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# CONTROLLED SWITCHING DEVICE: APPLICATION, USE AND MAINTENANCE PROBLEMS

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# CONTROLLED SWITCHING DEVICE

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TABLE OF CONTENTS

# Definitions

**Adaptive compensation:** Automatic compensation of systematic changes in Circuit Breaker (CB) operating times during consecutive operations**.**

**Break time1**: Interval of time between energising the tripping circuit, the circuit breaker being in the closed position and the instant of final arc extinction in the respective pole.

**Closing time2:** Interval of time between energising the closing circuit, the circuit breaker being in the open position and the instant when the contacts touch in the respective pole.

**Closing window:** Time interval around the target point for closing.

**Conditional compensation:** Compensation of variations in CB operating times depending on ambient temperature, control voltage, mechanical pressure, idle time, etc**.**

**CS Controlled Switching:** Operation of a switching device at a specific, pre-determined point in relation to the power frequency current or voltage.

**POW Point-on-wave switching**: In widespread use to describe controlled switching**.**

**CSD:** Controlled Switching Device.

**CSS:** Controlled Switching System. Comprises the circuit breaker, the controller, the necessary sensors and auxiliary equipment required to achieve controlled switching**.**

**CT:** Current Transformer

**CVT:** Capacitive Voltage Transformer

**HSILL:** High Surge Impedance Loading Line.

**HV:** High Voltage

**Gang operated:** Circuit breaker with a single operating mechanism which operates the poles at the same instant within the tolerance requirement.

**Idle time:** Time interval since the last operation of the CB. It is the time between consecutive operations (either close or open operations) of a circuit breaker during which the circuit breaker remains static.

**IPO**: (Independent pole operation) Circuit breaker with an independent operating mechanism for each pole, which can operate each pole at different instants.

**Intentional non simultaneous pole operation**: Operation of CB with a specific, pre-determined time delay between the operations of the individual poles.

**Make time**: Interval of time between energising the closing circuit (due to pre-arcing), the circuit breaker being in the open position, and the instant when the current begins to flow in the respective pole.

**Making voltage:** Voltage at which current is initiated in a closing circuit breaker.

**MAT:** Minimum Arcing Time

**Mechanical scatter**: Random statistical variation of the mechanical operating time of a CB excluding the influence of external variables and the effect of long term wear and/or drift.

**Mechanically staggered circuit breaker**: Gang-operated CB with fixed, mechanically implemented, non simultaneous pole operation.

**MOSA:** Metal Oxide Surge Arrester

**NCIT:** Non-Conventional Instrument Transformer

**Opening time**: Interval of time between energising the tripping circuit, the CB being in the closed position, and the instant when the contacts finally separate in the respective pole.

**UGC**: Under Ground Cable

# Executive Summary

Controlled switching is used for the elimination of harmful electrical transients upon the planned switching of mainly capacitor banks, shunt reactors and power transformers. The method is also gaining acceptance for the energising of extra high voltage (EHV) transmission lines and power cables, and to replace traditional pre-insertion resistors.

The development of controlled switching and its applications has built up an unique expertise in switching transients and the mitigation of related problems in both main and secondary circuits.

It can control the CLOSE and OPEN switching instant depending on the type of load. The switching command to the circuit-breaker is sent with an appropriate delay and offset to guarantee the optimum switching instant (e.g. in a current or a voltage zero-crossing). The purpose is to minimise the negative impacts on the power system.

The main advantages which arise from the use of this equipment are:

- Increased system reliability as a result of reduced voltage fluctuations and lower harmonic stress;
- Longer service life of equipment (breakers, insulator, etc…);
- Reduced switching over-voltages and inrush currents; and
- Possible replacement of costly, complex mechanical auxiliary equipment, such as closing resistors.

Controlled switching is usually adopted for the following network elements:

- Shunt capacitor banks;
- Shunt reactors; and
- No-load transformers.

Normally, the calibration and commissioning of these devices are carried out directly and exclusively by the breaker manufacturers.

Thus, the Transmission System Operator (TSO) does not have direct control over the functional status of complex and important equipment (CB) for the efficiency and safety of the network.

The problem becomes evident only in the event of malfunctions caused by the incorrect synchronisation of opening or closing, which causes significant damage either in terms of material (e.g. total or partial destruction of the CB) or in terms of continuity of operation (e.g. untimely trips during energisation of transformers or reactors).

TSO members, using such devices, have gathered their experiences on applications, settings and maintenance plans in a dedicated questionnaire, presented in this report.

# List of figures

# 1 INTRODUCTION

Switching operations are a major source of power system transients. For instance, capacitor bank switching can create current surges and overvoltage. Energisation operation can create a significant DC offset that can, in turn, saturate power transformers. Shunt reactor de-energisation can cause CB reignitions that can result in equipment failure. Transformer energisation typically creates significant inrush currents that create harmonics in the voltage and current signals. Harmonic, overvoltage transient can cause transmission line protection relays to misoperate. Energisation of transmission lines with trapped charges during fast reclosing can lead to line overvoltage that causes relay misoperation.

One method for reducing switching transients when energising or de-energising electrical equipment is to use pre- and postinsertion resistors. However, this approach is costly because it requires CBs that include these resistors. In addition, the protection schemes need to account for situations such as the failure of the pre- and post-insertion resistors and be able to bypass such failures in a timely manner.

The other method that is gaining favour in the last few years is what is known as ‘controlled switching’. The aim of power apparatus controlled switching is to reduce and possibly eliminate these transients and, therefore, contribute to protecting the power equipment, improving the power quality and reliability.

The combination of CBs with stable closing and opening characteristics and present-day digital technology has allowed intelligent controlled switching devices (CSDs) to be devised that can be applied to any equipment type. Controlled switching is best implemented with breakers with independent pole operation. Less efficient strategies can still be devised with gang-operated CBs. In this report, after a short description of the controlled switching principles of different equipment types, it is demonstrated how intelligent CSDs can be applied to achieve transient-free CB operations.

Main experiences from various TSO members and the elaboration of the data received through a distributed questionnaire is reported to understand the penetration, the diffusion about the CSD system and the problems of the maintenance and operation of such equipment within the European grid.

# 2 Controlled switching Basic Principles

The controlled closing of a power apparatus consists of triggering the electrical make of a CB pole contact at a desired voltage point-on-wave angle. This operation reduces or eliminates voltage or current transients that can result from closing in a random fashion. The nature of the voltage or current transients depends on the equipment type being energised. The performance of a controlled switching scheme depends greatly on the consistency of the CB mechanical characteristics and dielectric behaviour. In addition, the ability of the CSD to accurately predict the behaviour of the CB during its lifetime is an important factor. Desirable characteristics of a CB for use in controlled switching applications are:

- Consistent operating (Open/Close) time with mechanical reliability; and
- Excellent dielectric properties i.e. a steep Rate of Decrease of Dielectric Strength/ Rate of Rise of Dielectric Strength (RDDS/RRDS) Slope.

## 2.1 Circuit Breaker Operating Time.

The Operating Time (T oper) in a CB is the average time interval between the instant when the voltage step is applied on the CB pole closing coil and the instant when the two sides of the pole contacts touch (i.e. the mechanical make). A practical CB exhibits some variation of its operating times. As these variations may be relevant for the operating conditions, different approaches for corrections are used as they differ considerably for different types of CBs. First, it is important to distinguish between predictable and purely statistical changes in operating times as any changes in operating times that can be predicted with sufficient accuracy by the controller do not reduce the effectiveness of controlled switching. The $Toper$ of a circuit breaker can be expressed as:

$$Toper = Tnom + \Delta Tpredict + \Delta Tstatistic$$

$$\Delta Tpredict = \Delta Tcomp + \Delta Tdrift \quad \text{where:}$$

Toper: Operating time predicted by the controller before emitting the command;
Tnom Mean operating time under nominal operating conditions which is readily measured and programmed into the controller;
ΔTpredict: Predictable variation of the operating time (in relation with T nominal) that can be corrected by the controller;
ΔTstatistic: Purely statistical variation of the operating time that cannot be corrected by the controller;
ΔTcomp: The variation of the operating time with predetermined features, those depending on the operating conditions;
ΔTdrift: The variations of the operating time with adaptive features, such as long term drift and wear-related changes;
The predictable variations of the operating times (ΔTpredict) can be further split into those variations for which predetermined compensation can be applied (ΔTcomp) and those which can be dealt with adaptive features (ΔTdrift).

The following are the main influencing factors which can be compensated:

- Ambient Temperature: Temperature can influence the open/close coil resistance;
- DC Operating Voltage: Opening and closing coil control voltage affects the operating characteristic of the plunger, which releases the spring mechanism; and
- Idle Time: This is the amount of time the CB mechanism has been left idle between operations.

The variations related to predetermined compensation (ΔTcomp) are readily measured by appropriate sensors and transducers. Typical parameters such as control voltage (Vcontrol), stored energy of the drive (e.g. hydraulic pressure, Edrive) and ambient temperature (Ttemp) are often compensated for by the controller.

The operating time used by the controller on any given occasion is adjusted, on the basis of sensor inputs, according to a known set of operating characteristics, which have been determined under well-defined operating conditions during the testing for each CB type.

$$\Delta \mathrm{Tcomp} = \mathrm{f}(\mathrm{Vcontrol}, \mathrm{Edrive}, \mathrm{Ttemp})$$

The idle-time dependence of the drive is another factor that can influence the mechanical switching time of each CB operation. A timing deviation estimation method has to be developed for factory and/or field measurement to extract the contribution of each variable.

## 2.2 Electrical characteristics of circuit breakers' operation.

The making instant of a Controlled Switching System (CSS) should be referred to when pre-arcing between the contacts of CBs is initiated. There is a certain voltage level at which the contact gap will break down and current will be initiated for a given contact gap. Without considering arcing, a first approximation of the dielectric strength may be a linear increase with gap spacing after the contact separation. Knowing the travel characteristics of the CB contacts, the RRDS may be a time-dependent characteristic.

When interrupting small capacitive currents, there is a certain probability of re-ignition for particular CBs, depending upon the contact gap at current zero and the RRDS. The application of controlled capacitor de-energisation facilitates current interruption with a relatively large contact gap as dielectric strength can be increased with a contact gap. The application of CSS for small capacitive current interruption can avoid small arcing times and, therefore, the dielectric stresses and re-ignition probabilities can be markedly reduced.

When interrupting small inductive currents, there is again a certain probability of re-ignition as the contact gap at current zero may not be sufficient to withstand the recovery voltages, which is determined by the chopping current levels and load characteristics. The arcing time, and therefore the contact gap at current zero, should be sufficiently large to ensure interruption without re-ignitions. The application of CSS is the appropriate method of achieving re-ignition-free CB opening.

On the other hand, the mean value of the decrease of the withstand voltage can be approximated by a linear function of time when the contacts are close to touching during the closing stroke. The slope (RDDS) is proportional to the mean value of the closing velocity and the gas pressure for gas-blast CBs. The making (prestrike) instant is when the voltage across the CB exceeds the dielectric withstand strength of the contact gap.

For an ideal CB, the RDDS is infinite, while typical practical RDDS values are in the range of 35 kV/ms up to 100 kV/ms per break. It is important to note that values of the normalised RDDS (which is normalised by the rate of rise of the system voltage at voltage zero crossing) smaller than unity do not necessarily limit the use of a particular CB for a CSS.

When closing a CB, electrical conduction does not necessarily occur when the primary contacts touch but rather when an arc is established between them. As the CB contacts approach each other, the voltage across them may exceed the dielectric strength of the insulating medium, resulting in dielectric breakdown. This causes a prestrike arc to occur until the contacts mechanically touch.

During CB closing when the main contacts are moving towards the mechanical touching moment, the CB dielectric strength decreases proportionally to the space between the main contacts. If the mechanical movement is purely linear, so will the dielectric decrease be linear. This decrease can be represented graphically by a line, with a slope named RDDS. Even though the mechanical movement for a real CB is not strictly linear which makes the dielectric slope move slightly away from a straight line, this characteristics is considered linear and is represented by a constant.

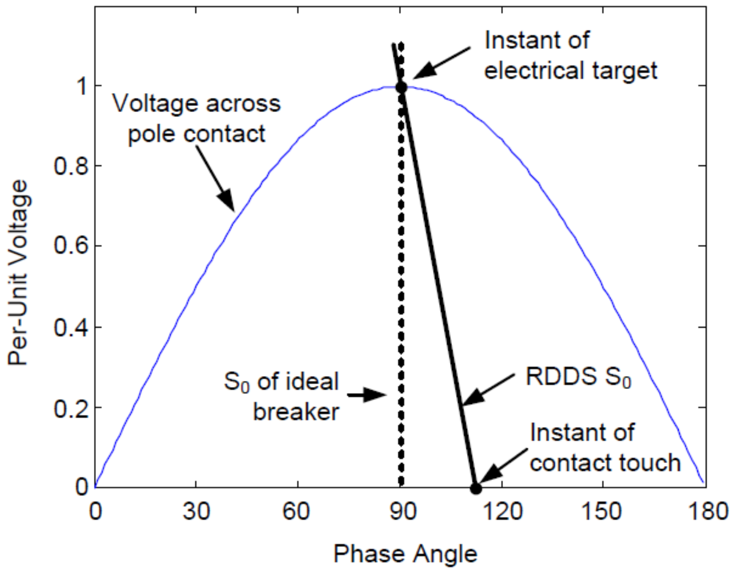



**Figure 1: Prestrike characteristic at a voltage peak [3]**

RDDS is normally defined by the CB manufacturer in kV/ms. This value must be converted in p.u. (relative to the network frequency) for ease of calculation and graphical representation, where 1 p.u. coincides with the voltage sinewave slope at a zero crossing. The statistical nature of dielectric breakdown has a significant influence on the RDDS. The actual withstand of the contact gap is a statistical property and exhibits some scatter, which may be given by the standard deviation of the withstand voltage distributions (3σelectrical).

In probability theory and statistics, 'variance' (dispersion or scatter) is a measure of how far a set of numbers are spread out. A small variance indicates that the data points tend to be very close to the mean (expected value) and hence to each other, while a high variance indicates that the data points are very spread out around the mean and from each other. An equivalent measure is the square root of the variance, called the standard deviation (**σ**). The standard deviation has the same dimension as the data, and hence is comparable to deviations from the mean.

When selecting a CB for a controlled switching application, the CB scatter should be lower than a specified value of '3**σ**' where the majority of operating times will fit (99.8%). A typical value of the CB scatter to specify for a CS application is less than ±1ms

During load interruption, the rate at which the withstand voltage between the CB contacts rises, as the contact gap is increased, is known as the RRDS. This is an important characteristic for CBs when used in controlled opening applications. CBs with high RRDS values can interrupt inductive loads without re-ignition as the CB dielectric withstand exceeds the transient recovery voltage (TRV) across the CB terminals. TRV is the voltage that appears across the CB contacts immediately after current interruption. A TRV with a steep rate of rise or high amplitude can lead to re-ignition or restrike following current interruption.

Normally, during CB opening, the CB main contacts are moving more rapidly than for the closing operation. Here, the CB dielectric behavior is also expressed with a line whose slope starting point is the beginning of the contact parting: RRDS. This slope must be sufficiently steep to prevent any TRV peak from being higher than the corresponding value on the slope line. Otherwise, the opening operation will not be successful and a re-ignition (if the current is re-established less than 1/4 cycle after current zero crossing) or, worse, a restrike (if the current is re-established more than 1/4 cycle after current zero crossing) could occur.

# 3 Principles of controlled switching

Controlled switching is the term commonly used to describe the application of electronic control equipment (CSD or Point of Wave) to facilitate the operation of the contacts of a switching device at a pre-determined point regarding an electrical reference signal for the purpose of reducing switching surges.

## 3.1 Controlled opening

The term controlled opening (de-energisation) refers to the technique of controlling the contact separation of each pole of a CB with respect to the phase angle of the current and, thereby, controlling arcing times to minimise stresses on the components of the power system.

Figure 2 provides a typical timing sequence for controlled opening or de-energisation using a CB with independent pole operation.

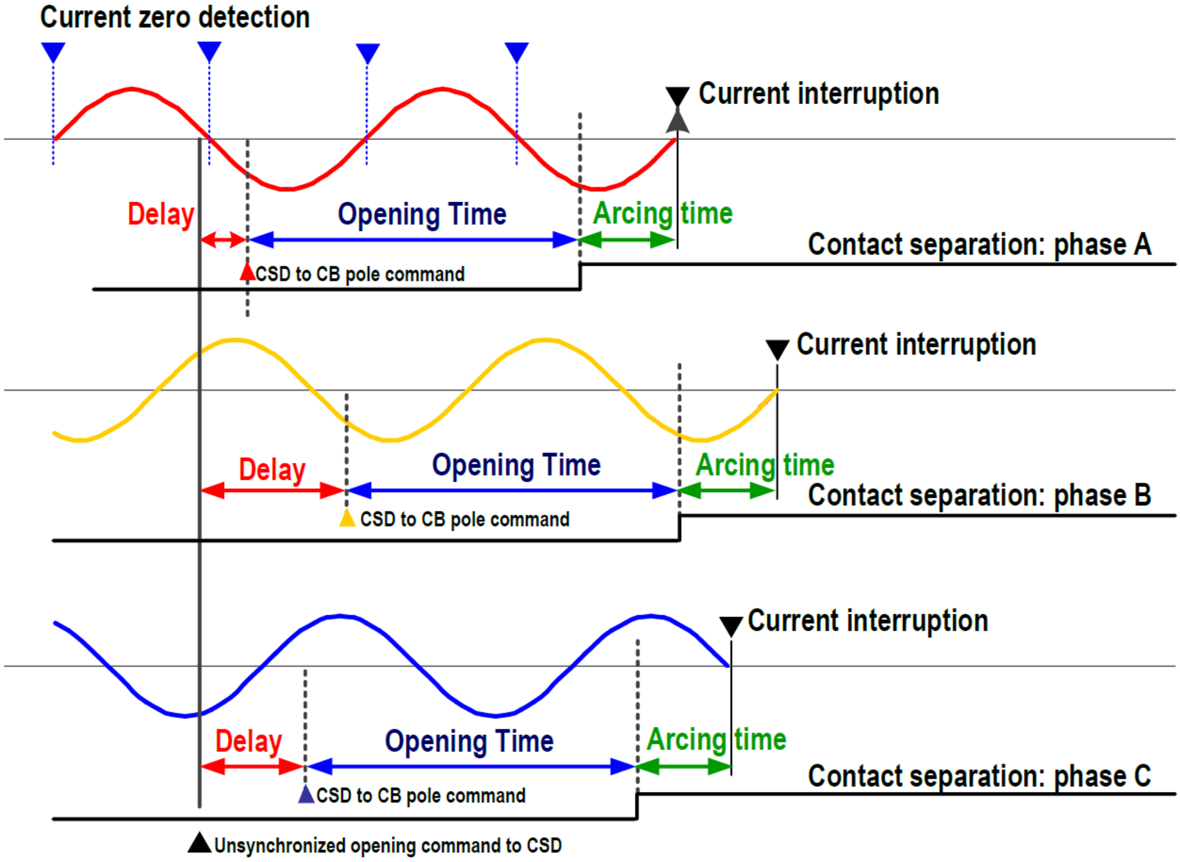



**Figure 2: Controlled de-energisation[1]**

To achieve controlled opening, the current through the CB or a reference voltage is monitored. In this example, the controller detects periodical current zero crossing as the reference synchronisation signal. The arcing time of each pole is controlled by setting the instant of contact separation with respect to the current waveform.

When necessary, the initial opening command is issued randomly to the CSD with respect to the reference signal. Then, the command to the CB is delayed to separate the contact of each phase independently when the CB can secure an optimum arcing time. It can substantially reduce the probability of restrike during consecutive capacitor de-energisation or avoid re-ignition in the event of reactor de-energization.

## 3.2 Controlled closing

Controlled closing is the technique of controlling the instant of making (current initiation) with respect to the system voltage waveform (phase angle). A typical timing sequence for the controlled closing of an independent pole CB (energisation) is illustrated in Figure 3, where the target is voltage zero.

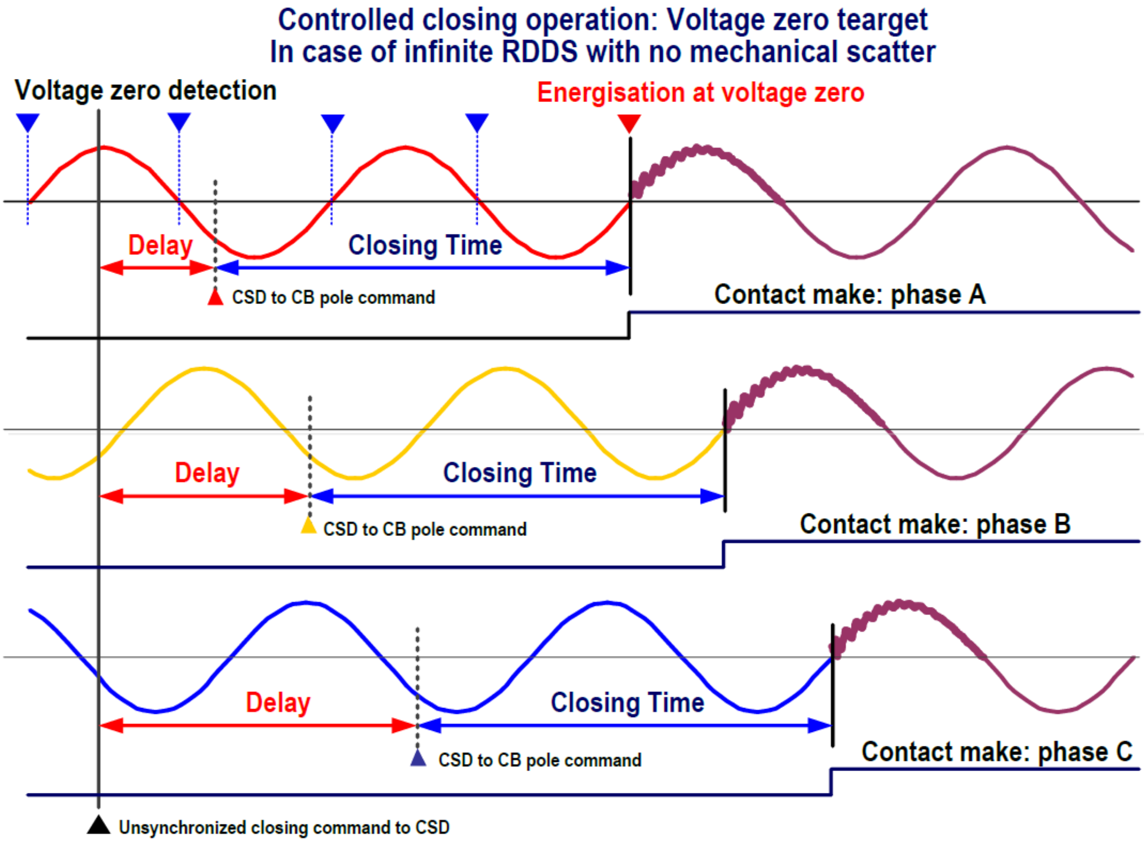



**Figure 3: Controlled energisation at voltage zero [1]**

For controlled closing, a source voltage is monitored by the controller. Again, the closing command to the CSD is issued randomly with respect to the reference signal. This command to each pole of the CB is delayed by the CSD so it is made at the optimum instant on each phase. The example relates to a discharged capacitive load, where the optimum making instant is the voltage zero, which can be attained with an ideal CB with infinite RDDS with no mechanical scatter. A pre-arcing before contact touch is not considered.

In the event of an inductive load, the optimum making instant to reduce the inrush current is the voltage peak as shown in Figure 4, where the pre-arcing time between the instant of prestrike and contact touch is assumed to be an eighth of a cycle. The closing time is dependent on the operating conditions as well as the prestrike behavior and are particular to each type of CB.

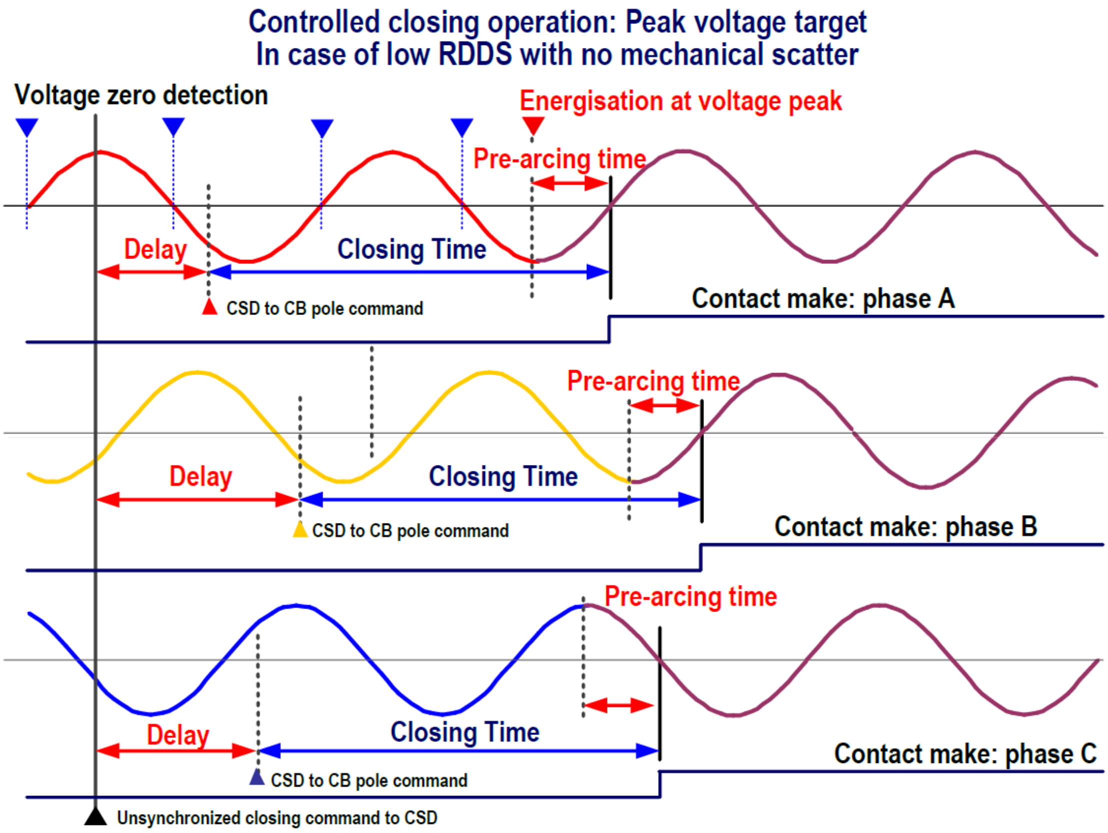



**Figure 4: Controlled energisation at voltage peak [1]**

# 4 Closure Control Strategy Based on the application

The following subsections give only an overview of the switching strategies for the four main application types. Depending on the user's expectation and the CSD available functionalities, the CSD can be configured/selected for one of the four usual application types and, if so required, for both opening and closing.

## 4.1 Controlled switching of transmission line

When an overhead line is energised by closing the line CB, switching transients will be generated mainly on the line but also in the supply network. The switching transients depend on the difference between the supply voltage and the line voltage at the instant of energising and are related to traveling wave phenomena on the line. Such switching transients are a concern on many transmission networks at rated voltages of 420 kV and above, and especially in regard to long lines. For these high voltages, the switching impulse withstand voltage of the system and equipment will only be about 2–3 p.u. and switching overvoltage has to be kept under control.

The physical phenomena governing line switching overvoltage is the propagation of electromagnetic waves along the line, generally called traveling wave phenomena. The wave propagation is initiated by the CB-making operation and the initial voltage amplitude is the CB pre-arc voltage, i.e. the instantaneous value of the voltage across the CB pole at the line charging current making instant. As shown in Figure 5, energising occurs at an instant with a large difference between (instantaneous) supply voltage and line voltage, when a large traveling wave will be injected onto the line. When this wave reaches the open, far end of the line, it will be reflected and a high overvoltage will be initiated. Controlled reclosing of the CB aims to minimise the initial voltage difference between the supply and the line, and thereby the switching transient.

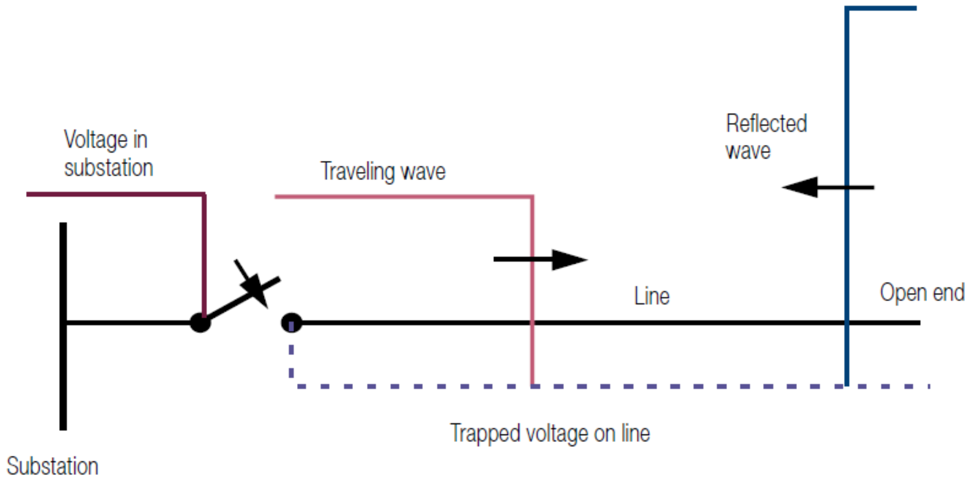



**Figure 5: Principle of traveling waves at energising of an uncompensated line at an unfavorable instant [2]**

The voltage on the line before closing or reclosing operations will vary from case to case.

Upon planned closing operations, there will be no charge on the line. Sufficient time has passed since the line was previously energised, and all trapped charge will have had sufficient time to decay for zero. Upon three-phase reclosing operations (normally after clearing of a fault on the line) with uncompensated overhead lines, there may be trapped charge on the healthy phases, with corresponding DC voltage. Such trapped charge may normally be disregarded in cases with magnetic voltage transformers connected to the line due to their low resistance to ground. With capacitive voltage transformers, however, the resistance to ground is high, and trapped charge may remain on the line for a considerable time, up to several seconds.

At reclosing operations of shunt compensated lines (shunt reactor connected on the line side of the CB), the voltage on the line will be a gradually damped sinusoidal oscillation, with a frequency determined by the line capacitance and the inductance of the shunt reactor. The frequency will generally be lower than the frequency of the supply voltage.

Consequently, there will be an amplitude modulated voltage oscillation across the open CB, with the actual shape determined by the degree of compensation of the line (See Figure 6).

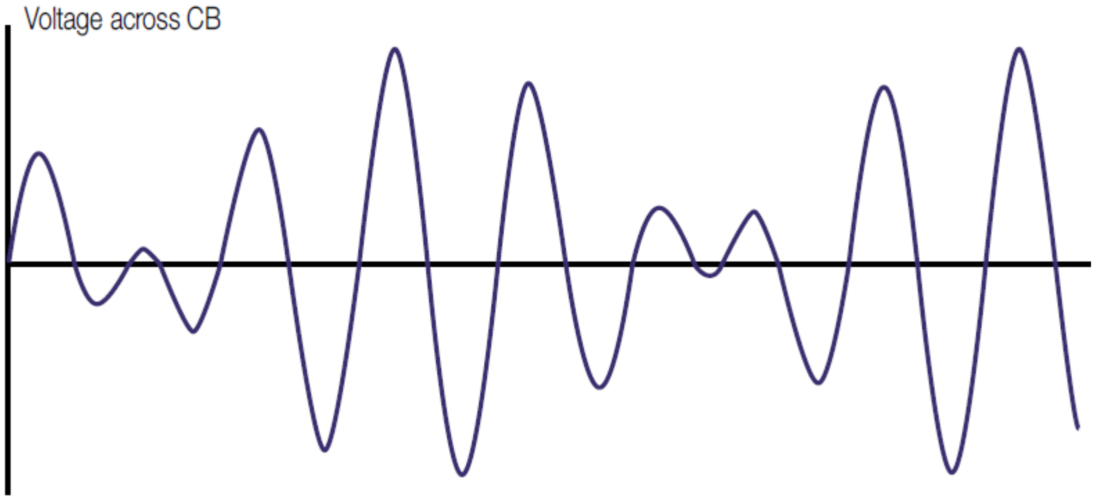



**Figure 6: Example of voltage shape across the open CB before reclosing of a shunt compensated line [2]**

## 4.1.1 Control of closing and reclosing operations, uncompensated lines

For uncompensated lines, the controlled switching of the line CBs may be arranged in two different ways. Both methods require the use of single-pole operated CBs:

- Trapped charge on the line, resulting from the opening operation, is not recorded (no-VT line side).

For closing, a compromise strategy is used that determines the targets for contact touch by a certain delay after supply side phase-to-ground voltage zero. The delayed targeting is determined by the CB RDDS with respect to the amplitude of the system voltage and its frequency. In this manner, the limitation of high overvoltage is achieved irrespective of the actual trapped charge. This is a straightforward method, and the resulting overvoltage level is often acceptable, especially when applied in combination with surge arresters. In many cases, the trapped charge will actually be zero or close to zero. This will be the case when sufficient time has elapsed from the opening operation, or even at reclosing operations, if the line is equipped with magnetic voltage transformers. The method gives best results with CBS with high RDDS.

- More efficient limitation of switching overvoltage is achieved when the trapped charge on the line is recorded and considered by the controlling device. This solution is especially useful in situations when considerable trapped charge is to be expected, i.e. for reclosing operations in situations when capacitive voltage transformers (CVTs) are used. The initial magnitude of the trapped charge can be recorded by the CVTs. As shown in Figure 7, the CVTs will show the DC voltage level, related to the trapped charge for a certain time interval after interruption, and this value will be used by the controller. Should the time interval before reclosing exceed 20s, the controller will automatically change to the assumption that the line is uncharged.

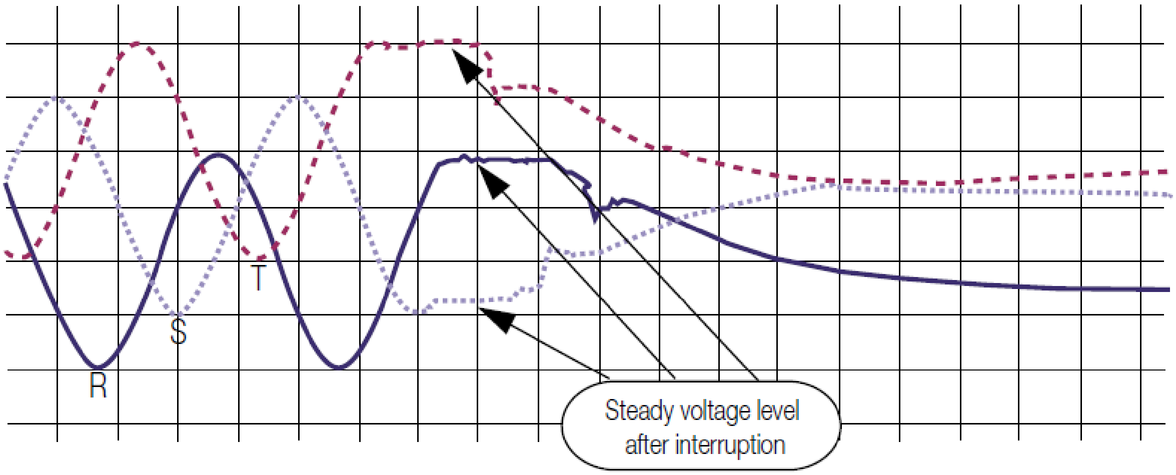



**Figure 7: Voltage signals from CVTs during interruption of an unloaded uncompensated healthy line. [2]**

### 4.1.2 Control of closing and reclosing operations, shunt compensated lines

For shunt compensated lines, the interaction between line capacitance and reactor inductance will lead to voltage oscillations of the healthy phases after interruption. In this case, due to the oscillating voltage shape on the line, the voltage transformers connected to the line will provide correct voltage signals. Controlled switching requires the use of single-pole operated line CBs. Reclosing may be set to occur slightly after (time dependent on RDDS) phase-to-ground supply side voltage zero.
The limitation of switching overvoltage that will be achieved by the use of controlled line switching depends on several factors, such as:

- Line length and configuration;
- Degree of compensation;
- Single- or three-pole reclosing
- Type of CSD utilised; and
- Position and type of surge arresters.

The acceptable switching overvoltage level depends on the insulation level of the system.
Due to the variation of parameters, the choice CSD must be made on a case-by-case basis, and often requires a study of the switching overvoltage.

## 4.2 Controlled switching of shunt reactors

Shunt reactors are mainly used in transmission networks. Their function is to consume the excess reactive power generated by overhead lines under low-load conditions, and thereby stabilise the system voltage. They are quite frequently switched in and out on a daily basis, following the load situation in the system. Shunt reactors are normally connected to substation busbars, but also quite often directly to overhead lines.

Alternatively, they may also be connected to tertiary windings of power transformers. The reactors may have grounded, ungrounded or reactor grounded neutral.
Three-phase shunt reactors may consist of three separate single-phase units or be complete three-phase units with a common core and tank. Common, three-phase cores may be of either five-leg (alternatively shell type) or three-leg design. Five-leg cores and shell type cores are mainly used for transmission voltages. They make the three phases magnetically independent, while three-leg cores leading to magnetic coupling between the phases.

## 4.2.1 Closing operations for Shunt reactors

Random energising of shunt reactors produces current asymmetry (Figure 8a) that saturates current transformers' iron cores and may occasionally lead to protective relay mis-operation. Controlled energising at each phase of respective voltage peak (Figure 8b) allows the reduction of current asymmetry and improves system reliability.

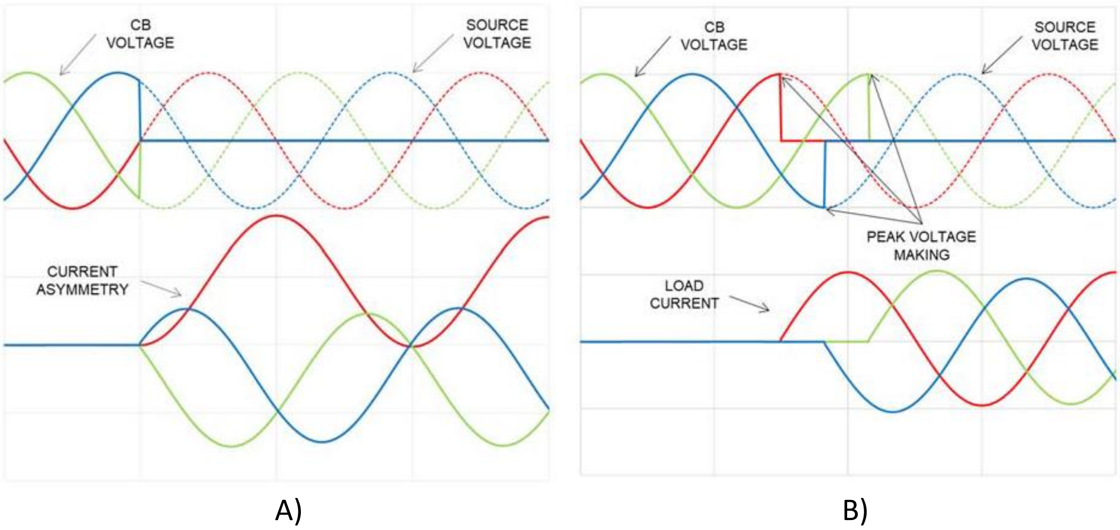



**Figure 8: Shunt reactor closing  A) random B) controlled [1]**

## 4.2.2 De-energisation operations for shunt reactors

In addition to the inductance of the winding, a shunt reactor always has some stray capacitance, in the windings, the bushings and in the connecting leads. When a reactor is de-energised, the voltage across it will oscillate, with the natural frequency determined by the inductance and stray capacitance. The oscillation frequency is typically a few kHz. Due to chopping (premature interruption) of the current slightly before the natural current zero, the oscillating reactor voltage will have a higher amplitude than the supply voltage.
For modern SF6 circuit breakers, typical magnitudes of this 'chopping overvoltage' are 1.2 to 2.0 p.u., with the highest values occurring for small reactors. The chopping overvoltage, with

its limited amplitude and frequency, is normally quite harmless both for the reactor itself and for the surrounding system. Due to the oscillating reactor voltage, there will be a high voltage stress across the CB. If the contact gap is still small, i.e. if the arcing time is short, the CB will probably reignite. A reignition will generate high-frequency transients (typically hundreds of kHz) in both reactor voltage and current. Following a reignition, the reactor current will be interrupted again, either at a high-frequency zero of the current, or most probably at the subsequent power frequency zero. Controlled opening by optimising arcing times (Figure 9) and separating arcing contacts within the free reignition window allows the reduction of current reignition probability and increase of equipment lifetime.

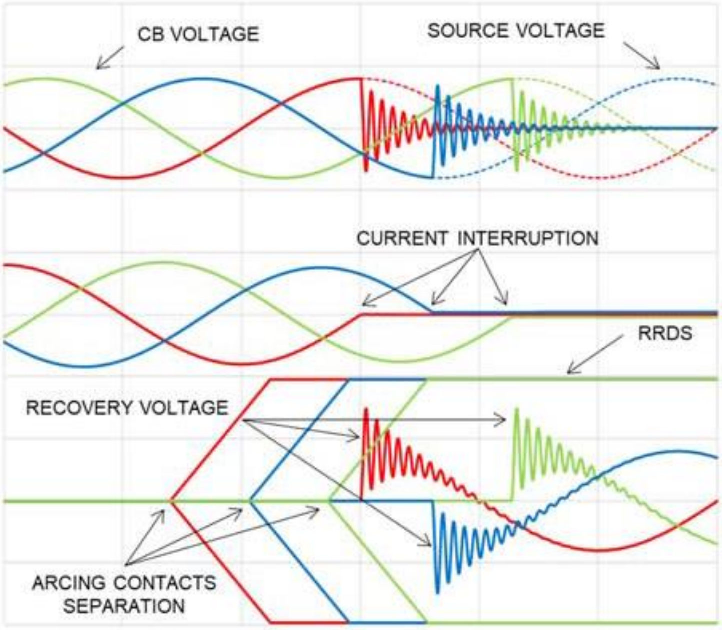



**Figure 9: Shunt reactor controlled opening [1]**

## 4.3 Controlled switching of Power Unloaded Transformer

When energising transformers, we must be aware of potential problems that may arise. This brief introduction recalls the issue of energising basic transformers for mitigation techniques, of which CSDs are also a part.

In steady state unloaded conditions, all the magnetic flux is well contained inside the transformer iron core so only a small magnetising current is needed, as shown in Figure 10.

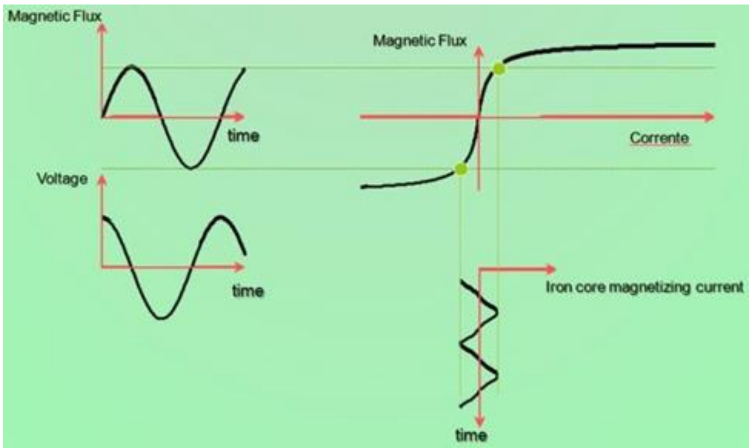



FIGURE 10: ELECTRICAL AND MAGNETIC SIGNALS IN STEADY STATE CONDITION (UNLOADED TRANSFORMER) [1]

As is well known, when a high voltage power transformer is de-energised, it keeps some residual flux in their iron cores, which may affect the inrush current magnitude at the next energisation, depending on the energisation instants.

As transformers are normally energised by arbitrarily closing the CB contacts, with the system voltage being applied on the transformer windings at random instants, this switching operation may introduce an asymmetrical magnetic flux in the windings, driving the transformer core into saturation. Consequently, transformer inrush currents of high magnitude are produced. The worst case with respect to the higher inrush current is shown in Figure 11.

As soon as the magnetic flux value goes over the saturation level (called the saturation knee), as for example when energising an unloaded transformer at the worst moment (see Figure 11), the current will increase faster than the flux and extra current will then be needed to further increase the magnetic flux density. This will produce an inrush current whose magnitude depends mainly on the transformer core characteristics, the closing moment on the network voltage (point on wave) and the amount of residual flux.

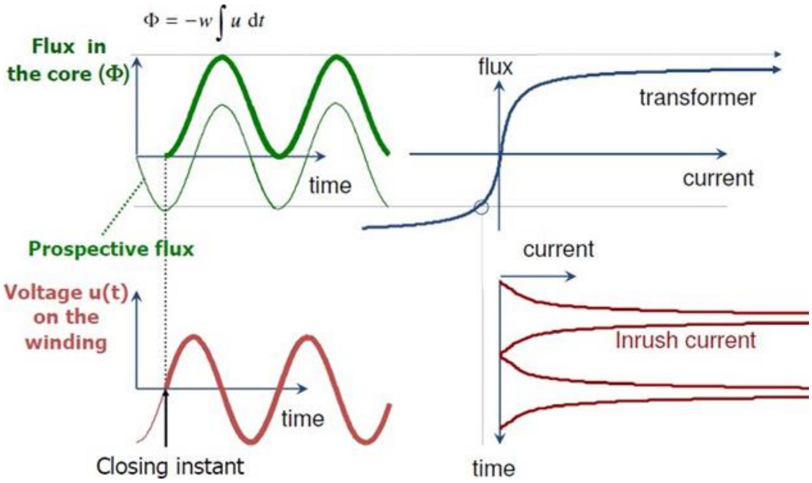



FIGURE 11: ELECTRICAL AND MAGNETIC SIGNALS WHEN ENERGISING AT ZERO-CROSSING VOLTAGE (FLUX = 0)[1]

Three-phase power transformers may consist of three separate single-phase units, or alternatively a complete three-phase unit with common core and tank. Common three-phase cores may be of either five-leg or three-leg design. The primary and secondary windings may be arranged in Y-(grounded or ungrounded) or D-configuration. Tertiary, D-connected windings are sometimes utilised in cases with Y-connected primary and secondary windings.

Depending on the core and winding arrangement, the individual phases may or may not influence each other during switching operations, and this must be considered when controlled switching is applied. The phases will influence each other in the following cases:

- Ungrounded neutral on the switched side;
- Three-leg core; and
- D-connected secondary or tertiary winding.

Energisation of an unloaded transformer can generate high amplitude inrush currents, which stress the windings and can cause the undesired operation of protection relays and prolonged temporary harmonic voltages, which in turn lead to degradation in the quality of electricity supply. High inrush currents also impose severe mechanical stresses on the transformer windings and may reduce the life expectancy of a transformer exposed to frequent energisation, for example step-up transformers in hydroelectric power plants are frequently switched to adapt with the daily load variation.

The interruption of no-load transformer currents is of a similar nature as for shunt reactors. However, the natural frequencies are much weaker, and the damping is very high, meaning that the overvoltage generated at de-energisation is extremely low in amplitude.

The magnetic circuits of transformers have magnetisation curves with a pronounced bend from the non-saturation region to the saturation region. For reasons of economy, power transformers are designed with an operational peak flux value as close as possible to the saturation value.

Energisation of a transformer at peak voltage without residual flux in the core will cause no inrush currents but fast voltage transients at the transformer terminals. Depending on the residual flux and the energisation instant, the flux change after energisation may, however, generate greater saturation of the magnetizing currents. Therefore, the optimum targets should be adjusted, considering the residual flux: the inrush current at energisation will be at a minimum if the prospective normal core flux is identical to the residual flux. Figure 12 shows the dynamic magnetic flux and the current behavior when a transformer is energised.

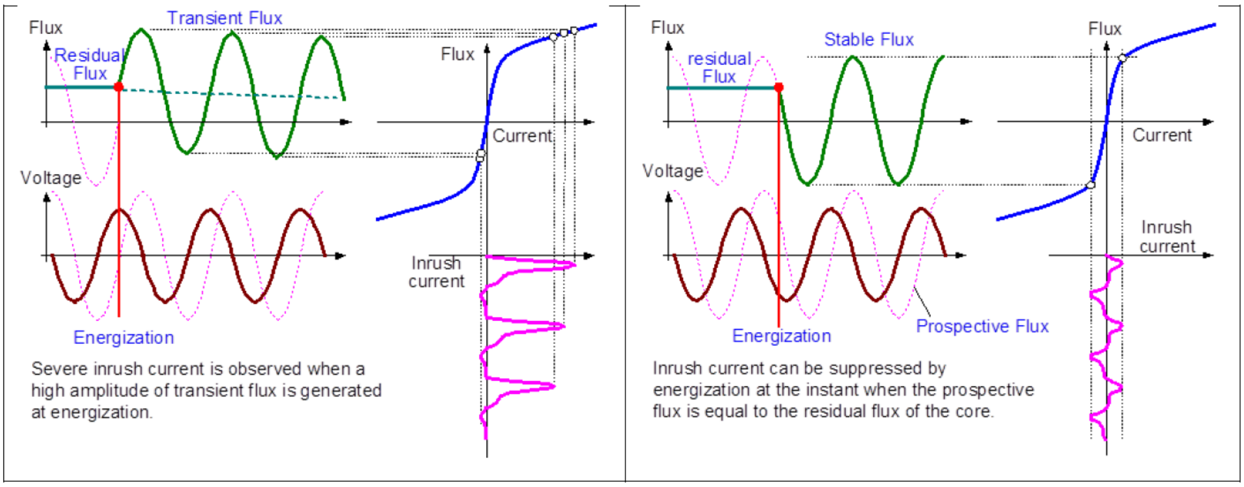



**Figure 12: Transformer magnetic flux and corresponding magnetising current [1]**

At the instant of making, a residual flux resulting from the previous opening can remain in the transformer. If this residual flux is of the same polarity as the dynamic flux, the resulting flux will be higher than the saturation knee, thus resulting in proportional inrush currents. A description of the processes occurring when a three-phase transformer is energised is more complex because the three phases are connected both magnetically and galvanically. The structure of winding connection (transformer vector group) and the configuration of the neutral point are factors that influence the value of the inrush current and the selection of the mitigation strategy.

### 4.3.1 Control of closing operations for an unloaded transformer with an isolated star point

The energising of a single phase has no effect as there is no flow path of magnetising current due to the isolated neutral point. The phase-to-phase voltage U13 is switched on at its maximum value at time t1. The corresponding stationary core fluxes ϕ1 and ϕ3 have instantaneous values of zero at this moment t1. They attain their maximum values 90 electrical degrees later at time t2; these are identical to the steady-state core flux values. This means that voltage U2 can be switched in without any transient reaction at time t2.

Figure 12 shows the IPO CB energisation strategy of a three-core transformer with Wye (Star) connection and isolated neutral.

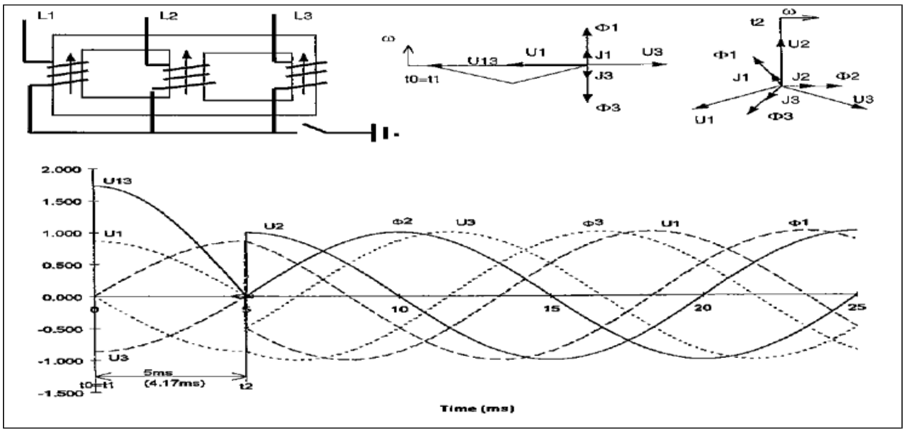


**Figure 13: Flux and Voltage diagram at Close in an isolated neutral transformer [1]**

It is easier to describe a general controlled closing principle by adopting the hypothesis that there is no core flux prior to transformer energisation. Only one CB pole is closed if the neutral of the primary winding is earthed and, otherwise, two poles are closed if the primary winding is isolated. The making target is the maximum line-to-earth voltage (earthed neutral) or at maximum phase-to-phase voltage (isolated neutral) such that fluxes are generated without transients. The making instant of the remaining phase(s) must be chosen such that the flux circulating in the corresponding cores since the initial closing is the same as the flux that will circulate in these cores under steady state conditions. This avoids the creation of flux transients in the cores.

## 4.3.2 Control of closing operations for an unloaded and solid earthed transformer

The following describes the IPO CB energisation strategy of a three-core transformer with Wye (Star) connection and solidly earthed neutral. Phase L2 is energized when phase voltage U2 is at its peak at time t1, as shown in Figure 14. The magnetising current J2 is able to flow through the earthed neutral point. The magnetising field ϕ2 begins without any transient. The associated magnetising current J2 must also provide for the excitation of the other two phases, each of which has half the flux during this stage. Consequently, this current has a value 1.5 times that of its three-phase steady-state value.

By the time t2, the fluxes ϕ1 and ϕ3 has reached levels corresponding to their three-phase steady-state value. Phase L1 and L3 may therefore be energised without transients at time t2. The phase L2 is wound around the middle core in the case of 3 or 5 leg (core) power transformers. The voltage of the different phases can be written as follows:

$U_1 = U \times \sin(\omega t + 2\pi/3)$,

$U_2 = U \times \sin(\omega t)$ ,

$U_3 = U \times \sin(\omega t - 2\pi/3)$

The making instant is given in relation to the zero voltage instant of U2.

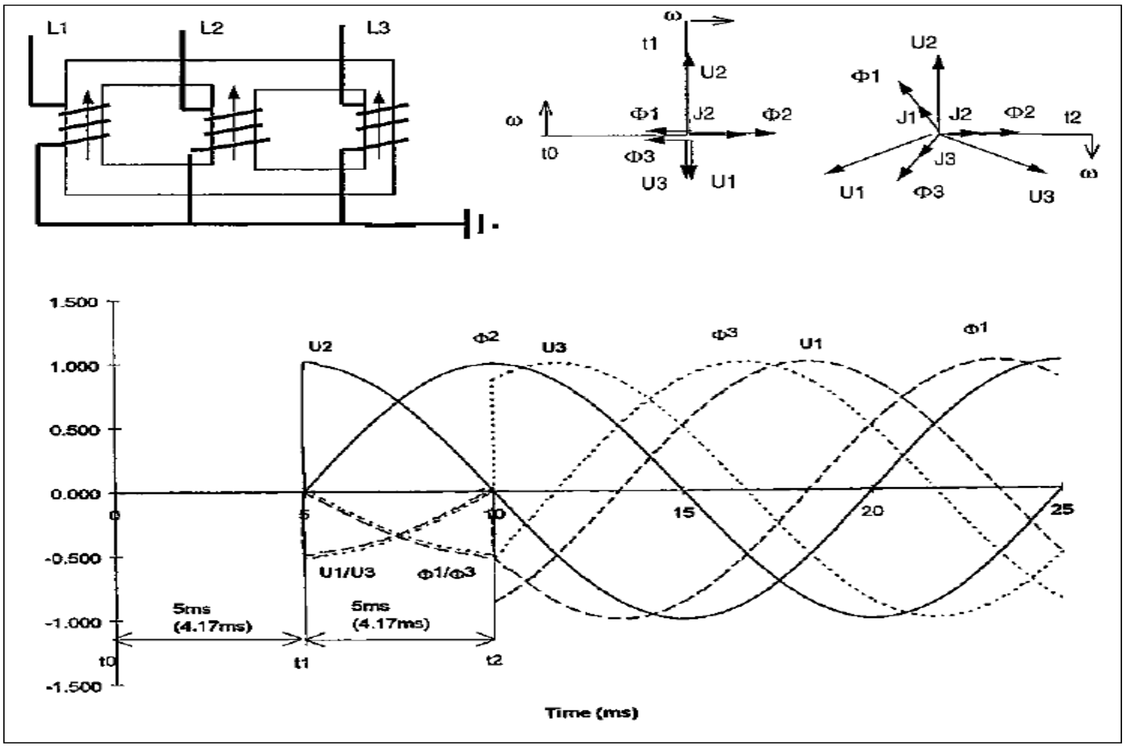



**Figure 14: Flux and Voltage diagram at Close at a grounded neutral transformer [1]**

Table 1 summarises the choice of the phases making instant of an IPO CB to obtain a minimum inrush current, with the assumption that there is no residual flux

| Primary winding connection | Secondary or tertiary coupling | Magnetic circuit | Making instant Voltage value Phase 2 | Making instant Voltage value Phase 1 | Making instant Voltage value Phase 3 |
|---|---|---|---|---|---|
| Wye (star) connection with isolated neutral<br>Y | Wye (star) or delta | • 3 or 5-core transformers<br>• transformer banks | 5 ms (50 Hz)<br>4.17 ms(60 Hz)<br>(90°)<br>1.5 $U$ | 0 ms (50 Hz)<br>0 ms (60 Hz)<br>(240°)<br>$U\sqrt{3/2}$ | 0 ms (50 Hz)<br>0 ms (60 Hz)<br>(120°)<br>$U\sqrt{3/2}$ |
| Wye (star) connection with earthed neutral<br>$Y_n$ | Wye (star) or delta | 3 or 5-core transformers | 5 ms (50 Hz)<br>4.17 ms (60 Hz)<br>(90°)<br>$U$ | 10 ms (50 Hz)<br>8.33 ms (60 Hz)<br>(60°)<br>$U\sqrt{3/2}$ | 10 ms (50 Hz)<br>8.33 ms (60 Hz)<br>(300°)<br>$U\sqrt{3/2}$ |
| Wye (star) connection with earthed neutral<br>$Y_n$ | Delta<br>Δ | transformer banks | 5 ms (50 Hz)<br>4.17 ms (60 Hz)<br>(90°)<br>$U$ | 10 ms (50 Hz)<br>8.33 ms (60 Hz)<br>(60°)<br>$U\sqrt{3/2}$ | 10 ms (50 Hz)<br>8.33 ms (60 Hz)<br>(300°)<br>$U\sqrt{3/2}$ |
| Wye (star) connection with earthed neutral<br>$Y_n$ | Wye (star)<br>Y or $Y_n$ | transformer banks | 5 ms (50 Hz)<br>4.17 ms (60 Hz)<br>(90°)<br>$U$ | 1.67 ms (50 Hz)<br>1.39 ms (60 Hz)<br>(270°)<br>$U$ | 8.33 ms (50 Hz)<br>6.95 ms (60 Hz)<br>(270°)<br>$U$ |
| Delta<br>Δ | Wye (star) or delta | • 3 or 5-core transformers<br>• transformer banks | 5 ms (50 Hz)<br>4.17 ms (60 Hz)<br>(90°)<br>1.5 $U$ | 0 ms (50 Hz)<br>0 ms (60 Hz)<br>(240°)<br>$U\sqrt{3/2}$ | 0 ms (50 Hz)<br>0 ms (60 Hz)<br>(120°)<br>$U\sqrt{3/2}$ |

To perform an optimum inrush current mitigation, the transformer cores' residual fluxes should be considered to select the optimum energisation instants, especially in the case of smaller capacitance between the windings to ground. Therefore, the inrush current magnitudes will depend on the following characteristics:

- the magnetic characteristics of the transformer cores;
- the making instants of the circuit breaker;
- the power transformer vector group;
- the residual flux magnitude and polarity in each core limb; and
- the electrical characteristics of the 'source' system.

A method to minimise residual flow is the control of closing operations after controlled opening operations,

The opening operations of the breaker are controlled to achieve a defined and repeatable residual magnetic flux in the transformer core. The procedure is normally to interrupt the no-

load current close to a natural zero passage, which results in minimum flux in the core. The subsequent closing operation is then controlled to minimise the inrush current, based on this knowledge. Sometimes, however, a higher value of residual flux is chosen as this will be associated with lower pre-arcing stress of the CB at the subsequent closing operation. This also improves the precision of the targeting process.
This method is suitable for the regular planned switching of transformers under no-load conditions. It is applicable in situations where the same CB will always perform the making and breaking operations.
If opening operations are performed at random, the resulting residual flux can be determined by the integration of the transformer voltage, see Figure 15. The voltage signals to the controller for this process may be taken from normal VTs or CVTs adjacent to the transformer. Based on the calculated residual flux, the subsequent closing operation is then controlled in such a manner that the inrush current is minimised. The method is mainly suitable for situations with unplanned operations, under varying switching conditions, and works when opening operations occur in connection with faults in the system. As each pole needs to be controlled independently, the method requires a single-pole operation of the CB.

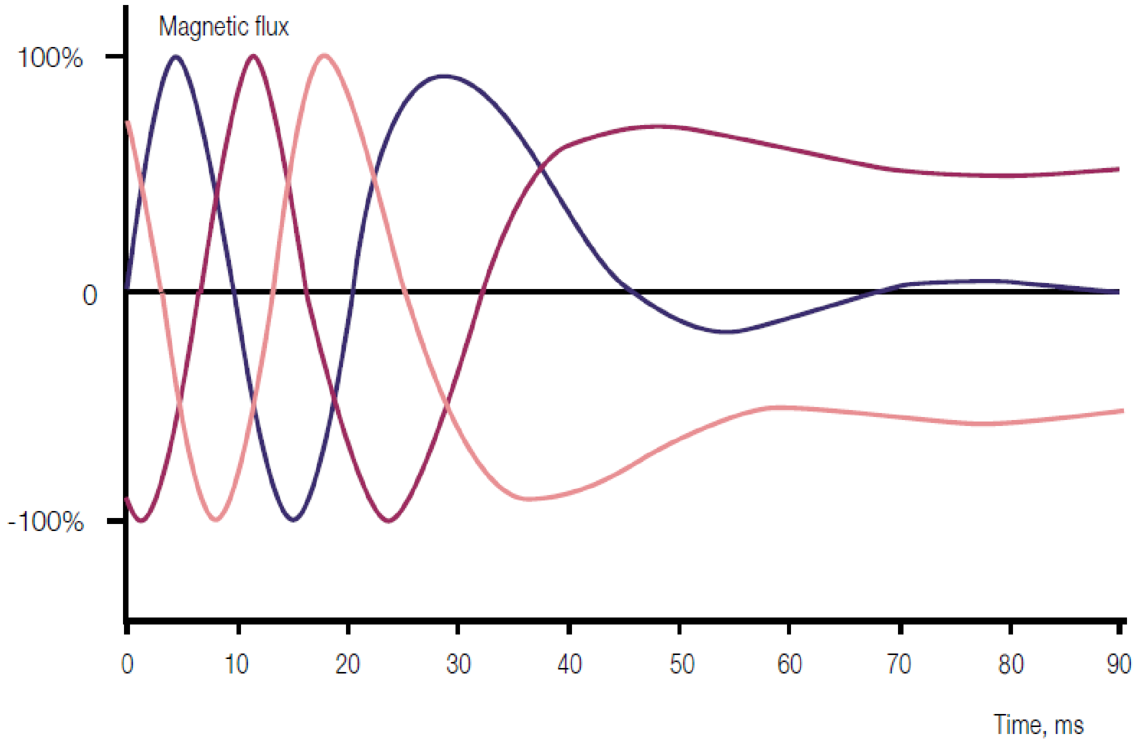



**Figure 15: Residual flux at interruption determined by integration voltage of transformer. D-connected [2]**

## 4.4 Controlled switching of shunt capacitor banks

When a capacitor bank or harmonic filter bank is de-energised, it takes a certain time for a residual charge to disappear. To avoid energising a capacitor bank, a time relay is normally

applied to block the CB mechanism. Build-in discharge resistors will ensure that the bank is discharged when the interlocking has expired.
A typical relay setting is 10 minutes from the opening of the CB to the earliest possible subsequent closing operation.
A discharged capacitor is similar to a momentary short-circuit when connected to a power source. If energised when the source voltage is high, the connection results in voltage and current transients that may cause serious problems. Depending on the grid configuration, the voltage surge may cause a dielectric breakdown somewhere in the high voltage network, and low voltage equipment may suffer insulation damage or malfunction. With back-to-back capacitor banks, the inrush current may have a high frequency and high amplitude. In extreme cases, it may threaten the mechanical integrity of both the capacitor bank and CB. Controlling the CB to energise a capacitive load at zero voltage across the contacts will eliminate harmful transients.

## 4.5 Control of closing operations for shunt capacitor banks with earthed neutral

Upon a closing operation, the contacts in a CB pole will have a dielectric withstand capability that rapidly decreases from a high starting value towards zero when the contacts touch. This property is often referred to as the RDDS of the CB.
In an ideal case, the CB contacts should touch exactly when the voltage across the contacts is zero. For this to be possible, the RDDS of the CB needs to be higher than the rate-of-fall of the applied voltage close to zero. In reality, there will always be a certain scatter in closing speed and dielectric withstand characteristics of the contacts. To minimise the adverse effect of such statistical variations and due to the limited speed, the nominal making target is therefore set slightly after voltage zero, as illustrated in Figure 16.

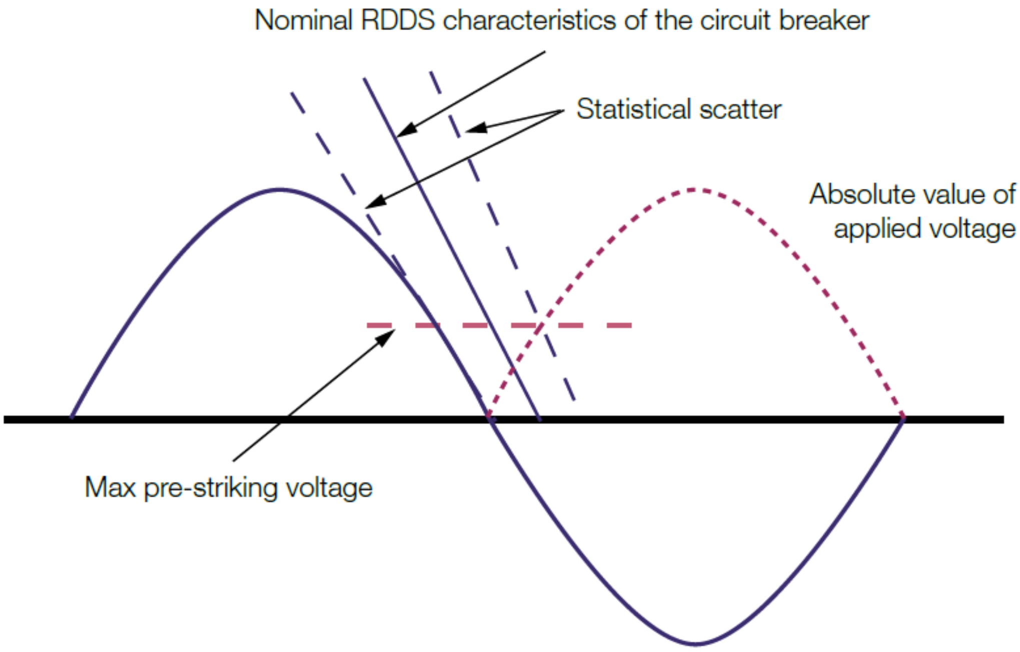



**Figure 16: Energising at voltage zero. The nominal making target is set slightly after voltage zero to minimise the influence of statistical variations [2]**

Even in a very unlikely case with the most unfavorable statistical scatter of closing time and dielectric withstand characteristics; the switching transient would be decreased to less than 30% of what may occur in an uncontrolled situation.

Traditionally, damping reactors are often used for single and back-to-back shunt capacitor banks. Because these reactors are intended to limit inrush currents, they are normally superfluous when controlled closing is utilised. The capacitor bank, CB and the system will normally be able to handle the stresses if an uncontrolled making operation for some reason should occur.

Sometimes, however, damping reactors are utilised to limit high frequency transients created by the interaction of the capacitor bank with other parts of the network in connection with faults outside that bay. In this case, the capacitor bank CB is not involved, and damping reactors are still required when controlled switching of the CB is used.

The idle time compensation is recommended for the drives of which operating times have the idle time dependence. The adaptive control could also be required to compensate for any drift in operating times that persist over a number of consecutive operations.

In the event of a single-pole operated CB, CSD will control each pole individually to make it close at the right time. For a three-pole operated CB, with only one operating mechanism, the poles are mechanically adjusted (staggered) to close at the right instant. For the switching of a shunt capacitor bank or harmonic filter, the actual choice of staggering depends on:

- Connection of the neutral of the load - grounded or ungrounded; and
- System frequency – 50 or 60 Hz.

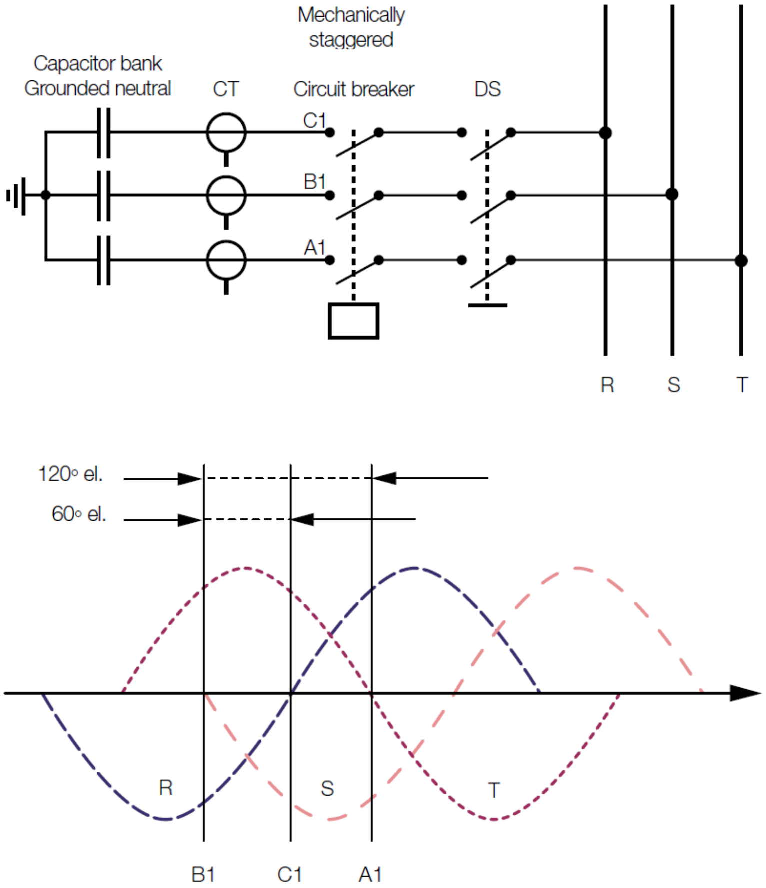



**Figure 17: Connection of a staggered CB for shunt capacitor bank with grounded neutral [2]**

## 4.6 Control of closing operations for shunt capacitor banks with an isolated star point

In the case of a shunt capacitor bank with an isolated star point, the moment of zero voltage across the capacitors translates differently in terms of the closing sequence than when the star point is grounded. Instead of energising each phase at its zero-crossing, the first two phases are connected simultaneously when their voltages are equal, hence the zero voltage across the capacitors at the moment of connection. Then, a quarter of a cycle later, the third phase is connected when its voltage crosses zero, which also corresponds to a zero voltage to the neutral point. Such typical switching sequence is shown in Figure 18. This closing sequence requires a single-pole operated CB or a three-pole one, with the third pole mechanically delayed by a quarter of cycle.

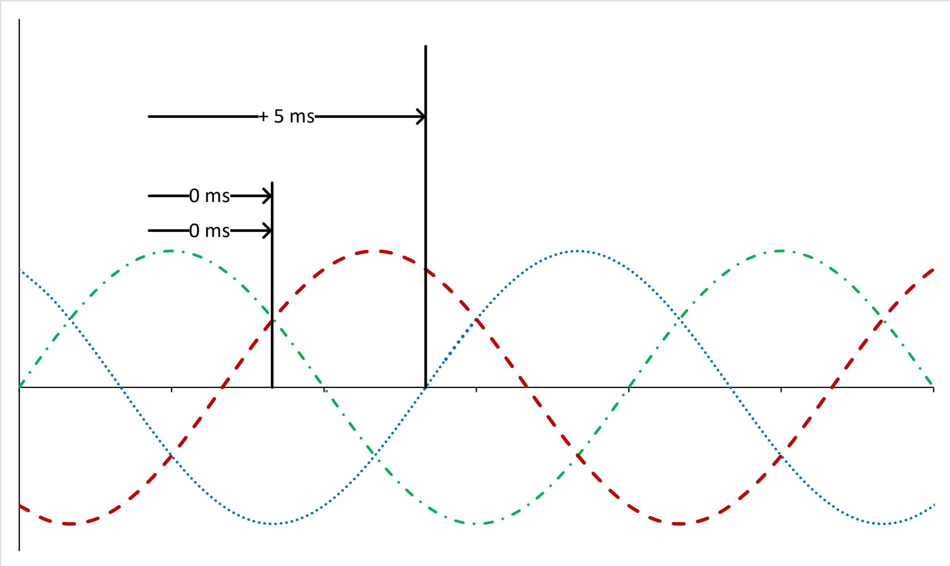
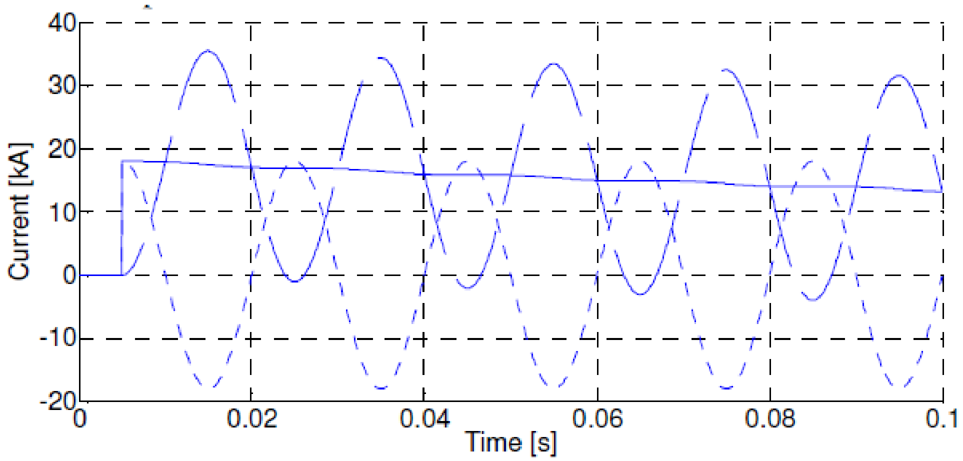



**Figure 18 – Typical switching sequence of shunt capacitor bank with isolated neutral**

## 4.7 Controlled switching of power cables lines.

From the point of view of their impact on transient energisation and de-energisation, long underground cable lines are fully comparable to overhead lines, as described in section 4.1.
Here, too, the CSD system will be designed according to the presence of reactor compensation, the arrangement of conductors and the physical characteristics of the cable.

Another phenomenon related to shunt compensated cable energisation is zero-missing current.
Due to the large capacitive reactive power of high voltage alternating current (HVAC) cables, shunt reactors are needed for power compensation. For unloaded cable systems, the shunt reactor current is almost in phase opposition to the current in the cable, reducing the amplitude of the resultant AC component through the circuit breaker. As the current in the shunt reactor has a transient DC component, the resulting current in the CB may have a DC component larger than its AC component. When this happens, the current passing through the CB does not cross zero until the DC component becomes smaller than the AC component. During its energisation, the cable is unloaded, and the resistance of the system (cable+shunt reactor(s)) is very small. Consequently, the DC component may take several seconds to be damped, a period during which the CB cannot be opened.
As for the zero-missing phenomenon, the value of switching overvoltages depends on the voltage value when connecting the cable/reactor system. However, to avoid the zero-missing phenomenon, the connection should be made when the voltage is at its peak, whereas the opposite applies for avoiding switching overvoltage.




Current in the breaker (I1=IL+IC, solid line)- in Reactor(IL, dashed line),-in the Line capacitor (IC, dotted line

**Figure 19: Breaker Current in Zero Missing Phenomenon [6]**

As explained before, the DC component is zero for a shunt reactor energised at voltage peak. For direct connected shunt reactors, the cable and shunt reactors are energised simultaneously, and it is not possible to use this method because of switching overvoltage. However, if the shunt reactors are connected via CBs, it is possible to connect the cable when the voltage is zero, and after a short period connect the shunt reactors when the voltage is at a peak value.
For this countermeasure to be completely effective, the CB associated to the shunt reactor must operate in single-pole mode and be controlled by its own CSD.

# 5 Controlled Switching Device

CSS have become an economical solution and are commonly used to reduce switching surges for various switching applications. Recent developments in transformer switching taking account of the residual flux can realise an effective means of mitigating severe inrush currents and temporary overvoltage that may lead to the false operation of protective relays and a degradation in power quality. CSS combined with metal oxide surge arresters can reduce undesirable overvoltage caused by the energisation of a long transmission line to meet the insulation coordination.

## 5.1 CSD (Point-on-Wave) device

The CSD is an intelligent controller designed to send open or close commands to a CB to synchronise the mechanical operations of the CB with an electrical target to reach. Figure 20 shows a schematic of a typical CSD installation with its relevant inputs/outputs

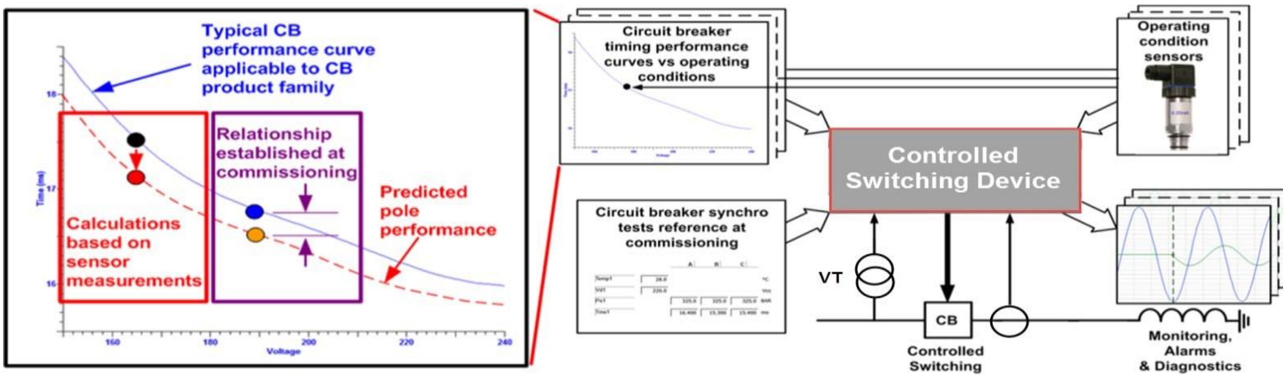



**Figure 20: Example of a typical CSD installation [1]**

One of the biggest challenges of a CSD system is to dispatch control commands such that the CB contacts start moving and are able to reach the desired electrical and mechanical targets at the optimal moment. For that, the CSD needs to predict the required CB operation time under all possible circumstances. To do so, the CSD needs firstly to be configured with an implemented optimal strategy, proper calibration and basic information provided by the manufacturer (such as CB timing performance curves, equipment characteristics, RDDS, etc.), Secondly, a CSS commissioning must be realised to validate CB behaviour and if necessary, extract missing information (especially for retrofitting applications), such as the average operation time of each pole. Despite the fact that under identical operating conditions the timing performance of each CB pole is unique, it is generally agreed in the industry that the timing variation of each pole will follow the same trend as the performance curves gathered during type tests of the CB, the only difference being their average operation time.

In a modern CSD normally, the following functionalities are available for the widest range of uses:

Frequency adaptation:
CSD controllers are fully frequency adaptive. All controllers are designed to work for system frequencies between 16 and 66 Hz.

*Input check:*
Normally, controllers execute an input command check prior to processing an input command. An input check lasts about 40 ms.

*Operating modes:*

Many types of CSD controllers have the option of operating either in rapid or secure mode.
In rapid mode, after the input check has been performed, the controller accepts the first found reference voltage zero.
In secure mode, the controller will accept the fourth reference voltage zero after completion of the input check. Each cycle time of the last three cycles, prior to output activation, must agree with the continuously measured cycle time within specified tolerances. If not, a new countdown starts in order to find an accepted reference point. This will ensure a more precise determination of the final reference prior to activation of the CB coil.

*Reference:*
Normally CSD controllers use for reference a busbar voltage transformer signal. Any phase-to-ground or phase-to- phase voltage can be used.
A reference point is a reference voltage zero with positive derivative. Reference voltage frequency is continuously monitored, and adaptation is automatically done for frequency variations.
For special applications where the phase shift between voltage and current may not be constant, such as when interrupting a loaded arc furnace transformer, it is possible to use a current/ voltage converter and switch with reference to a current zero rather than a voltage zero. This will ensure a fixed contact separation target with respect to the wave shape of the current.

*Targets:*
The targets for controlled switching may either be fixed or be determined by the interrupting conditions.
Some CSDs are used to switch the controlled CB at fixed switching instants (fixed making or contact touch instants and/or fixed arcing times at interruption). Another controller works with the switching instants will vary. The targets will vary depending on the previous interrupting conditions, and the target for the next making operation is determined by load side voltage measurements.

*Phase shifts:*
Targets are expressed with respect to a reference time instant, for controllers this is a busbar voltage zero or in special applications a current zero.
For controlled closing, the target(s) are defined as a certain phase shift(s) with respect to the reference.

For controlled opening, the ultimate targets are certain contact separation instants with respect to the phase shift of the load currents. As the reference is a busbar voltage and the targets are to be expressed with respect to this, it is assumed that there is a true phase shift of 90 electrical degrees (lagging or leading depending on inductive load or capacitive load) between the currents and phase-to-ground voltages.

*Input command:*
The controller has to manage remote switching command given from external sources (SCADA, Local control etc.) to CSD.

*Output command:*
The command is processed in such a manner that the activation of the closing and/or opening coil occurs at instants that will result in the intended optimum making instants and/or contact separation instants, assuming that make times and opening times are predictable so that delayed command from the controller to the CB is processed.

*Voltage transformers and Current transformers (VTs and CTs) used by CSD:*
The reference signal should be a permanent supply side voltage (busbar voltage). The reference voltage must be applied at least 300 ms prior to the given switching command.
For CSD operation, any type of VT already existing in the system is suitable. Normally power consumption is less than 0.1 VA.
When making instant and/or interrupting instant is monitored, a CT secondary signal is required. Any CT already existing in the system is suitable and no separate core is needed.
For residual flux at interruption, determined load side voltage measurements (calculations) are necessary.

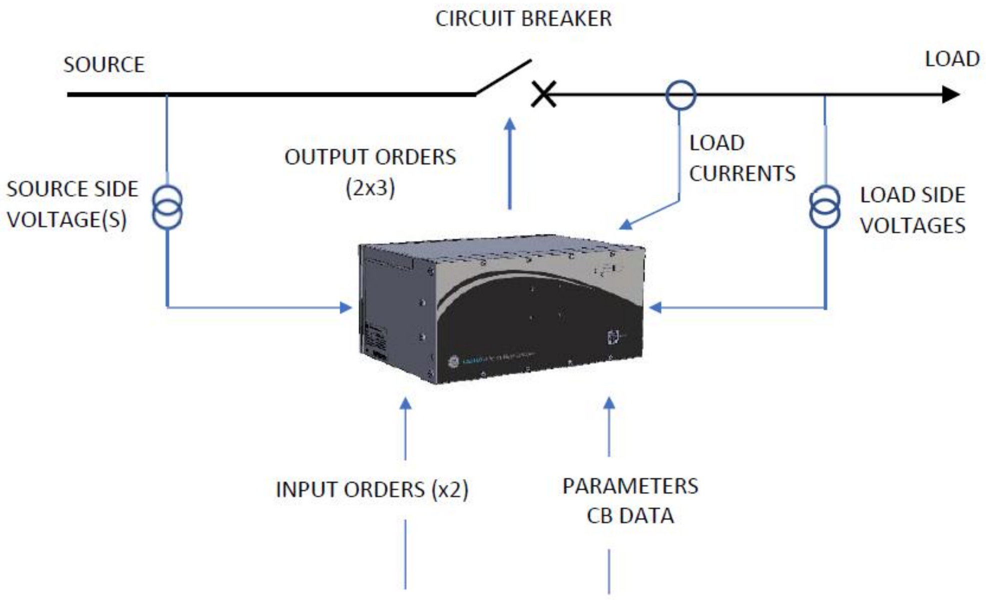



**Figure 21: Controlled switching simplified layout [4]**

## 5.2 Operating mode Control

Normally CSDs are arranged to operate under the following operative modes:

- **Single mode**: CSD operation on a fixed program;
- **Multiple load switching (MLS):** Operation on multiple load in complex substation layouts with tie CB such as 1.5 CB, 1.3 CB, ring configuration or in case of variable load (with variable rate of compensation, moving neutral position…)

- **Dual switching (source side / load side):** Manage reversal of the source and loadside for synchronisation in substation layout with a tie circuit breaker (1.5 CB, 1.3 CB, ring configuration, H configuration)
- **Test mode**: Allows to operate each pole of the circuit breaker independently for wiring check and operating time measurement purpose
- **Bypass**: Circuit breaker operations are performed randomly and simultaneously through an external bypass circuit switched by the bypass relay

## 5.3 Adaptive Control

In addition to the compensation of external factors, the adaptive control function is used in most CSDs to continually compensate for drifts in operating times due to CB aging and wear. The previous performance of the circuit breaker operation is measured and is then used to optimise the next switching operation to meet its target.
Adaptive control refers to the use of previously measured operating times to detect changes in operating characteristics and to predict the operating times for the next operation. Adaptive control can effectively compensate for any drift in operating times which persists over a number of consecutive operations, such as that associated with long term aging and wear.
Various algorithms may be used, and a simple example for purely adaptive control is given here.

$$T_{next\ (n+1)\ operation} = T_{last\ (n)\ operation} + \sum w_n \times (T_{measured\ of\ n\ operation} - T_{expected\ of\ n\ operation})$$

The weighting factor Wn determines to what extent the measured changes of operating times are considered. To ensure that statistical and periodic changes are not amplified, w is limited to be less than 1.
Gas circuit breakers are commonly designed using several sliding parts such as contacts and sliding seal rubbing between metal surfaces during close and open operations. Consequently, operating characteristics are affected by the change of friction or sticking force on the surfaces of these parts due to long term aging and wear. As the change will progress considerably slowly, adaptive control can effectively compensate for the drift of operating time caused by the consecutive operations. The effect of adaptive control varies with the number of previously measured operating times and their weighting factors. These parameters are decided by detailed investigations of a series of mechanical endurance tests

# 6 Commissioning and periodical test

As summarised in the previous paragraphs, CSD systems act in relation to the current voltage with very short timings. Moreover, as these systems are closely linked to the switch to be controlled, they are influenced by dynamic variables (mechanical, pneumatic, environmental,

etc.). For these reasons, both the commissioning and periodic testing operation are fundamental for the correct functionality of the system.
CIGRE WG A3.07 published a CSS application guide describing the testing requirements for the CB and the CSD from which the operating instructions for these fundamental activities for the correct functioning of the system are derived.

## 6.1 Commissioning operation:

The following steps are required to properly commission a CS system:

- Collecting the information relative to the CSS application such as:
  - Electrical apparatus information (CB manufacturer and model, CB electrical and mechanical performance data, type and characteristics of the load, measurement transformers and sensors);
  - Single line diagram;
  - Control & protection diagrams; and
  - Communication infrastructure details, etc.
- Preparation of the CSD configuration tailored to the application, which may include:
  - CB timing tests on site;
  - Verification of the physical CSS installation, including the wiring;
  - Start-up of the CSD, including its configuration and the initial verifications;
  - Off-line testing of the CSS;
  - Live tests (on-line) of the CSS, specific for each type of application; and
  - Follow-up of the installation and post commissioning verifications.

The execution of the commissioning tests might slightly differ according to the location of the CSD installation (integrated with the CB or installed remotely in the control and relay room) and to the end-user requirements for a Factory Acceptance Test (FAT). Nevertheless, it is the joint responsibility of the commissioning engineer and the CSS project manager to provide a detailed documented commissioning to ensure the proper behaviour of the CSS for a long period of working under various conditions.

Important are the operations of:

### 6.1.1 CSD configuration

The CSD configuration is prepared from the CSS information collected at the initial stage of the project. Depending on the CSD model and manufacturer, the parameters may be set using a front panel keyboard and display from a configuration sheet. However, modern CSDs rather use configuration files prepared offline on a computer running a dedicated software and then uploaded and saved in the CSD.

In both cases, it is advisable to manage and document the different versions of the configuration file. Once finalised, a copy of the configuration files should be securely saved by the customer, because the loss of this information might require the re-commissioning of the system in the event of the catastrophic failure of the CSD.

### 6.1.2 CB timing tests and timing compensation

The CSS performance is directly related to the CB mechanical switching repeatability and the CSD ability to accurately predict the CB switching time in its operating conditions. As previously described, the CB timing is usually influenced by the DC control voltage, its operating temperature, the drive mechanism stored energy level, the idle time, etc. Although the dependence on these parameters is characterised by the manufacturers during the type tests of CBs intended for CS applications, and CB timing measurements are a part of CB manufacturing routine tests, a number of additional tests are required on the site at commissioning because the CB timing may vary after its erection on the site and over its operating life. Therefore, the CB timing information to be set in the CSD must be that validated or obtained during commissioning at the site, and the timing compensation data should be made available by the CB manufacturer to the commissioning engineer.

It should be noted that the CB timing tests should not only validate the opening time and closing time of the main contacts (arcing contacts) but also the timing consistency of the CB (mechanical repeatability) as well as the timing of any auxiliary contacts (52a/52b) or other sensor installed to measure CB operating time. These are often used by the CSD as feedback for automatic adjustment and CB operation timing verification. When CB timing tests are performed, the CB operating conditions must be measured and noted (control voltage, temperature, pressure of the driving fluid for hydraulic drive at time of testing) because otherwise the tests are meaningless. The operating time has to be measured with the permanent DC control power supply to prevent any wrong measurement due to the inability of the timing test power source to deliver enough power to drive the operating coils under nominal/normal conditions

Filtering of the circuit breaker analyzer device inputs has to be set in a similar manner as the one of the CSD to retrieve consistent measurement, particularly for the auxiliary contacts. Measurements performed by the CB analyzer and the CSD can be compared to verify consistency. Measurement performed by the CSD is preferred in case of drift between the 2 measurement series.
When multiple coils are used to operate the CB (e.g. trip 1, trip 2), CB analyzer wiring has to be arranged to operate the one normally operated with the CSD, using the same circuitry.

### 6.1.3 Final on-site commissioning test.

The performance test of the CSS always involves several on-site switching operations. These commissioning tests should be minimised to limit the inconvenience for network operation and site test costs. Nevertheless, utilities must be fully aware of the importance of making provision for a sufficient number of commissioning tests to ensure satisfactory in-service performance in the long term and not only during commissioning.
Because these commissioning tests are carried out online, they require proper preparation and planning to avoid excessive disturbance. The first tests are normally performed in a safety zone (defined for each application) that provides sufficient safeguard against excessive

network transients and equipment stress. As the CB is subject to mechanical scatter, the same tests should be performed sufficient times to get a good sampling group from which valid CSD settings can be established.

Prior to load energisation, which is the most critical commissioning moment, there should be a last check to ensure all test connections and equipment have been removed and links re-installed where applicable. The CB should be left open to ensure the power system is ready for energisation by the operation personnel.

A specific commissioning procedure is used for each type of CSS application despite the fact that the same following general verification principle applies. During the online tests, enough CB operations are carried out (open, close or both) while measuring the voltages, load current and CB operation feedback using the integrated CSD waveform recording functions or by using other recording means (IED or multichannel recorder). The waveforms are analysed to ensure that:

- each pole of the CB is operated at the expected moment;
- current flow is interrupted or initiated at the expected electrical target; and
- no excessive transients (inrush current and voltage disturbances) are observed on the power system which would indicate the incorrect operation of the CSS.

When available, transducers and/or the CB auxiliary contacts are also used to verify that the main power contacts separation/making of each phase occurred at the right moment to achieve the desired result.

Specific arrangement to confirm pre-arcing time setting and limit grid disturbance (energise a bus section with the load not connected) can be performed prior to load energisation in some cases.

## 6.2 Maintenance tests

The switching transient mitigation efficiency on the power system provided by the use of a CS system is strictly related to its ability to switch at the optimum moment at all times. As for any other device, CSD requires periodic inspection after commissioning whereby the CB opening and closing moments are validated to be at their optimum instant. This can be done by verifying the last switching waveforms captured by the CSD (if that functionality is provided) or by other monitoring equipment.

The last task related to an optimal CSD commissioning procedure is often neglected or simply not performed: the capture of all CB operation events and alarms, followed by their analysis as required. This task is performed using one of the most important and underestimated features of a CSD: its imbedded monitoring capability, which provides extensive supervision and auto-diagnosis of the system, including its components. The collected data provides extended operating information which can be analysed for the improvement of the CB modelling. The important characteristic enhancements to be extracted are:

- the idle time influence;
- a better evaluation of the dielectric slopes; and
- a more complete statistical distribution of the mechanical operating time.

Ideally, follow-up involves the creation of a database and the use of a software tool to extract the required parameters for each application and each type of CB targeted.
After commissioning, CSD alarms are of upmost importance as they indicate that inappropriate behavior has occurred and that action must be taken quickly, starting with analysis of the alarm. Most of the CSD/CB problems are related to timing deviations of the CB or unexpected configurations uncovered during the planning stage. Some organisations provide services for the monitoring of the equipment, provided that remote communication access is granted.
For the above reasons, it is considered necessary to adopt a policy of periodic and on-event testing that must include:

- CSD Alarm indication;
- Comparison of measured values by CSD and actual values on control voltage, ambient temperature, operating pressure;
- Check operational records (error between estimated and measured operation time less than specified value in recorded past-operations); and
- CB Insulation resistance.

# 7 DEVICE APPLICATION EXPERIENCE

This section of the report presents some experiences of CSD devices' application by TSOs that have applications in service.

## 7.1 **CASE 1:** 87T shunt reactor trips due to CSD malfunction on TERNA (Italy) grid.

In the Italian 400 kV grid, Terna extensively uses shunt reactors connected to station busbars to control overvoltage in periods of minimum load, as shown in the diagram in Figure 22, which also provides a schematic representation of the protection system.

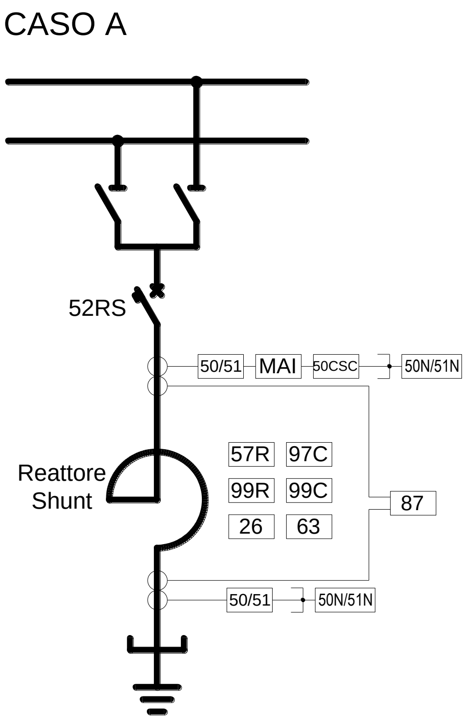



**Figure 22: Shunt Reactor on 400kV BB**

The CBs on the HV side of the reactor are equipped with CSDs supplied by the same manufacturer. The purpose of these devices is to control both the closing of the three poles of the switch to minimise the magnetisation current of the machine and the manual opening of the same to optimise the current cut-off of a purely inductive load and avoid dangerous overvoltage.

In particular, in the event of a non-synchronised closure of a reactor, a high unidirectional component due to the magnetisation of the machine may occur, as shown in Figure 23

Note the two extreme cases of phases 8 and 12: on the one hand, the closure of the switch occurs almost exactly at the maximum voltage of phase 8 (a favourable case and similar to what happens in an almost synchronised closure); on the other hand, it coincides with the moment when the voltage of phase 12 is close to zero (an unfavourable case). Consequently, the current of phase 12 is characterised by a strong unidirectional component (see also Figure 23) that attenuates in time until it is cancelled approximately 1.5 ÷ 2 s after the closing instant, depending on the network conditions.

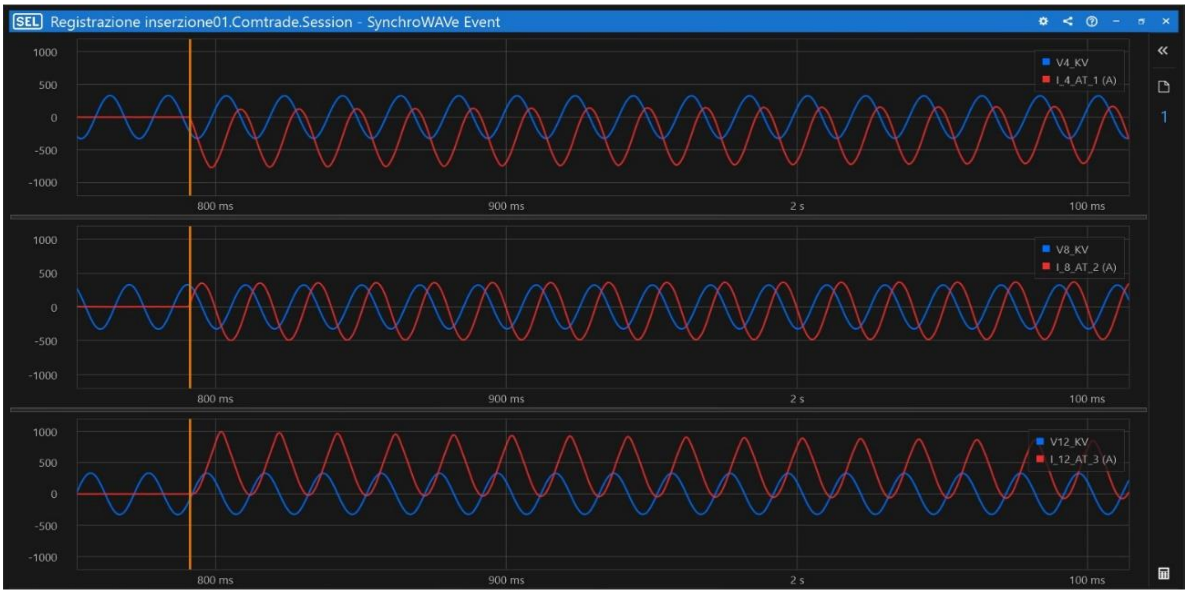



**Figure 23: Reactor no control energisation; focus on closure time**

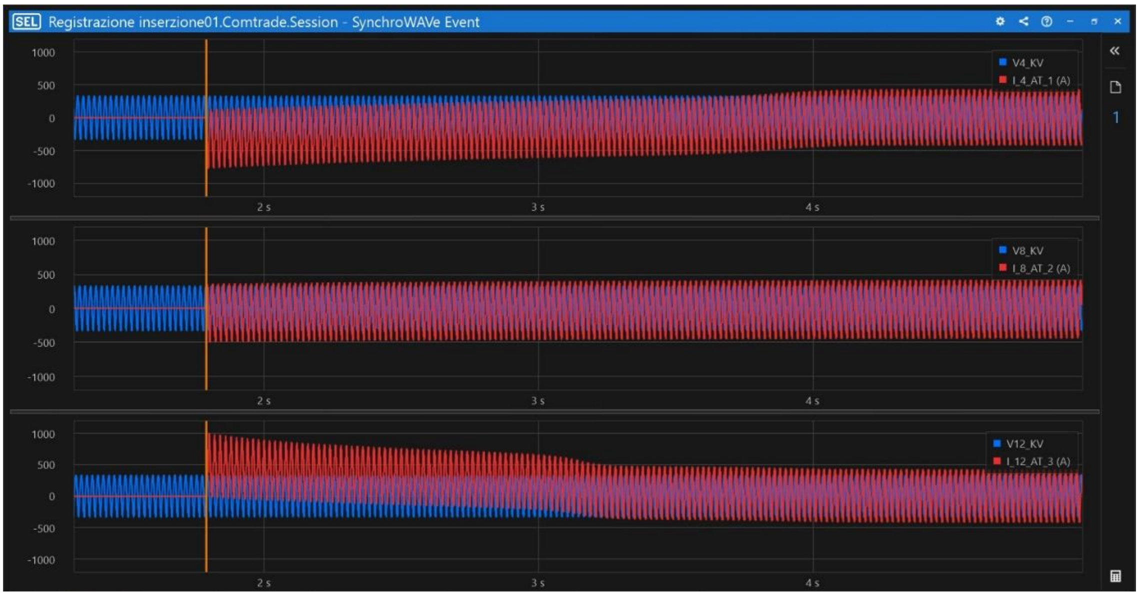
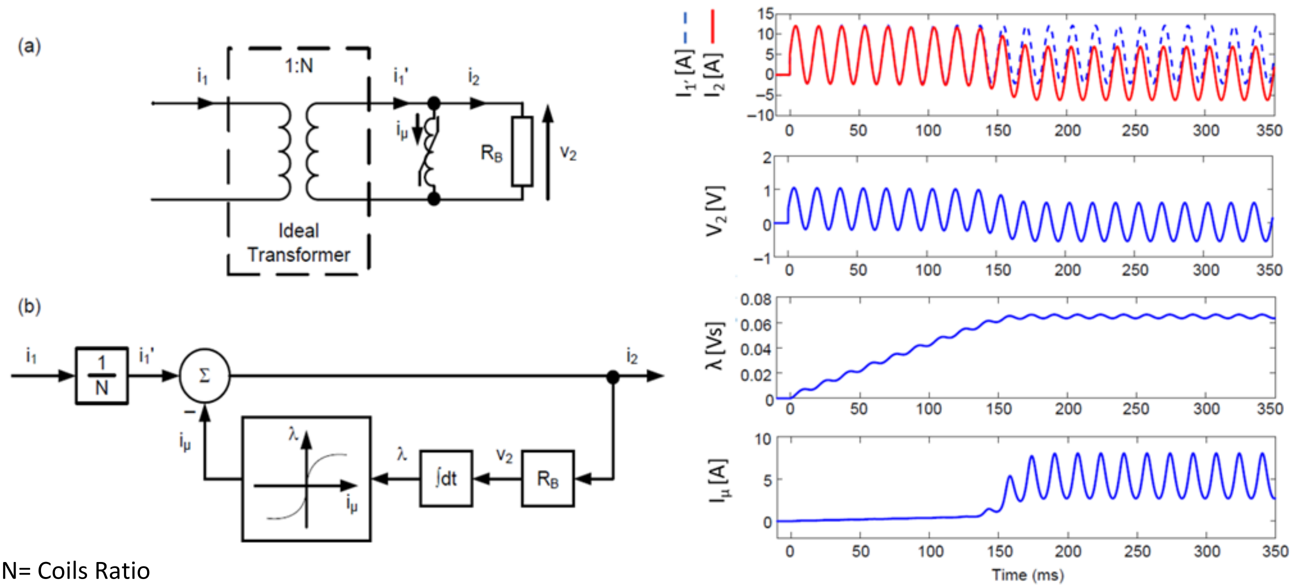



**Figure 24: Reactor no control energisation; focus on current trend**

This unidirectional component of the current is damped by a time constant τ given by the L/R ratio of the entire grid, including the newly reactor inserted. The new reactor energisation has an important effect on the overall L and thus on τ, leading to a slow decay of the unidirectional part: this component can lead to CT saturation.

This phenomenon can be explained using Figure 25, which shows the circuit model of a CT: (a), a block diagram representing its dynamics (b) and the trends of the electrical quantities that can be observed when the same CT is crossed at the primary by a current with the presence of a unidirectional component.




N= Coils Ratio

RB=Total resistence CT secondary circuit

**Figure 25: PHENOMENON CT THE CORE SATURATION DUE TO A DC COMPONENT OF THE CURRENT[7]**

When fully energised, a CT cannot reproduce a DC signal at the secondary because the prerequisite, i.e. the variability of the current signal i1 at the primary, is not present. When the ballast is energised, the long duration DC component, characteristic of the switching on, passes instantaneously from the value 0 to a defined value which, when the switch is closed with phase voltage passing through 0, can reach 1.5 ÷ 2.0 $In_{RS}$. The sudden onset of $i1_{DC}$ induces in the CT secondary a reaction current *i2DC* which, circulating, determines a continuous voltage $v2_{DC}$ expressed by the relation:

$$v2_{DC} = i2_{DC} \cdot RB$$

where RB = (Ri+Rw+RC+RP)

represents the total resistance of the secondary circuits, consisting of the sum of:

- Ri: CT internal resistance
- RW: resistance of the wiring
- Rc: resistance of the terminal board
- RP: internal resistance of the protection (negligible in digital relays)

The voltage $v2_{DC}$ is superimposed on the secondary alternating voltage $v2_{AC}$ and tends to remain constant for a long time because its decay is only related to the ohmic losses of the CT's secondary circuit.

At the secondary, an increasing magnetic flux is produced, expressed by the integral of *v2*: we can consider a term that we will call transient flux ϕt related to $v2_{DC}$ to distinguish it from the sinusoidal flux at steady state ϕr related to the voltage $v2_{AC} = i2_{AC}$-RB

$\phi = \phi r + \phi t = \int v2_{AC} \cdot dt + \int v2_{DC} \cdot dt$

The transient flux $\phi t$, given the slow damping of $v2_{DC}$, actually increases linearly with time.

This causes the increase of the magnetising current $i\mu_{DC}$ due to the continuous component of the current, in accordance with the CT magnetisation curve (Figure 26). The growth of $i\mu_{DC}$ is modest as long as the flux remains in the linear section of the magnetisation characteristic; once the knee is reached and exceeded, the growth of $i\mu_{DC}$ becomes rapid and, in a very short time, equals the primary direct current returned to the secondary $i1_{DC}'$.

Once the equilibrium $i\mu_{DC} = i1_{DC}'$ is reached, the secondary direct current $i2_{DC}$ is cancelled ($i2_{DC} = i1_{DC}' - i\mu_{DC}$) and consequently the voltage $v2_{DC}$ is also cancelled: from this moment on, the flux produced by the direct component does not increase any further.

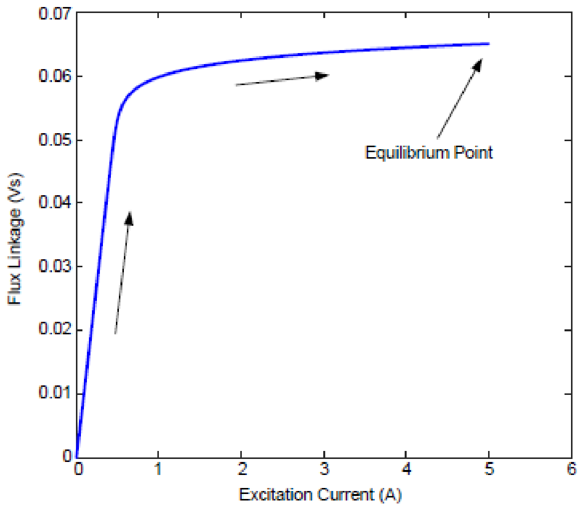



**Figure 26: Tipical CT MAGNETISATION CURVE[7]**

With the CT already operating beyond the knee point, the alternating excitation current $\mu i_{AC}$ (responsible for the flux $\phi r$) also increases and, therefore, the steady state current is now reproduced at the secondary ($i2_{AC} = i1_{AC}' - \mu i_{AC}$) with amplitude and phase errors. In contrast, however, to typical CT saturations on short-circuit, when the currents involved are very high, in this case the current $i1_{AC}$ is only the load current of the ballast; for this reason, although the CT is already saturated, the flux variations are not of enormous amplitude and the reproduction of $i1_{AC}$ at the secondary appears relatively good (see Figure 26, top right).

In the course of 2019 and 2020, there were 5 interventions of the machine differential protection at the connection of the reactors on the 400 kV grid. From the analysis of the data fault recordings, it was also possible to attribute these events to the phenomenon described below; regardless, in all these cases there was an anomaly in the CSD.

The machine differential protection of a type A ballast, as already seen in Figure 21, is supplied for each phase by a CT placed on the HV side and by a CT placed on the Star Centre side.

The different construction characteristics of these two CTs can certainly lead to different responses to the secondary during a non-synchronised shutdown of a reactor.

As described previously, the overall resistance (RB) of the secondary circuits of the two CTs can also be a further discriminating factor.

In Figure 27, the trends of the secondary currents of the phase CTs, HV side and Star-point side, during the insertion of the SS Marginone Reactor on 31/07/2019 at hours 00.08

Reactor bay system protection, function 87R is active within the numerical IED.


IAW1_A,IBW1_A,ICW1_A

Current EHV Side

IAW2_A,IBW2_A,ICW2_A

Current Star-Point Side

**Figure 27: Current EHV side and Star-point side at Reactor energization**

The unidirectional component due to the non-synchronised closure occurs on all 3 phases, but the saturation phenomenon occurs in particular on the CT on the Star Centre side of phase B: the result is a clear difference (both in modulus and in phase) between the currents feeding the 87R protection.

The machine differential protections, in general, implement the comparison between the values of the currents downstream of a filtering that tries to eliminate the components at frequencies other than the fundamental. In Figure 28, the values of the currents of phase B downstream of the forementioned filtering are analysed: although the unidirectional component has been eliminated, the saturation phenomenon present still involves the manifestation of a differential current due to the different modulus and phase errors between the currents at fundamental frequency at the two extremes.

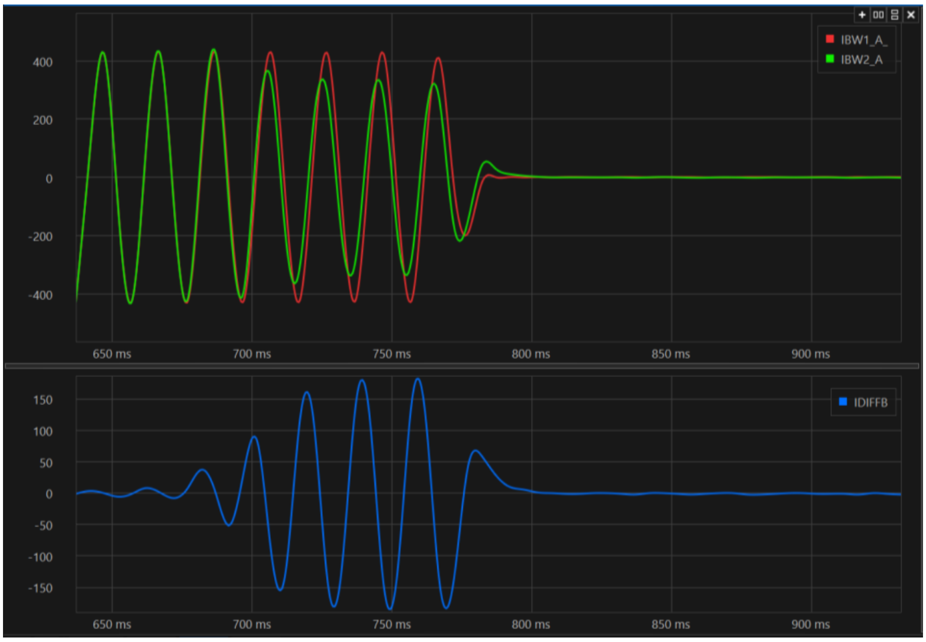



**Figure 28: Analysis of the fundamental components of phase b currents**

Figure 28 shows the graph of the differential current IOP = |I1 + I2| and the stabilisation current IRT = |I1| + |I2| calculated by the 87R protection during the event. It should be noted that the values are in p.u. with respect to the nominal current of the machine at tap 1 of the OLTC, corresponding to the maximum value of reactive power in nominal conditions. In the case examined, the VSC was in position 10; therefore, the absorbed current was corresponding to about 0.8 p.u.: the calculated stabilisation current, before the CT saturation phenomenon on the Star point side, is in fact equal to about 1.6 p.u.

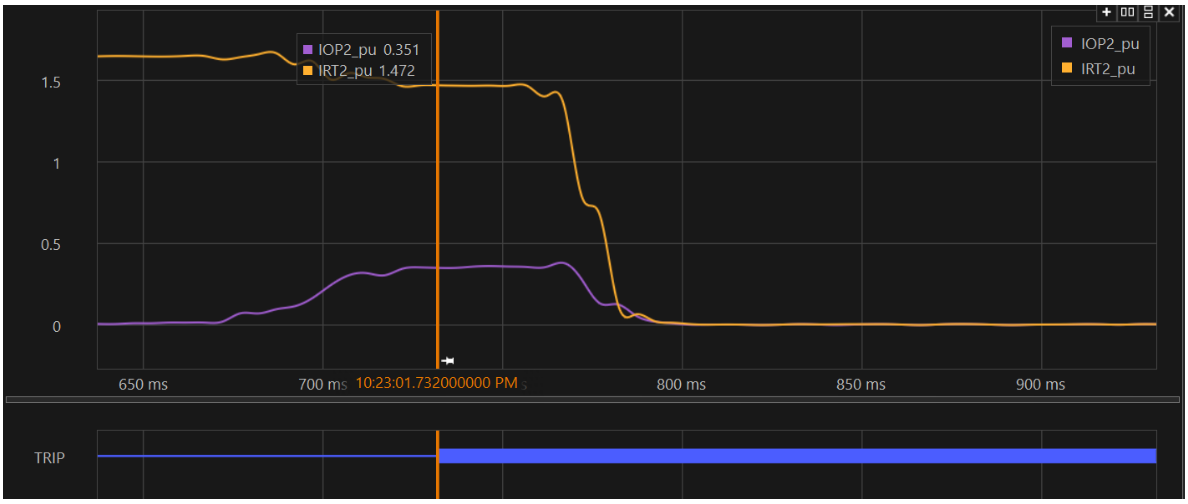



**Figure 29: Differential and stabilisation currents calculated by protection**

Figure 29 shows the point given by the above values positioned within the characteristic set in the device: it can therefore be seen that the trip of protection 87R has been corrected

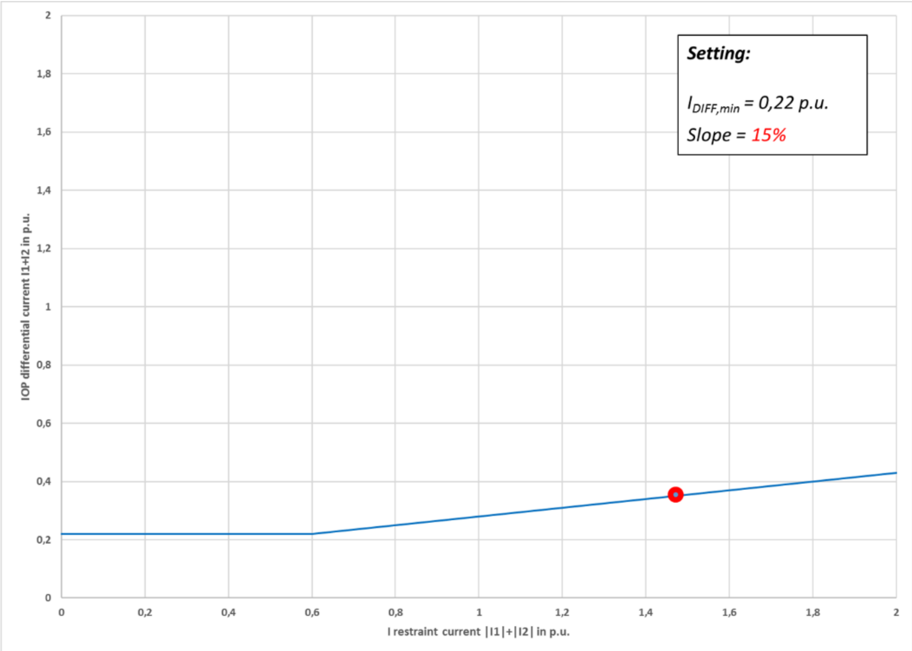



**Figure 30**: **Trip characteristic implemented in the 87r**

The characteristic shown also considers the function, present in the 87R protection, thanks to which the inclined line is shifted upwards in proportion to the detected quantities of second and fourth harmonics. Essentially, the equation that determines the line and thus the trigger area can be expressed as:

$$I_{DIFF,min} = SLOPE1 * I_{STAB} + c$$

where:

- IDIFF, min = minimum differential tripping current
- SLOPE1 = slope of the first sector
- ISTAB = retraincurrent
- c = additional retrain given by the contribution of 2nd and 4th harmonics

It must be considered that in transformers, there is typically a saturation of the ferromagnetic core at each unsynchronised no-load insertion, with the consequent absorption of a distorted magnetising current characterised by a high 2nd harmonic component.

On the other hand, in the case of shunt reactors, given the presence of an air gap which guarantees a practically linear magnetic characteristic, the magnitude of the harmonic current components of higher order than the fundamental is much lower. For this reason, the harmonic blocks, even if activated, are less effective for the recognition of this type of transient than in the case of transformers.

## 7.2 CASE 2: INTERNAL ARC IN SHUNT REACTOR BREAKER CHAMBERS IN PSE (POLAND) GRID:

In the year 2018, in substation 400/110kV in north-eastern Poland there was an emergency trip of a CB in 400kV Shunt Reactor Bay (50Mvar).

After visual inspection, the extinguishing chambers of the 400kV SF6 circuit breaker were burst. Based on the explanations provided by the manufacturer, and the opinion of the appointed independent expert, the Committee for Disruptions Analysing in PSE found that, regarding the main cause of the fialure, there was a link to the manufacturing defect of the circuit-breaker, the effect of which was multiplied by the incorrect configuration of the device used to improve the switching process of the CB, i.e. a CSD.

Both devices CB and CSD were from the same manufacturer. Configuration and settings of CSD were provided by manufacturer.

The explosion occurred in chamber in pole L3 of Circuit breaker; the explosion damaged the whole CB.

The explosion was caused by arising pressure of SF6 gas, which was caused by not-extinguished arc.

The arc was burning for 15 seconds after the main switch of CB was opened.

Investigations showed that there was a factory defect (faulty batch) of cylinders in CB chambers; this defect was multiplied by the incorrect work of CSD, which hastened breaker failure.

The other irregularity was the incorrect setting of the CBF function 50BF; the current threshold was set to default, which was higher than the rated current of the shunt reactor.

## 7.3 CASE 3: SERIOUS BREAKDOWN FOR A BRAND NEW 420 KV PORCELAIN REACTOR CIRCUIT BREAKER IN STANETT (NORWAY) GRID:

Since the early 2000s, CSD has been used on a large scale by Statnett in Norway. In the beginning it was mainly used for CBs for transformers, and later also for CBs for reactive components. The principle has been to use CSD for power transformers larger than 150 MW, shunt reactors larger than 50 MVAR and shunt capacitors larger than 50 MVAR.

Major voltage challenges after the year 2000 forced Statnett to install many reactive components. The main focus was to reduce the voltage at 300 kV and 420 kV by several reactors. Consequently, many new reactor-projects were started during 2009–2018, summarised up to appr. 4000 MVAR. The new reactors installed were adjustable, basically 80–150 MVAR and 90–200 MVAR.

Setting and commissioning have historically been done by Statnett internal personnel, and there is a mix of different manufactures of CSD and circuit breakers. Manufacturer for CSD and CB are not necessarily the same.

Traditionally, this concept has worked well, but in October in 2013 things began to happen which motivated us more deeply examine this issue.

420kV Klæbu 2013: During commissioning, we experienced a serious breakdown of a brand new 420 kV porcelain reactor CB at the first switch-out. The explosion happened only 1 min after 1.st energising. Porcelain pieces were thrown more than 50 meters away, but luckily no personal injuries were sustained. We observed that the current in pole L3 kept going in the arc after contact separation. After 10 sec., the CB exploded because of the heat. It was never clarified what was the real reason was why the switch pole continued to conduct current. At that moment, we had 23 such reactor CBs (same manufacturer) operating or under construction, and of course it led to an uncertainty associated with the CSD and shunt reactor switching.

**420kV Kristiansand 2014:** Breakdown for a composite CB for shunt reactor, which had been in operation several years. Thanks to composite insulators, the explosion did not result in consequential damage.

As a consequence of these two serious incidents, we had to open and investigate other reactor CBs:

**420kV Kristiansand neighbour reactor CB**: As picture A in Figure 31 shows, the nozzle was totally damaged and the CB was not far from breakdown. The damaged nozzle was caused by re-ignition because of the incorrect adjustment of POW. Most likely, there had been a re-ignition nearly every time the reactor had been switched off (approx. 1100 times).

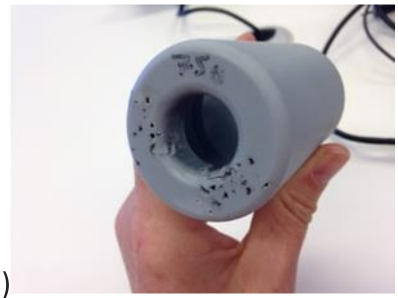
A)  B) 

FIGURE 31: TEFLON NOZZLES FOR CB FROM LEFT A)KRISTIANS AND B)VANG

**300kV Vang reactor CB:** As picture B in Figure 31 shows, the nozzle had some injuries. The CB had been in operation for appr. 4 year and had been switched appr. 750 times to a 80–150 MVAR shunt reactor. The CSD was 7 ms incorrectly tuned, which led to contact separation appr. 4 ms before zero crossing. This mistake led to switching on the border to re-ignition.

**300kV Flesaker reactor CB:** Examination of the CB showed that the nozzle was fine inside, even with a 1–2 ms. deviation from the optimal setting of the POW-device. The CB had been in operation for 2 years and had been switched 770 times.

Successful reactor switching is crucial to keep the circuit breakers healthy and to avoid further breakdowns. The voltage across the switch is at a peak when the current is zero, which leads to large voltage stress across the contacts when they are about to open. Therefore, it is essential that the maximum contact separation must be established when the zero crossing takes place. Based on the opening time for circuit breakers, our experience is that we have to ensure that the contact separation must start approximately 7–9.5 ms before the next zero-crossing of the current. The goal is to switch off the current at the first zero-crossing. If not, a re-ignition situation could occur.

As seen above, nozzles made by Teflon at the end of the contact are exposed if the re-ignition takes place. Our hypothesis: They can withstand appr. 1000 couplings with re-ignition before breakdown. A re-ignition will leave a wound at the nozzle, which over time will break it down and may further lead to CB breakdown.

Lessons learned after these incidents:

- Re-ignition struggles a lot on the nozzle over time, and action must be taken to avoid this;
- We had to go through CSD settings for our shunt reactor CBs;
- Reactor CBs must fulfill IEC-requirements 62271-110; and
- Re-ignitions can be avoided by using a properly tuned phase control switching unit (CSD).

Measures that were implemented:

- For shunt reactor CB, a choice of CSD shall follow the recommendations from the CB manufacturer
- If we have two CBs for shunt reactors, two different CB manufacturers are chosen to reduce the risk;
- To avoid serious damage in the event of breakdown, composite insulators are chosen for shunt reactor CB. Existing CBs for shunt reactors were replaced; and
- More training for internal personnel who take care of the setting and commissioning of CSDs.

## 7.4 CASE 4: THE CLOSING STRATEGY OF SHUNT REACTORS IN THE NETWORK WITH THE UNGROUNDED NEUTRAL POINT

In the Czech transmission system operated by CEPS, shunt reactors are largely used for voltage control in the grid nodes. Shunt reactors are connected both to the busbars of 400kV level and in the part of the network connected to the tertiary winding of power transformers. Nowadays, CEPS controls voltage by almost three tens shunt reactors. CBs that connect or disconnect shunt reactors to system voltage are usually equipped with CSDs. Lately, new CBs of shunt reactors are always installed with CSDs. At the end of year 2021, there were 21 CSDs in the Czech transmission system. Given the fact that most shunt reactors are installed in the tertiary side of power transformers, there are considerable CSDs there too. The manufacturer of the CSD is always the same manufacturer as the attached CB because the CB and the CSD together form essentially one functional unit.

Weekly, we execute up to a hundred switching operations of shunt reactors by CSDs over our whole system. It is possible only automatically to check such the amount of operations. For these purposes, we use a software tool developed for CEPS that can recognise disturbances in operation records. These records are created by fault recorders or CSDs in case of, for example the opening or closing operation of a CB. The software tool can warn about the restrike of CBs, overvoltage, feroresonance and the like. It also checks the proper working of all our CSDs switching shunt reactors.

Soon after its launch, this automatic system pointed out that the closing operations of shunt reactors connected to the tertiary windings of power transformers are sometimes out of tolerance (electrical error above 1.5 ms). Tertiary windings of transformers are designed in delta connection and magnetically non-coupled shunt reactors are made in wye connection, with the neutral point ungrounded. A closing strategy was set by the manufacturer and according to their manual for this specific application. The setting was intended to close two poles at the same time in the positive peak of their phase-phase voltage and, after 90°, to close the CB of the remaining pole (see Figure 32).

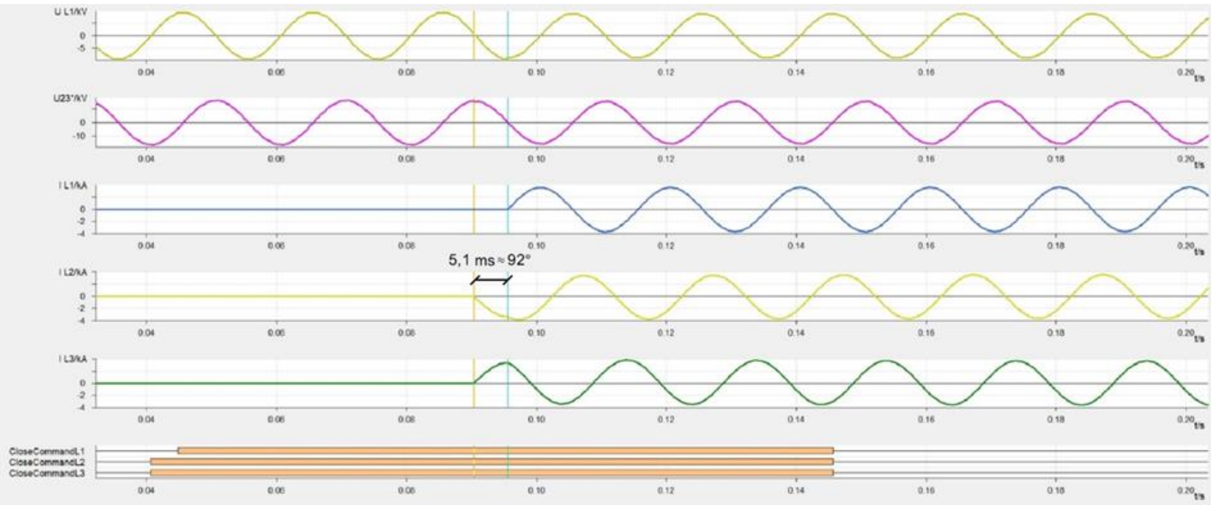



**FIGURE 32: ORIGINAL CLOSING STRATEGY**

The sequence of particular phases was random, and the adaptive correction of electrical errors was turned on. Detected events were found on a few places, but one case of a CSD relatively often repeated in a short time. We found these effects in a total of 6 events during 44 closing operations (even 5x electrical error above 2 ms) in this worst case (see Figure 31). Of course, less accurately controlled switching resulted in a raised inrush current (1.3–1.5x IN) and the saturation of CT (see Figure 32). In Figure 33, we see that the switching instant of the poles L1 and L3 does not accurately correspond with the peak of the L1–L3 phase-phase voltage and, similarly, the switching instant of the pole L2 with the peak of the L2 phase-ground voltage. In addition, the time difference between the switching of the poles L1–L3 and the pole L2 is not intended to be 5 milliseconds (90°).

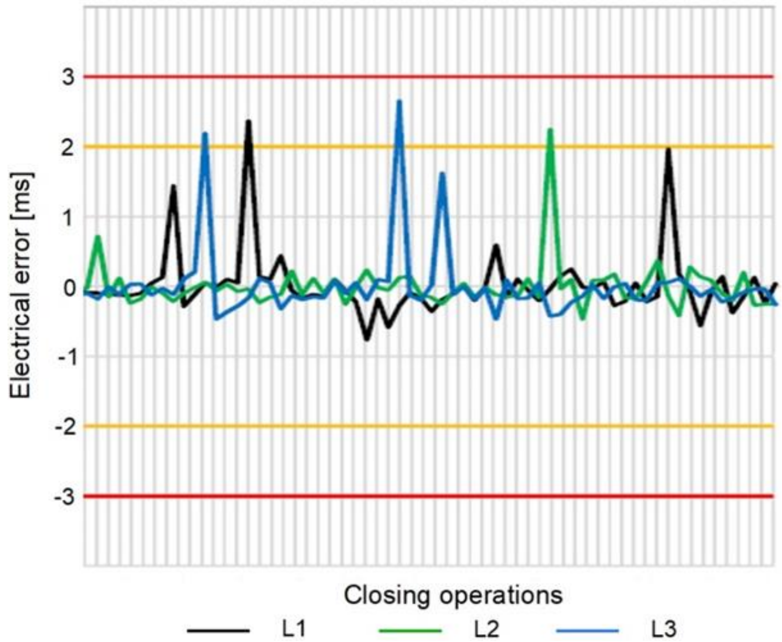



FIGURE 33: ELECTRICAL ERRORS DURING CLOSING OPERATIONS

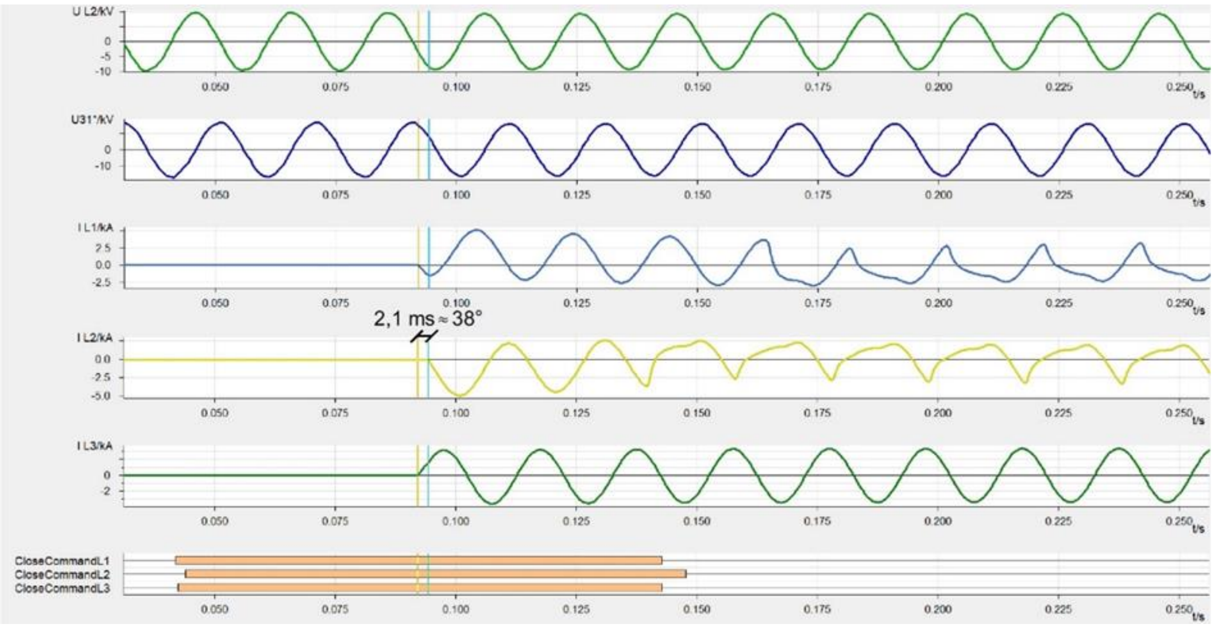



FIGURE 34: CLOSING WITH A MAJOR ELECTRICAL ERROR

We discussed the issues with the manufacturer, who provided the explanations. The occurrence of the above-mentioned phenomenon was caused by the combination of the closing strategy and the adaptive control.

The adaptive control works with internal evaluated electrical errors of previous closing/opening operations, and it calculates the time correction for the next operations. The concurrent closing of the first two phases is not usually simultaneous in practice. When the first phase is closed but the second is not yet closed, there is no current due to the ungrounded connection of load. The prestrike in the first pole does not occur in the anticipated instant because the contact gap of the second pole does not enable it, so the current occurs later. However, the adaptive control of the CSD evaluates the time difference between the predicted prestrike instant in the first pole and the occurrence of the current, like the operational error. It creates a methodical error that is included in the correction for the next operations and does not correspond with the real mechanical time scatter of the CB of the first pole. The variability of the true first phase (L1, L2 or L3) in the case of the random phase sequence further complicates the problem. Consequently, closing commands from the CSD to the poles of the circuit breaker have incorrect timing.

The manufacturer recommended a new closing strategy, as follows:

a) The sequence of phases is fixed;

b) The first phase is closed before the second with a secure margin; and

c) The adaptive control is turned off for the first phase.

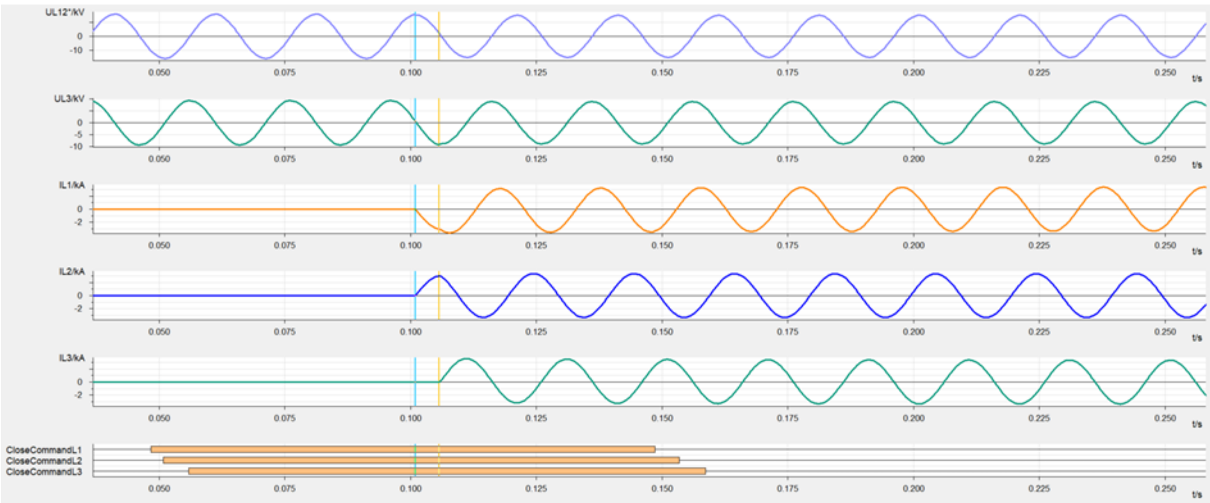



**Figure 35: NEW USED CLOSING STRATEGY**

Subsequently, the new strategy in CEPS is as follows (see Figure 35):

1) The phase L1 is closed two milliseconds before the peak of L1–L2 voltage, but there is no prestrike and current;

2) The phase L2 is energised in the peak of L1–L2 voltage and current occurs;

3) The phase L3 is energised 90° after L2 energisation; and

4) The adaptive control checks and corrects commands only for phases L2 and L3.

We changed the new strategy in CSDs with the most frequent occurrences. The all new CSDs also have this setting. We have had a good experience with the new strategy so far.

## 7.5 Case 5: REF (restricted earth fault) trip under Energising of compensated cable with CSD

The described event occurred in the Danish network 200 ms after energising a 41.16 km 150kV cable (approx. 100 Mvar) compensated by a permanently connected 40 Mvar shunt reactor. The line was tripped by the shunt reactor protection.

In Energinet, the protection of shunt reactors is by default diff. protection, which also includes a 'restricted earth protection' (REF).

In the event of a trip from the reactor protection, the breaker at both ends of the cable will trip as the reactor does not have its own breaker.

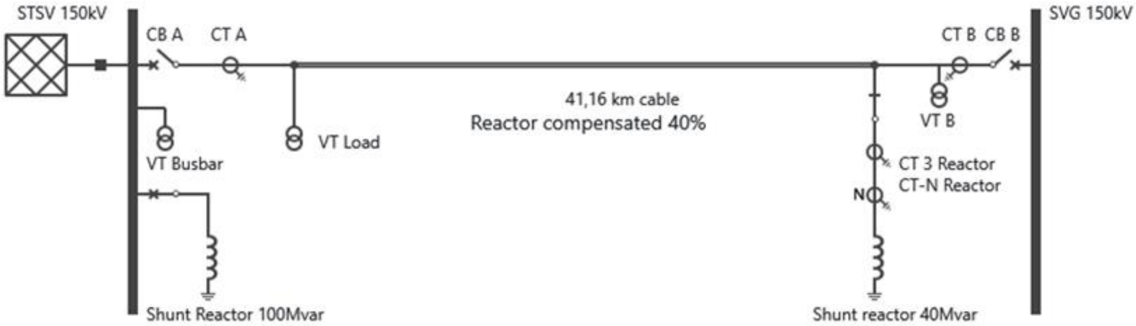



**Figure 36: Energising of compensated cable by closing CB A**

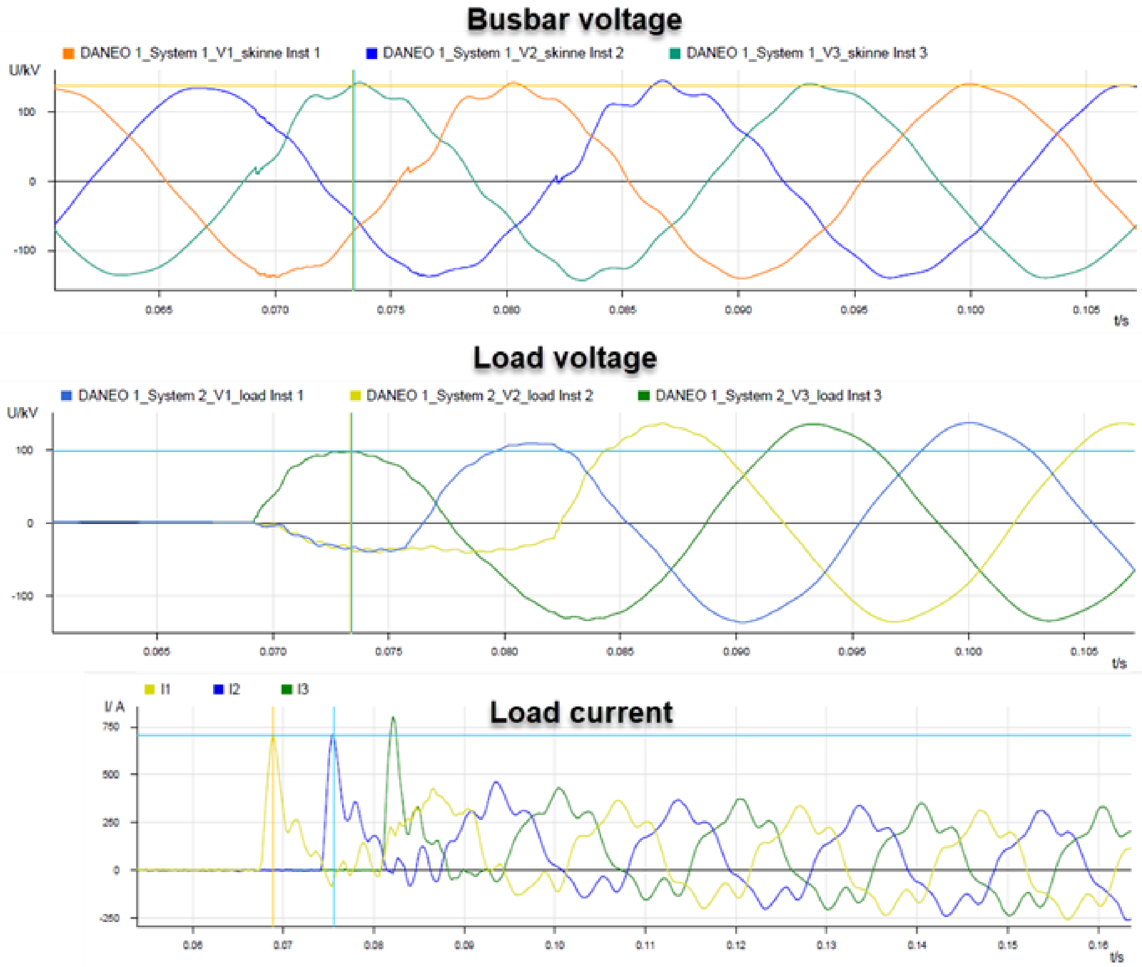



**Figure 37: Energising of the cable, measured current and voltage from VT Busbar, VT Load and CT A load current**

Restricted earth faults compare IN and Ix; if they are in the opposite direction, it is an external earth fault, and the same direction is an internal earth fault.

The analysis of currents and voltages shows that, because the CSD closure of the breaker occurs in a voltage zero crossing, a large DC current occurs in the reactor bay (see Figure 37)

The DC current is added together in the star points current transformers (see Figure 38), and as it is an almost pure DC current, the current transformer goes into saturation.

When the DC-current is damped, and due to the current transformer DC charging, the Ix current changes polarity. (Figure 37)

The REF protection compares IN and Ix, and as Ix has changed polarity, it is seen as an internal earth fault, and the protection trips the line breakers.

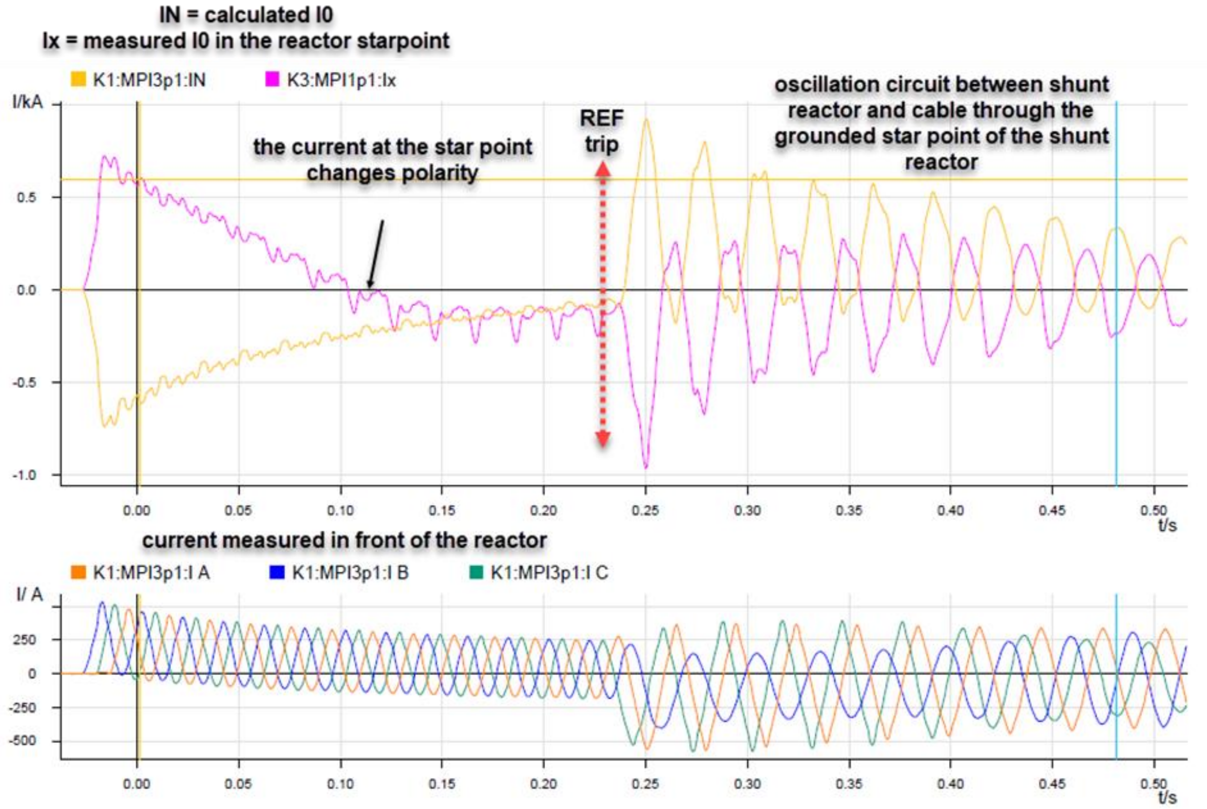



**Figure 38: Current measured in the shunt reactor bay (CT3 and CT-N, see Figure 35)**

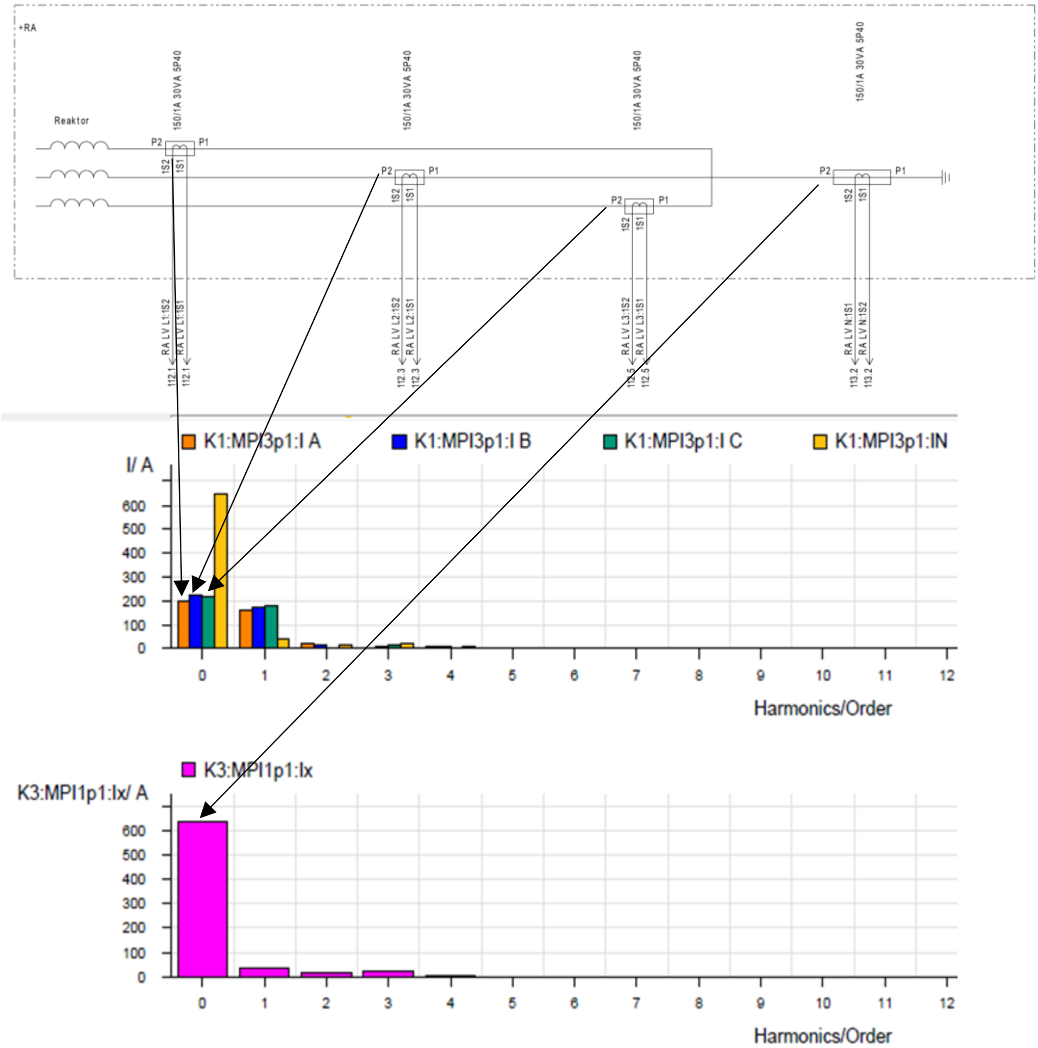



**Figure 39: DC-current in the current transformer**

It is clear that the CSD has an effect when energising a compensated cable, both for inrush current and voltage (see Figure 39)

In Energinet, it has been decided to turn REF protection off if CSD is used to energise a compensated cable or overhead line.

# 8 TSOs' questionnaires

A questionnaire was fulfilled by TSOs represented within or contacted by ENTSO-E SG Protection Equipment subgroup, in order to know the use and challenges of operation, reliability and maintenance of CSD devices.

The questionnaire was divided into three main groups:

- Application;
- Type of POW device; and
- Field Experience.

Below is a brief analysis of the return data for each question, accompanied by a histogram representing the sum of the answers grouped by similarity or area. TABLE 2 shows the 11 members of ENTSO-E SG Protection Equipment that fulfilled the questionnaire.

| ***NR*** | ***TSO (country)*** |
|---|---|
| 1 | REN (PT) |
| 2 | APG (AT) |
| 3 | STATNETT (NO) |
| 4 | CEPS (CZ) |
| 5 | ELIA (BE) |
| 6 | MAVIR (HU) |
| 7 | TEE (RO) |
| 8 | TERNA (IT) |
| 9 | PSE (PL) |
| 10 | NGET (UK) |
| 11 | ENERGINET (DK) |

TABLE 2: TSOs participants in the questionnaire

## 8.1 Application

Q 1.1 **In your grid, are there any devices for reactive power control (such as capacitor banks or shunt reactors, UGC) or high rated power transformers? (typically power >100 MVA)?**

The first question sought to ascertain the presence of machinery, the energisation/de-energisation of which could cause problems for the network or operating elements.

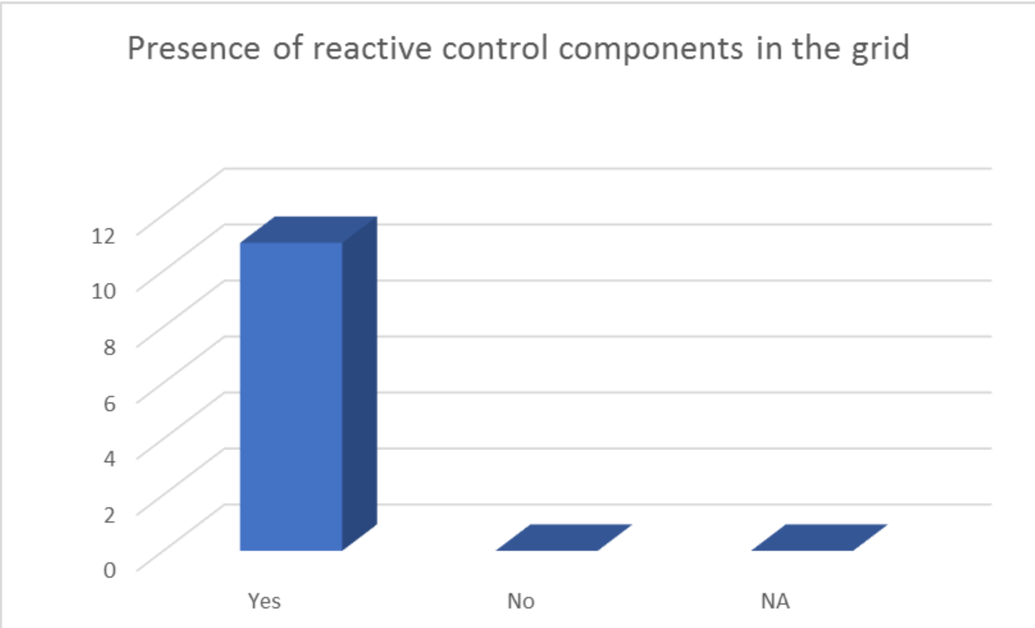



**Figure 40: Distribution answers to Q1.1**

All responding TSOs report this issue

Q1.2 **If yes, how many devices for reactive power control are installed in your TSO (number of units and rated power, voltage level of connection)?**

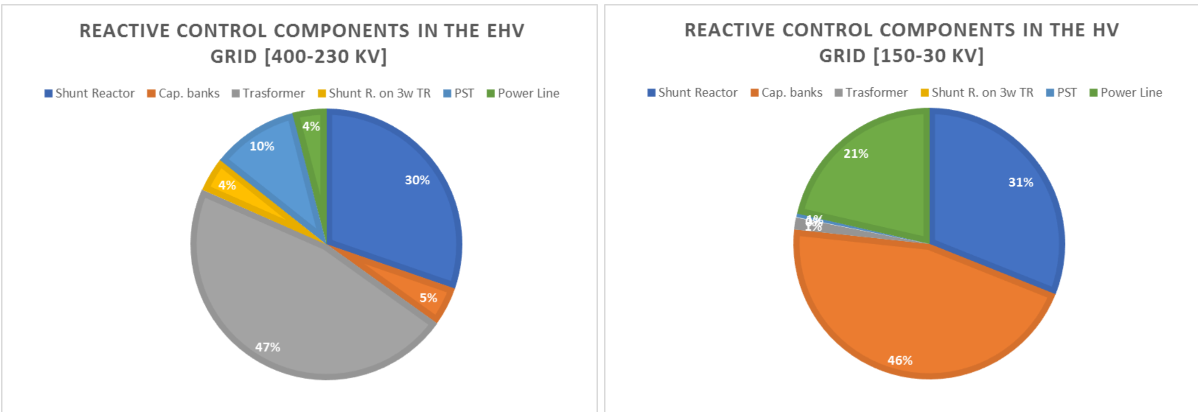
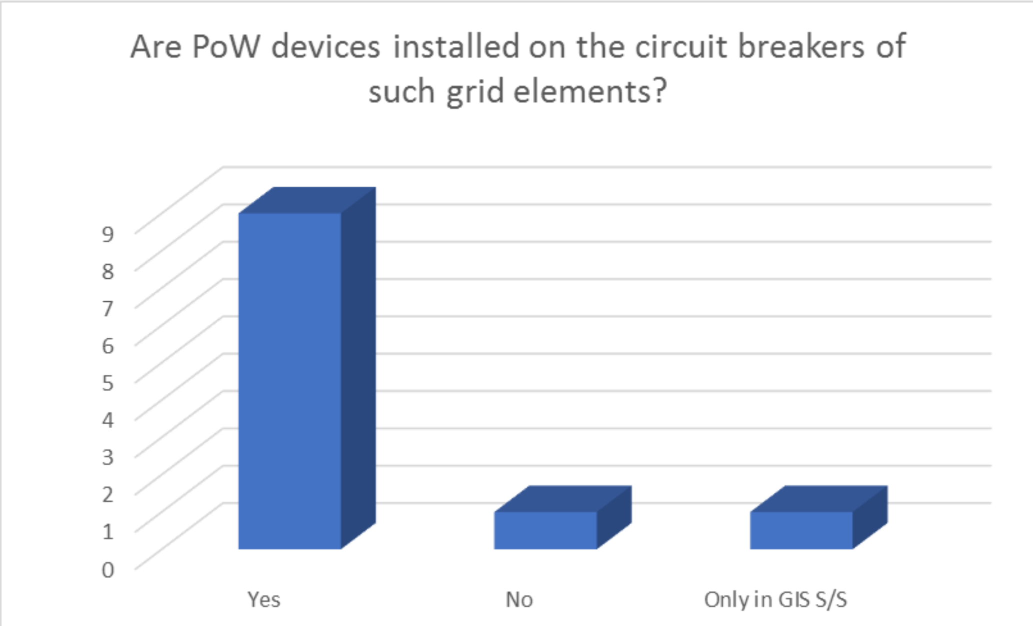



**Figure 41: Distribution answers to Q1.2**

The second question goes into detail about the type of components and their presence in the respective networks of EHV or HV. It can be seen that for the EHV level, the TR (ATR) make up the vast majority of this equipment, while for HV, it is the capacitor banks.

Q1.3 **Are PoW devices installed on the circuit breakers of such grid elements?**




As shown in the histogram, almost all TSOs install closing/opening control systems (CSS) on this machinery for all types of installation. Only one TSO installs such devices on a ‘special’ SS.

Q1.4. **If yes, how many PoW devices do you have in operation (number of units, rated power and voltage)?.**

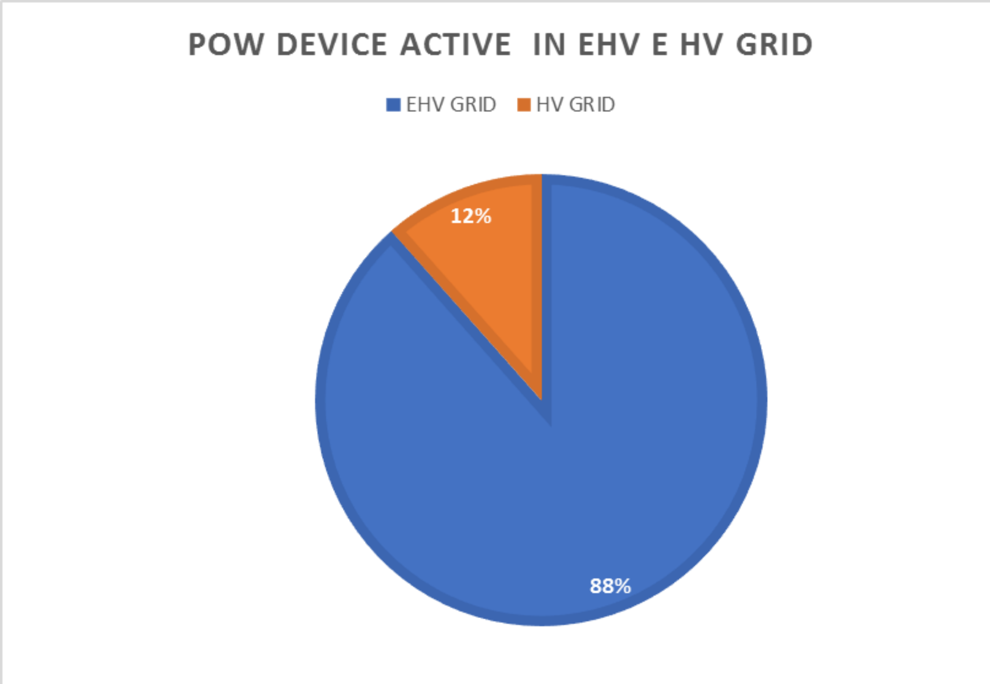



**Figure 42: Distribution answers to Q1.4**

The answers to question 1.4 show that the majority of devices are installed on the EHV network.

Q1.5. **Where are the PoWs (Switch Cabinet, Control and Protection Kiosk, S/S Control Room, etc…) physically installed?**

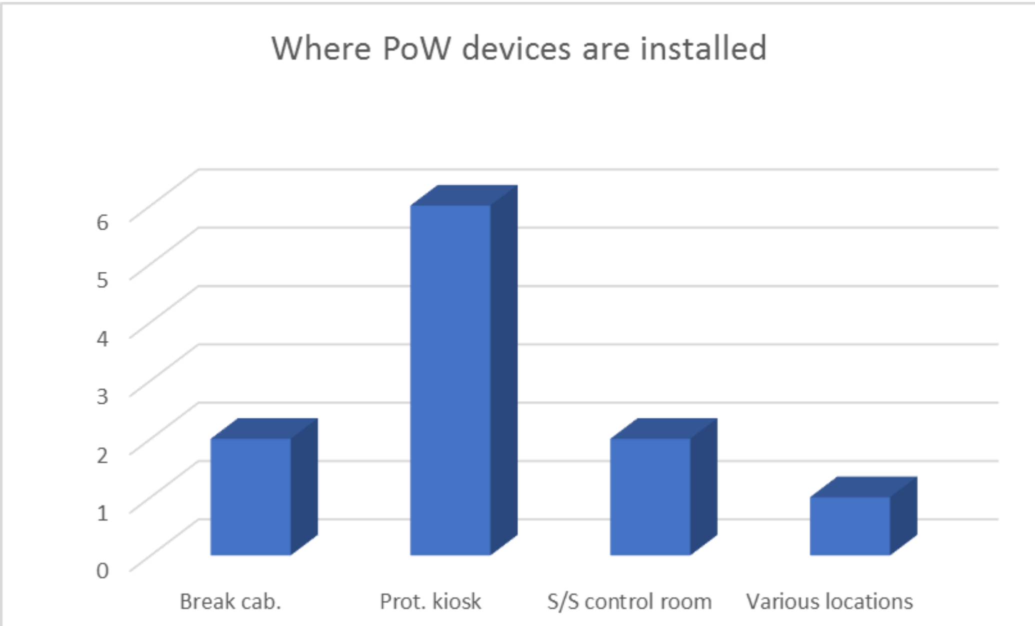



**Figure 43: Distribution answers to Q1.5**

Answers 1.5 show that the place of installation of CSD devices is varied, with a preference for protection system boxes.

Q1.6. **What are the driving criteria for PoW positioning? (e.g. Breaker proximity; distance from CTs & VTs; presence of conditioned climate Cabinet etc.)**

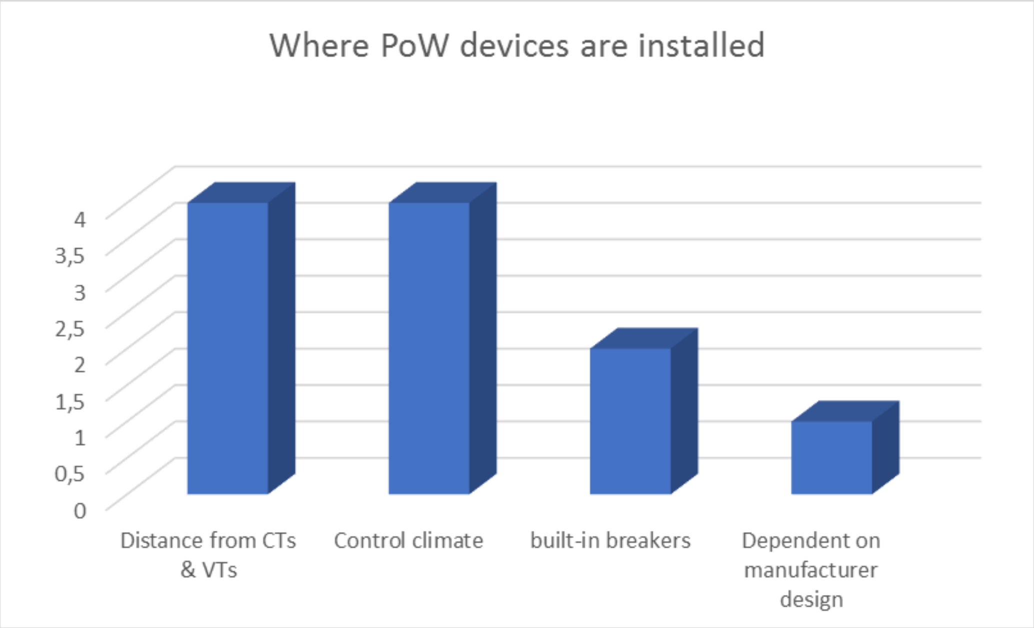



**Figure 44: Distribution answers to Q1.6**

The motivations driving the choice of CSD location are consistent with the previous answers of proximity to CT and VT and a climate control room.

Q1.7. **Use of PoW in bus coupler bay (e.g. for instance in the event of failure of POW in its bay, what are the procedures – spare PoW on S/S)**

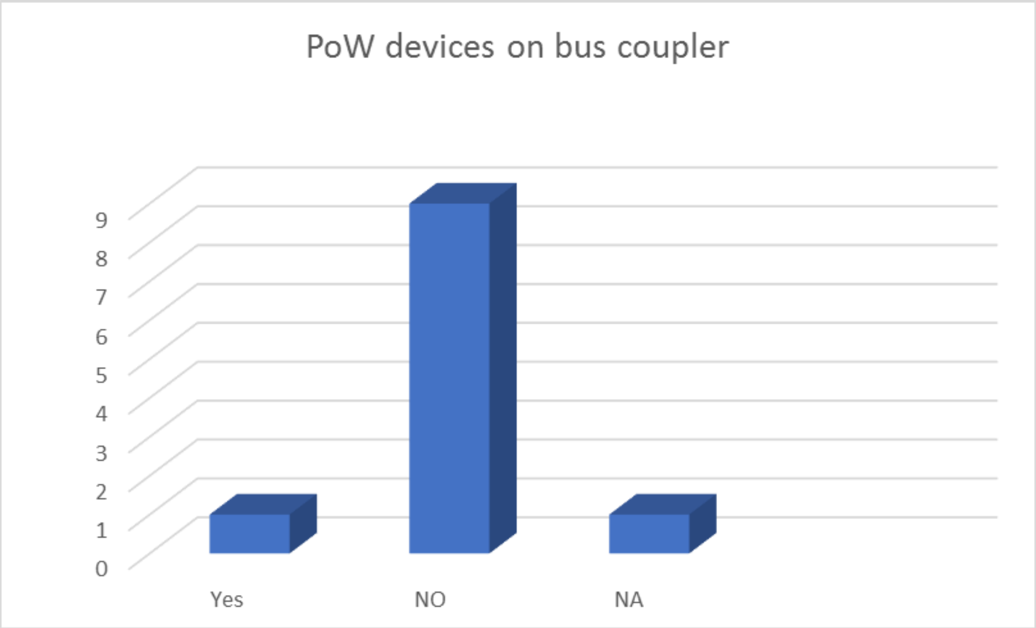



**Figure 45: Distribution answers to Q1.7**

Responses to 1.7 show that responding TSOs do not use such devices on bus couplers even as spares in the event of a main bus failure.

Q1.8. **Does the POWS take into account the remanent flux of the power transformer?**

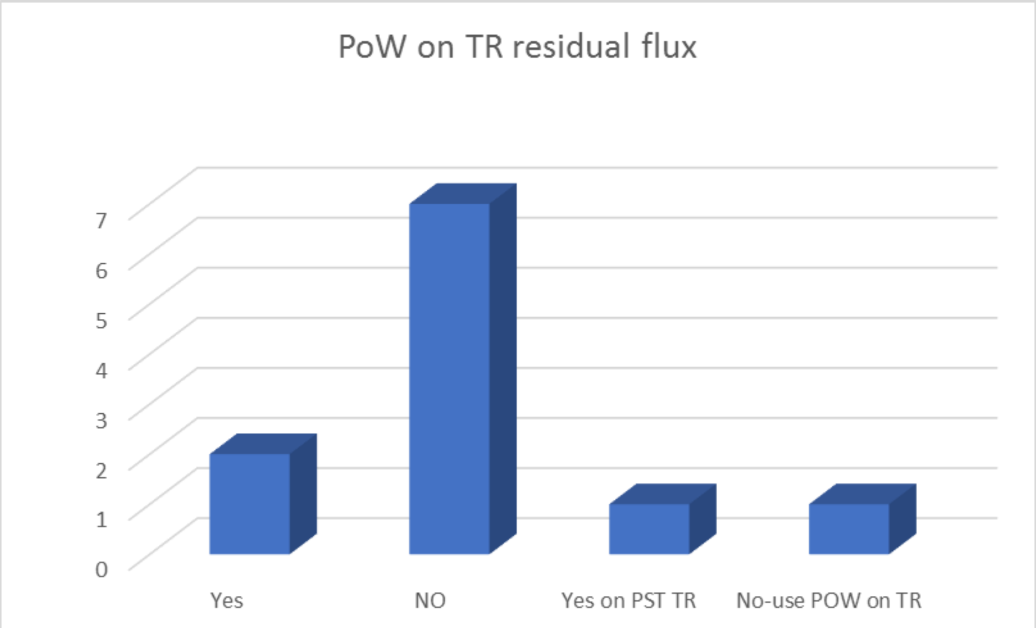



**Figure 46: Distribution answers to Q1.8**

The answers to question 1.8 show that the majority of TSOs do not use the residual flux calculation function for TR energisation control (see 4.3.2) which, as we have seen, is the most widely used application for POWs.

Q1.9. **Does the POWS compensate for the idle time of the circuit-breaker? If yes, what is your experience with this function?**

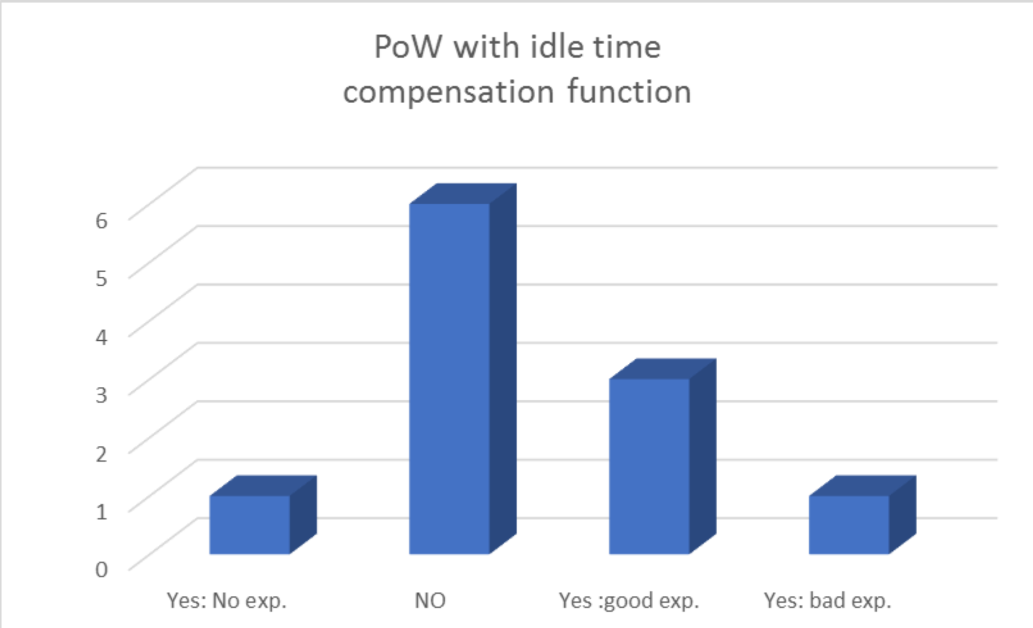



**Figure 47: Distribution answers to Q1.9**

Question 1.9 refers to the use in installed POWs of the automatic idle time compensation feature of the associated CB. About half of the responding TSOs use this feature, with good reliability results.

## 8.2 Type of PoW device and Setting

Q2.1 **Are the settings defined and implemented by the manufacturer or by the TSO?**

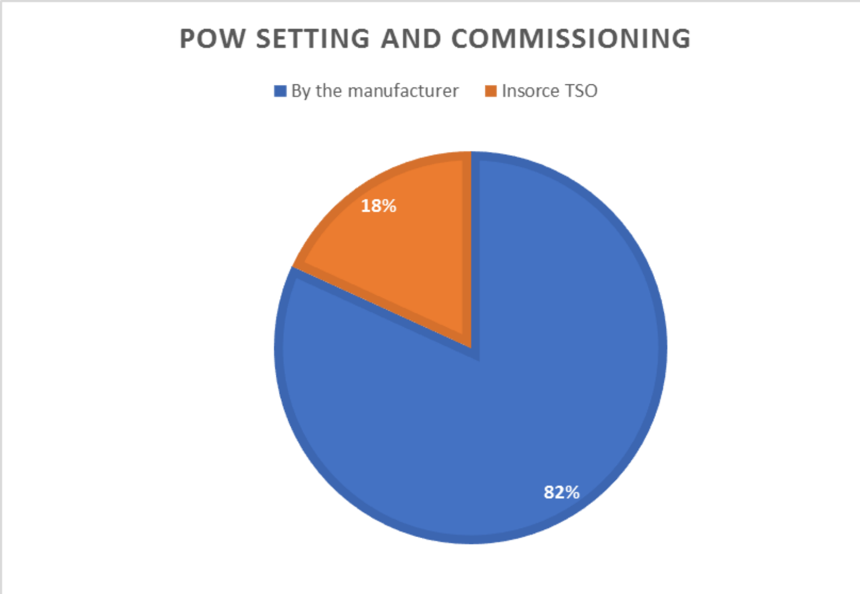



**Figure 48: Distribution answers to Q2.1**

The graphical representation of the answers to question 2.1 show that in almost all TSOs, the operations of setting up the POW devices are carried out by the manufacturer of the device and not by the TSO engineers.

Q2.2 **What are the calibration criteria/the aimed target? (a deviation of ideal time in milliseconds, a proportional content of n-harmonics in the inrush current, the amplitude of the peak inrush current, etc.)**

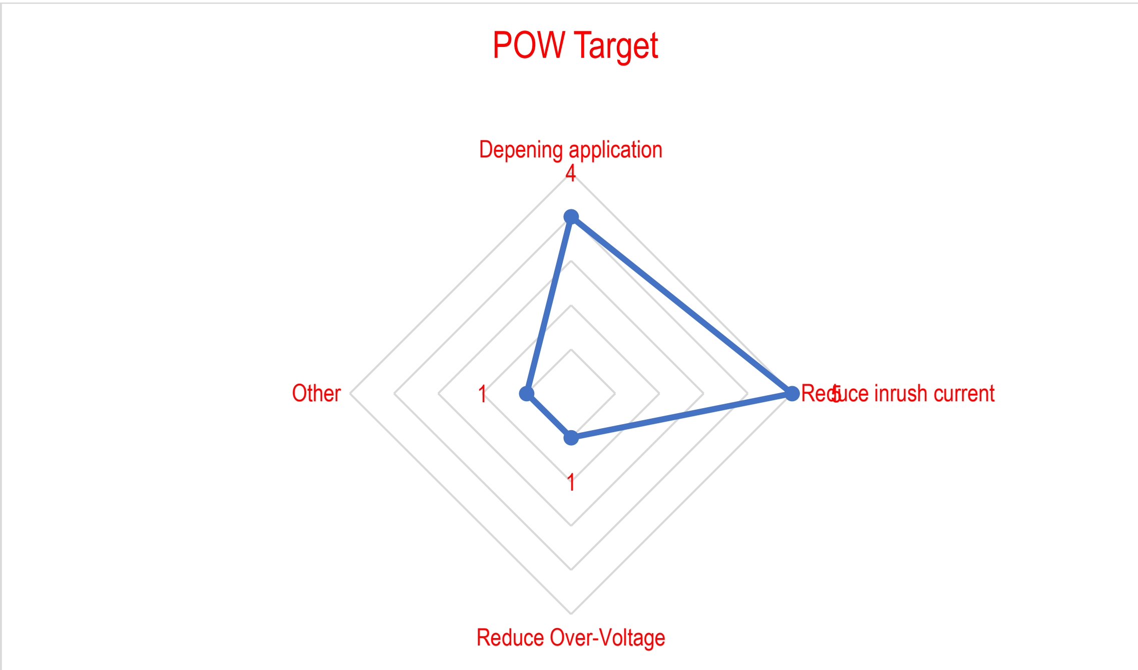



**Figure 49: Distribution answers to Q2.2**

As shown in Figure 40, the type of feature used is the majority type for reducing inrush currents. This shows (as shown in 1.2) that the greater use is in TR.

Q2.3 **Do you use a function of the adaptive correction of switching times? (correction by experience from previous operations)**

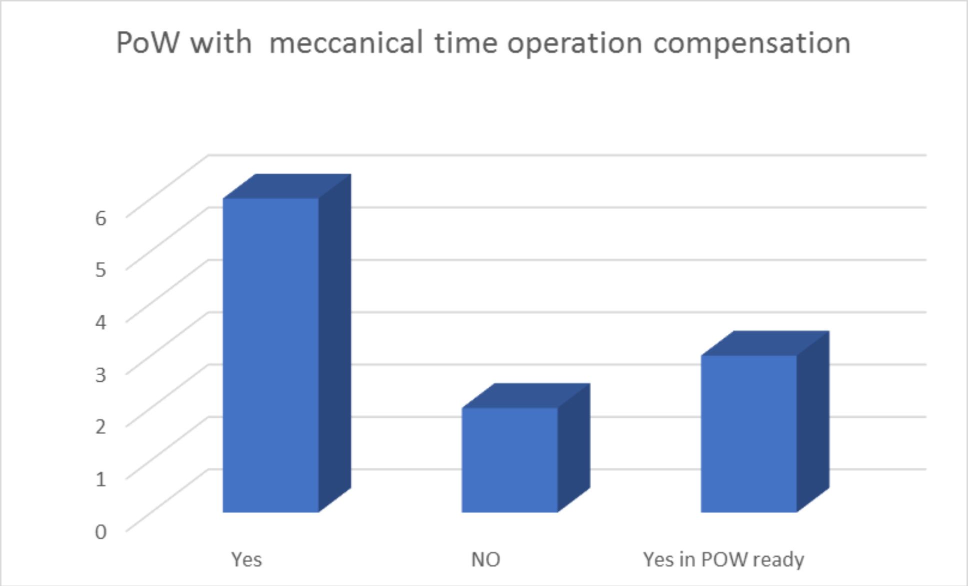



**Figure 50: Distribution answers to Q2.3**

With regard to the adaptive functionality of some POW devices that vary the times according to the last operations carried out by the CB, the majority of TSOs clearly use this functionality in the predisposed devices.

Q2.4 **Do you use another form of compensation (for environmental conditions, for example) of switching times? For both operations or only for closing/opening?**

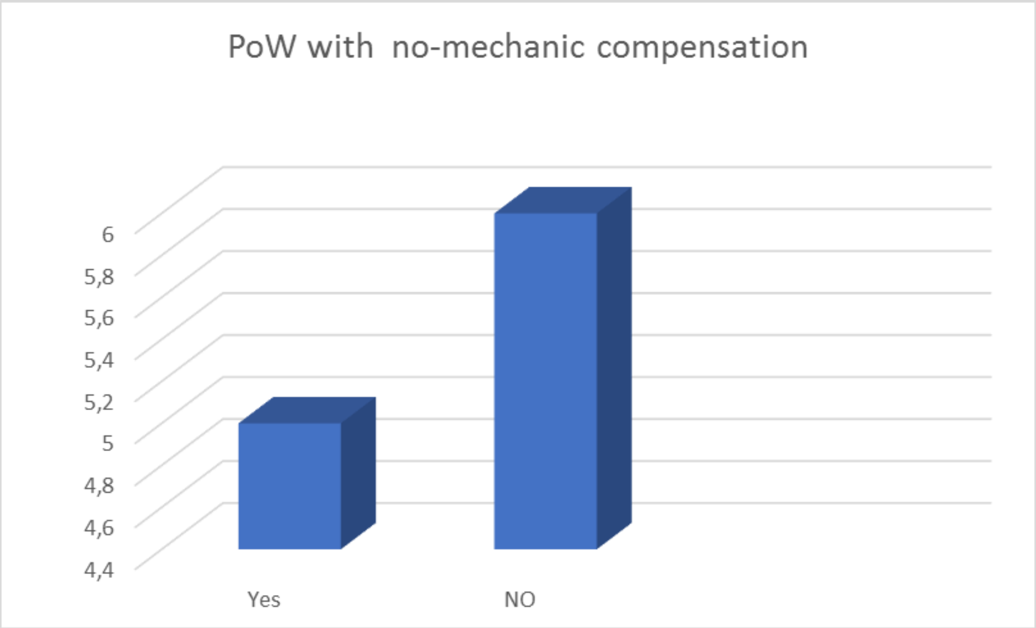



**Figure 51: Distribution answers to Q2.4**

As shown in Figure 51, only less than half of the TSOs use POWs with the compensation function enabled for variations in non-mechanical quantities such as temperature, voltage, etc.

Q2.5 **If yes, what do you compensate switching times by? (temperature, control voltage, drive pressure, etc.)**

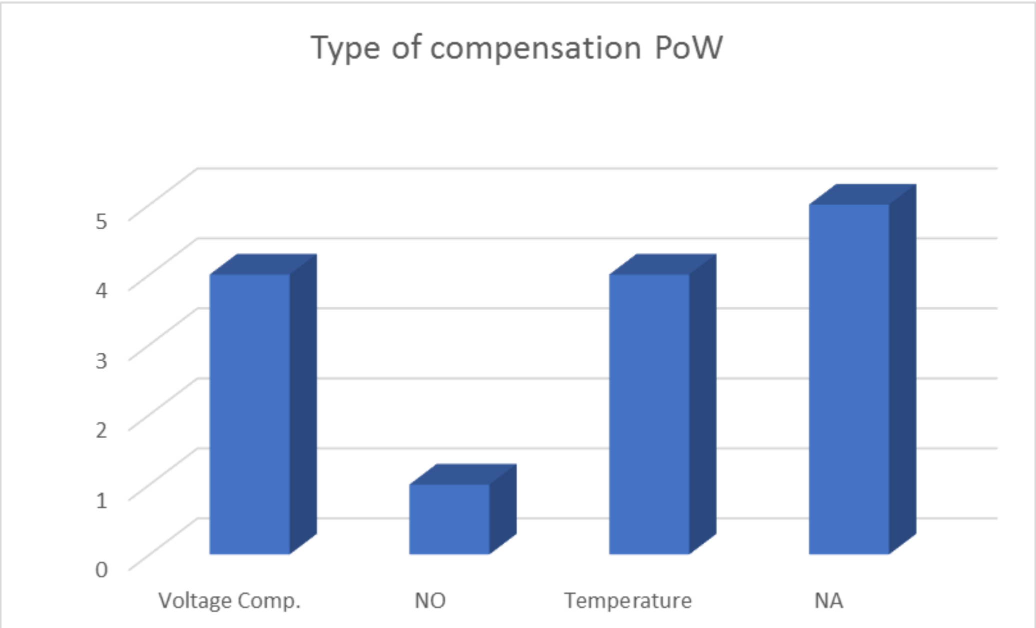



**Figure 52: Distribution answers to Q2.5**

From the questionaries, the physical quantities most commonly used for automatic compensation of the operating times of POWs adopted by TSOs are the ambient temperature where the CB is operating and the supply voltage of the switching circuits.

Q2.6 **Do you use a bypass of the PoW device?**

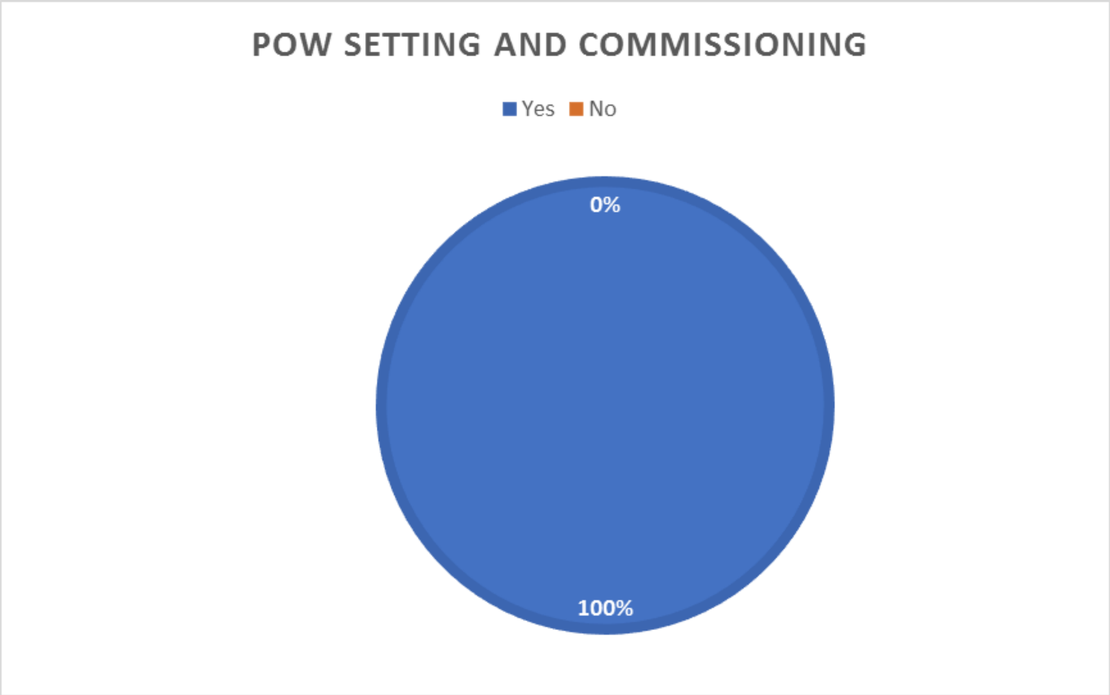



**Figure 53: Distribution answers to Q2.6**

From the answers to question 2.6, all TSOs using POW for CSS use the bypass function as a mode of operation.

Q2.7 **If yes, what kind of bypass is that? (internally in PoW software, externally by change-over switch, etc.)**

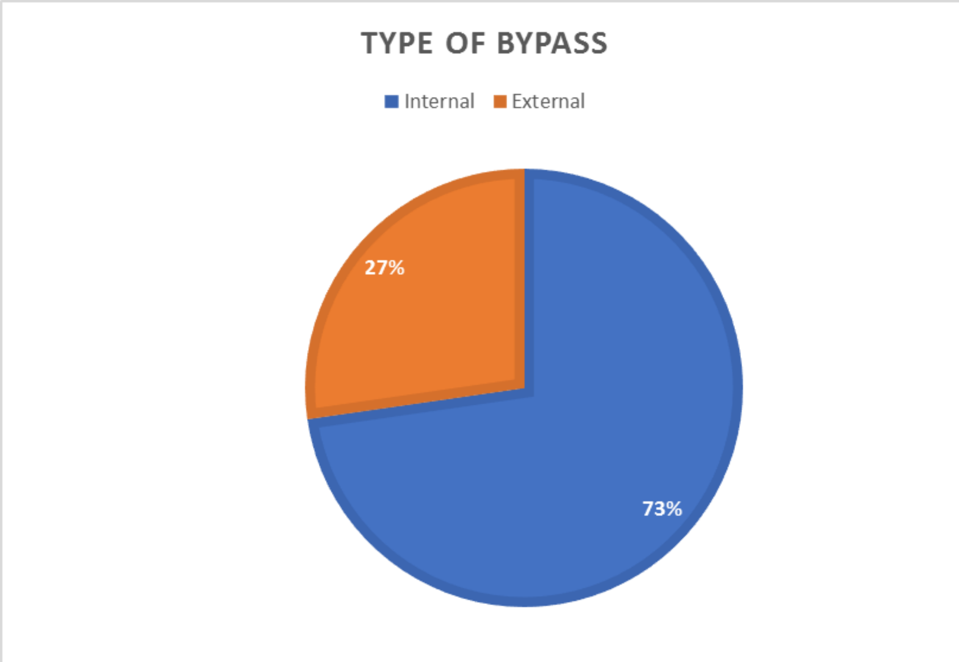



**Figure 54: Distribution answers to Q2.7**

The Bypass operating function is used for the most part using device setup/configuration. One third of TSOs use this operational function through independent external circuits.

Q2.8 **Are any trip signals from protection devices going via PoW (e.g. some time delayed functions)?**

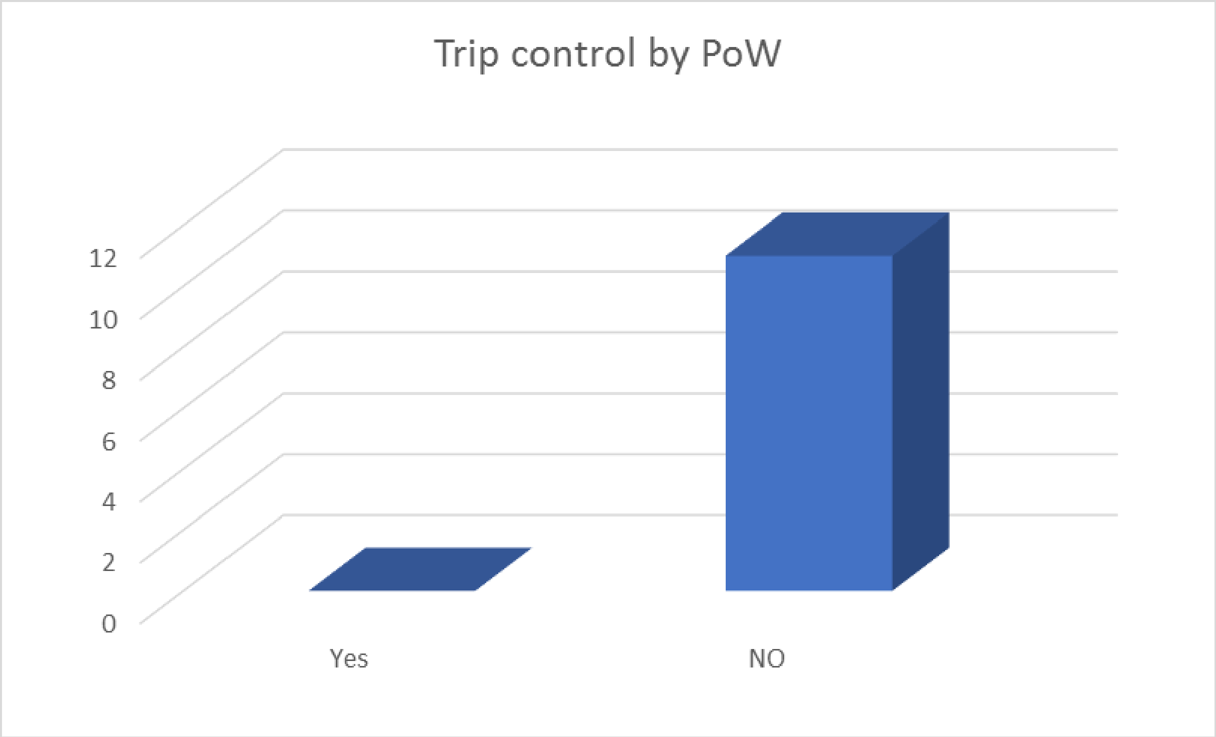



**Figure 55: Distribution answers to Q2.8**

No TSO conditions the trip circuits from protection system to POW devices.

## 8.3 Field experience

Q3.1 **How long have these POW controllers been in operation?**

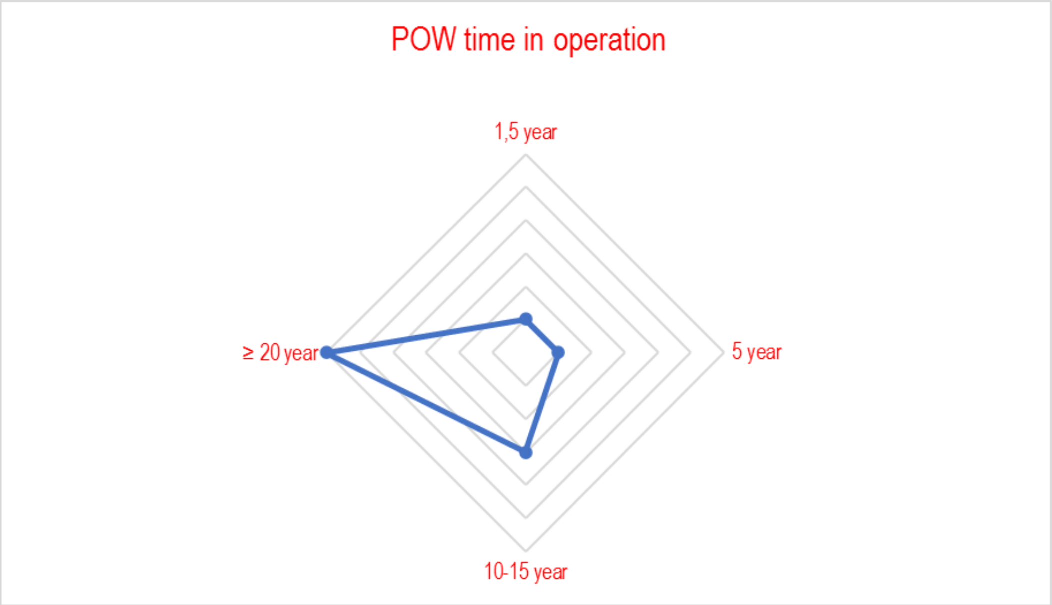


**Figure 56: Distribution answers to Q3.1**

Almost all TSOs have had CSDs in service since around the beginning of the 2000s.

Q3.2 **Have the systems always operated correctly?**

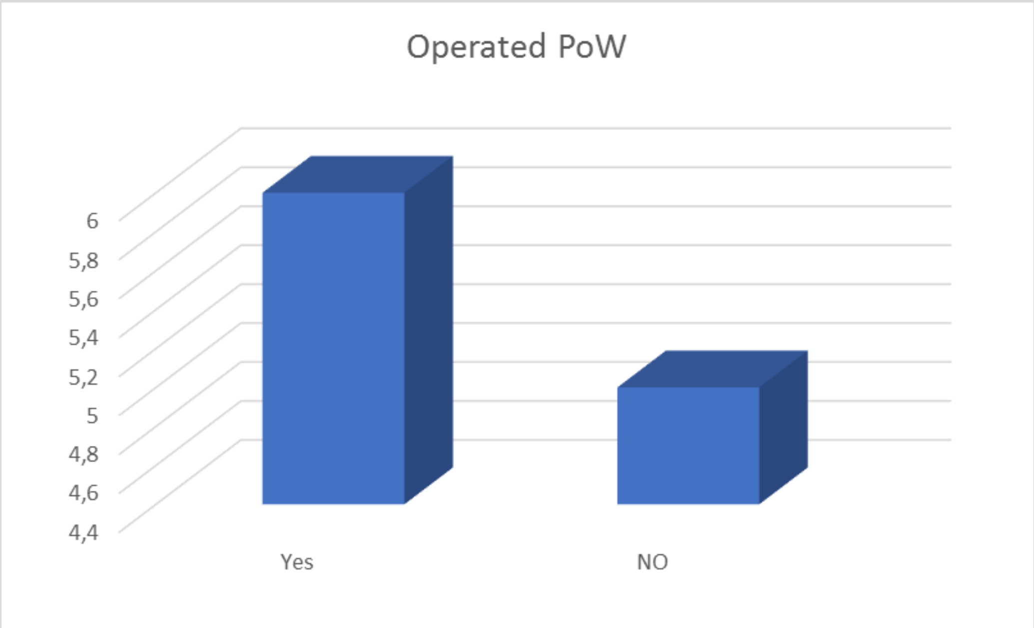



**Figure 57: Distribution answers to Q3.2**

There is a 50% split among respondents as to whether CDSs functions completely correctly

Q3.3 **Do you continuously check the proper functioning of PoW devices and how?**

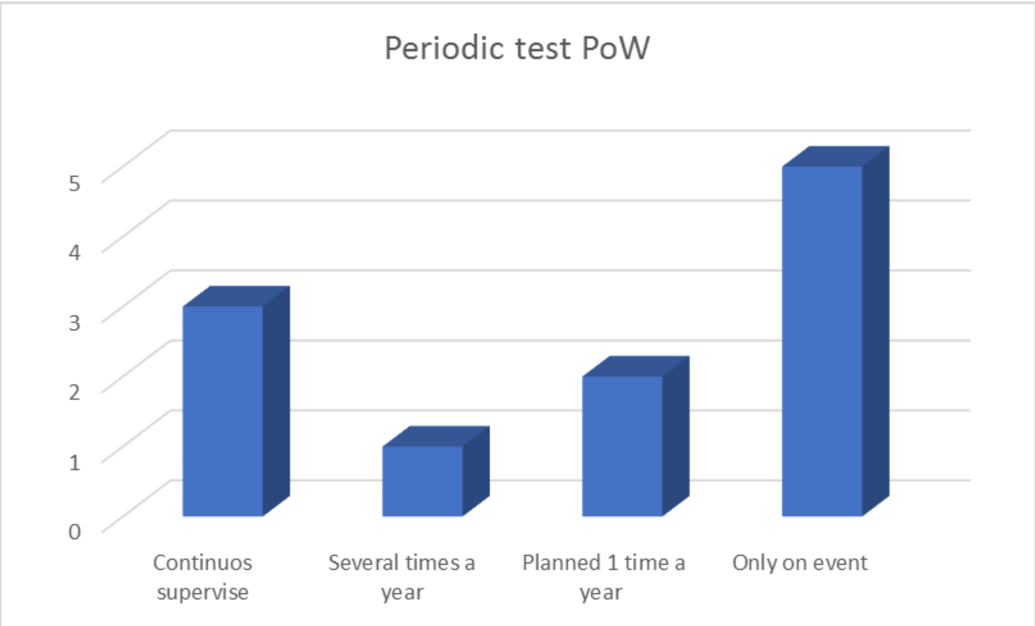



**Figure 58: Distribution answers to Q3.3**

Most TSOs only check POW devices at events (e.g. on alarm), whereas the remainder are equally divided between those who carry out scheduled checks during the operating year and those who continuously check functionality (e.g. by analysing operation records).

Q3.4 **Did the malfunctioning of the PoW cause component failures (switch damage or other) or grid failures (e.g. untimely intervention of the protective system)?**

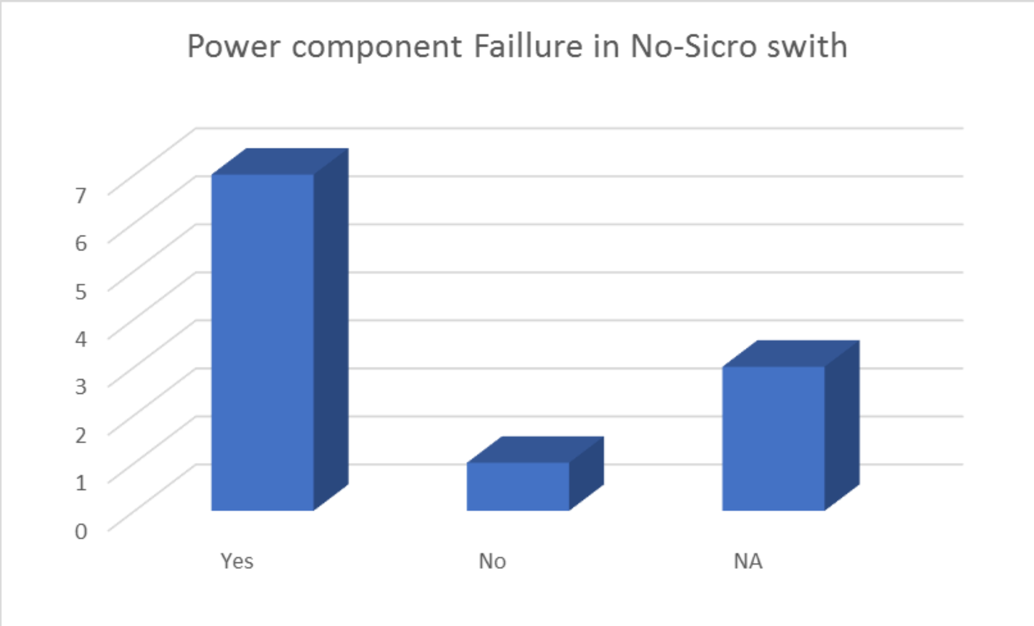



**Figure 59: Distribution answers to Q3.4**

Most TSOs detect damage to power equipment or malfunctions of the protective system resulting from the incorrect operation of CSDs.

Q3.5 **If yes, can you briefly describe the event and the corrective actions performed?**

See chapter 7 for case applications

Q3.6 **Is the maintenance and testing of PoW scheduled or event-based? If scheduled, please indicate the periodicity**.

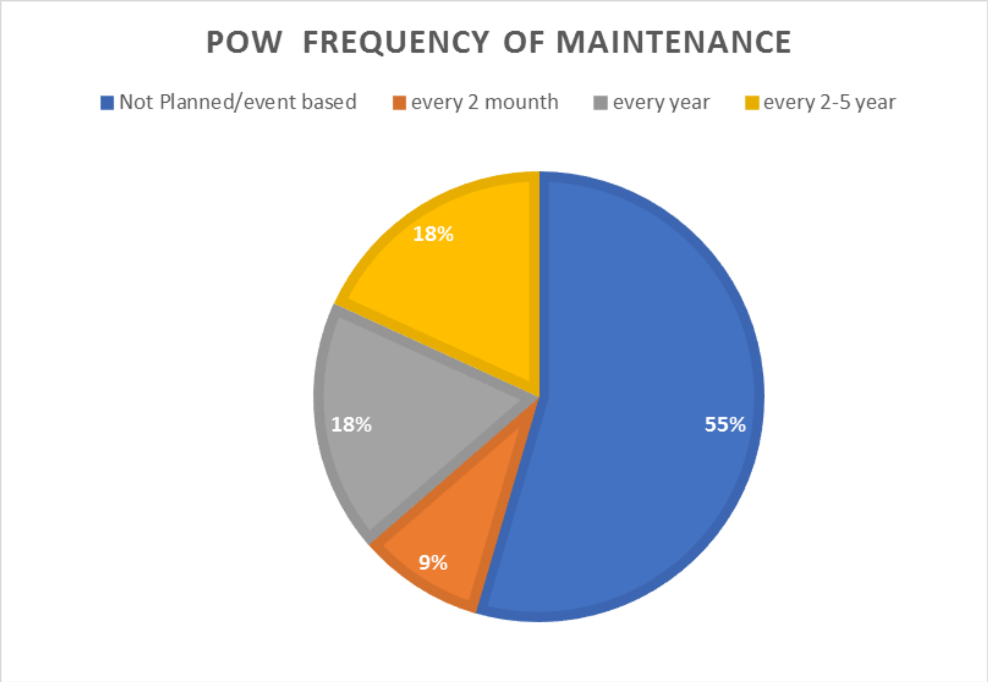



**Figure 60: Distribution answers to Q3.6**

The chart in Figure 59 shows the distribution of the frequency of planned maintenance of the various TSOs. Approximately half do not currently have planned maintenance plans.

Q3.7 **Instead of PoW, are other methods adopted for closure control (e.g. pre-insertion resistors, calibration sets active only on close, special switches with high breaking capacity aperiodic currents, etc.)?**

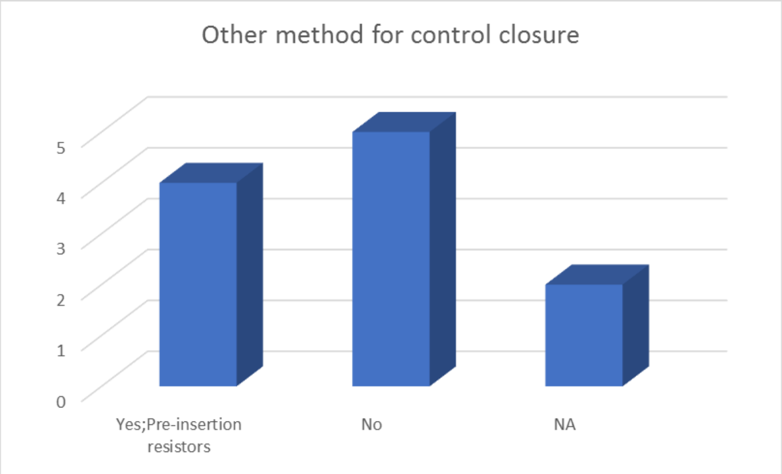



**Figure 61: Distribution answers to Q3.7**

The only alternative methods adopted instead of CSDs were pre-insertion resistors, adopted by about 45% of TSOs.

Q3.8 **What is your experience with POWS applied to UGC with bolted shunt reactors?**

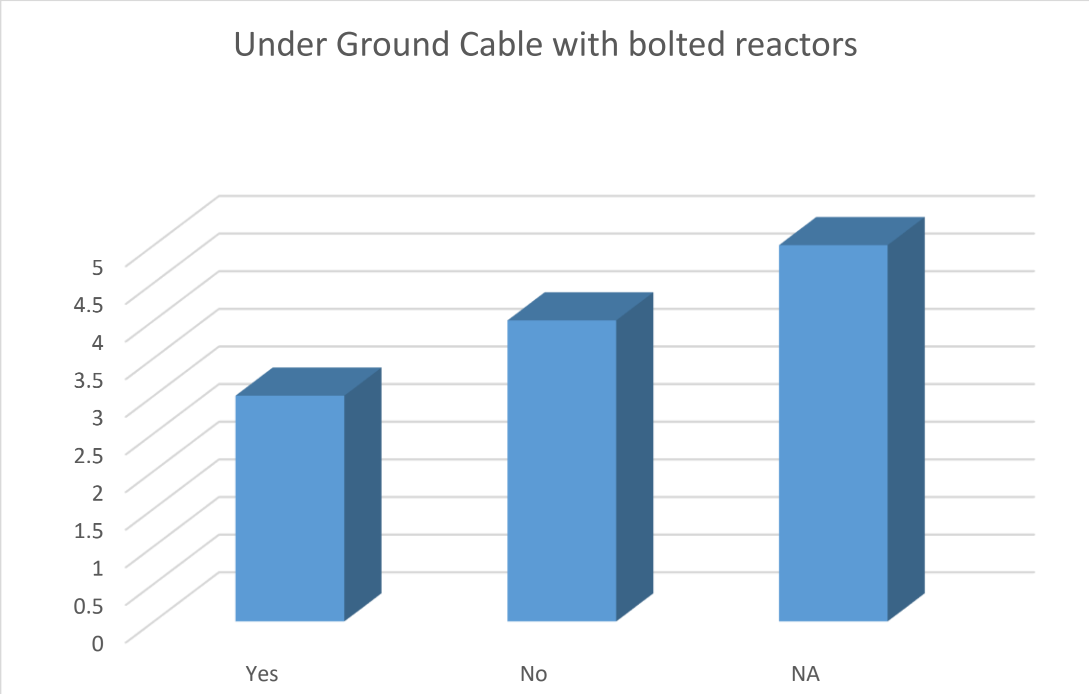



**Figure 62: Distribution answers to Q3.8**

Only three TSOs report experience with POW systems applied to underground cable lines with a compensation reactor solid connected to the line.

# 9 Conclusion

The purpose of this report is to share operational experiences and knowledge on the use, functionality and good practice of the installation and maintenance of CSDs in the European network, for both EHV and HV voltage levels.

The report, following a presentation on the purpose of installation, operation, typical functionalities in relation to the components to be controlled (TR, Condesator Bank, long OHL or CL, etc.), presented best practices for commissioning and testing these components according to international standardisation bodies and as applied by the major manufacturers on the European market.

At the heart of the report are the results of the questionnaire distributed to member TSOs, whose answers, together with the cases of interest, are reported in chapter 7.

It can be concluded that:

- The use of CSDs is widespread in the European grid, in particular in the uses for TR (ATR) energisation control on the EHV voltage level.

- The use of such a device for capacitor banks for the HV voltage level is also widespread.
- As far as the installation, setting and control of such systems are concerned, the majority of TSOs opt for engineering solutions with external staff (almost always the CSD manufacturer's technicians).
- Many TSOs do not have a specific verification and scheduled maintenance plan for CSDs, and consequently act only on an event basis, which in many cases has led to damage to assets (CBs) or to network operation problems (untimely or missed trips of the protection system).
- Many TSOs that constantly follow the functionality and targeted maintenance on these devices (eg. through the analysis of the records on the operational behaviour of these complex systems) are very satisfied with the level of reliability and completeness that these systems have reached in their latest digital versions, which can effectively replace the traditional and more expensive solutions adopted so far (Pre -Insert-resistors, Damping Voltage etc).

It is also particularly relevant to examine the case studies presented in Chapter 7, which show how the incorrect or lack of complete functionality of the CSD devices can compromise the power components or the protection system (with untimely interventions), or not exploit their full potential.

These anomalies are detected only with the deep learning of the functionality of the devices in interaction with the components and the specificity of the network, in which the experience of the technicians of the various TSOs makes the difference and, therefore, the exchange of experience is fundamental to increasing the security, economy and resilience of the European grid.

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