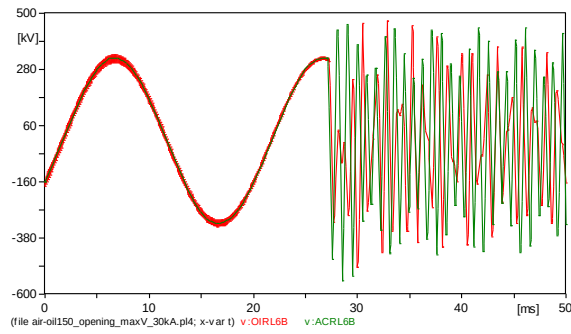


Figure 217 – CASE 9 – Source-side voltages OIR vs ACR overlap – Phase B (detail).

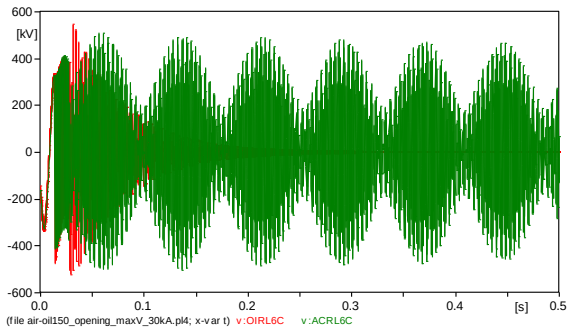


Figure 218 – CASE 9 – Source-side voltages OIR vs ACR overlap – Phase C.

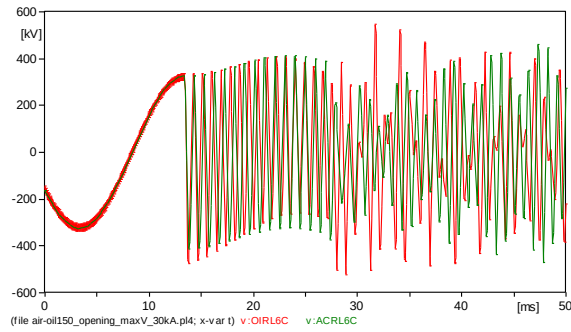


Figure 219 – CASE 9 – Source-side voltages OIR vs ACR overlap – Phase C (detail).