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Present and Future of Controlled Switching Commissioning

On behalf of CIGRÉ WG A3.35

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ABSTRACT

With the help of a controlled switching (CS) mitigation technique, transient surges are reduced when operating a circuit breaker (CB) connected to a shunt capacitor bank, shunt reactor, transmission line, cable or power transformer. However, its performance depends greatly on the consistency of the CB's mechanical and dielectric behavior, variations in the operating conditions, a proper strategy for implementing the controlled switching device (CSD), and on the ability of the CSD to accurately predict the operating time of the CB during its lifetime.

In 2004, CIGRE WG A3.07 published a guide that emphasizes the importance of CB operating time compensation due to external variables such as ambient temperature, control voltage and the mechanical energy of the drives. This led to the publication of IEC Technical Report 62271-302 to standardize CB testing procedures with a non-simultaneous pole operation. The report also takes into account other conditions that may influence CB operating times such as the idle time, which is greatly dependent on the CB driving-mechanism technology. These timing variations, if acquired by proper type tests and routine tests, can be compensated by the CSD. It is also widely acknowledged that, after the CB installation, its operating times can undergo small variations. Therefore the values to set in the CSD must be those validated or obtained during commissioning when connected to the real network and under actual system conditions.

The final performance test of the CSS comprising a CB and CSD always involves several live switching operations. These operations must be limited to the minimum number possible in order to minimize inconvenience for network operation and site test costs. Nevertheless, utilities must be fully aware of the importance of making provision for sufficient commissioning tests to ensure satisfactory in-service performance in the long term and not only during commissioning tests. In the case of retrofitting a CSD on an existing CB, a practical method exists to estimate CB timing performance by analyzing past operation records.

Whilst there are similarities in the processes and procedures for commissioning a CSS, CIGRÉ SC A3 has identified a need for updated guidelines in support of the best commissioning practices. These will reflect recent field experience from various manufacturers and utilities world-wide, including pitfalls to avoid. For this purpose, CIGRÉ WG A3.35 is currently investigating different applications; its work will result in recommendations for the improvement of relevant standards and in the publication of a technical brochure providing a detailed guide for CSS commissioning and follow-up. The objective of the present article is to report the work done and results obtained so far by WG A3.35 and also to encourage experts to contribute their own findings.

KEY WORDS

Controlled switching, Testing of UHV equipment, Installation and commissioning

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Introduction

With the help of a controlled switching (CS) mitigation technique, transient surges are reduced when operating a circuit breaker (CB) connected to a shunt capacitor bank, shunt reactor, transmission line, cable or power transformer [1, 2, 3]. Since the late 1990s, the number of CS installations has increased rapidly due to satisfactory service performance [4]. However, this performance depends greatly on the consistency of the CB mechanical and dielectric behavior, the operating conditions, a proper strategy for implementing the controlled switching device (CSD), and the ability of the CSD to accurately predict the behavior of the CB during its lifetime.

The objective of the present article is to report the work done and results obtained so far by CIGRÉ WG A3.35 and also to encourage experts to contribute their own findings.

1. Current CSS test requirements

In 2004, CIGRE WG A3.07 published a CSS application guide based on an international survey that highlighted the importance of CB operating time compensation due to external conditions such as ambient temperature, control voltage and the mechanical energy of the drives [5]. Other variables that may influence CB operating times were also discussed, such as the idle time when using a particular driving mechanism technology. Testing requirements for the CB and the CSD were proposed; they are summarized in Table 1. This led to the publication of IEC Technical Report 62271-302 to standardize the testing procedures of circuit breakers with non-simultaneous pole operation.

Table 1: Testing requirements for CSS components and integrated system

Components and System	Test Items	Characteristics / Remarks
Type tests for circuit breakers	Electrical performance	Rate of Rise of Dielectric Strength (RRDS) Rate of Decrease of Dielectric Strength (RDDS) Maximum making voltage for voltage zero target Minimum arcing time for restrike-free or reignition-free
	Mechanical performance	Scatters of operating times Variations of operating times on operating conditions Delay of operating time after an idle time
Type tests for controllers and sensors	Functional test	Timing scatters of open / close commands All compensation functions Self-check function, etc
	Electromagnetic, Mechanical, Environmental	Dielectric withstand, EMI Vibration, Shock, Seismic Cold, Dry heat, Temperature / Humidity, etc
Commissioning tests for integrated system	Controlled switching test	Distribution of switching instants Distribution of making voltage Verification of restrike-free or reignition-free interruptions

2. Routine tests and type tests at the factory

Each component used for CSS (CB, CSD and related sensors) is normally tested individually at the factory as a part of the routine and type tests [6]. Subsequently, tests are performed to validate the complete system performance; for retrofitting applications where a CSD is installed on an existing CB, these last tests are performed on site. The following sections present factory results using the procedures to be described in the next WG A3.35 technical brochure.

2.1 CB mechanical performance

The following example illustrates an investigation [7] of the variations in the closing/opening times at different control voltages and ambient temperatures using one pole of a three-phase 145-kV spring-operated gas-insulated circuit breaker. Forty CB operations were performed to evaluate the closing/opening time deviations from the standard operating time. The deviation is then plotted in the form of a mesh map to be configured into the controller (CSD) to increase the overall performance. This kind of mesh map is normally different for each CB type and should be evaluated.

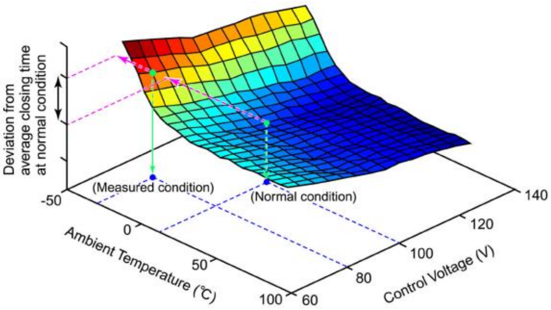


Figure 1: CB timing deviation example

However, this CB characteristic could be difficult to extract from the timing measurements if the CB operating time is also influenced by the idle time between operations, especially for some CBs with hydraulic operating mechanisms. A timing deviation estimation method has to be developed for factory and/or field measurement to extract the contribution of each variable. To help understand the process, Figure 2 shows trend curves from 117 closing-time measurements obtained during half a year on an in-service 35-year-old 420-kV SF_6 CB with hydraulic drive.

By plotting a best-fit trend curve for the measurement points of each idle-time group, the influence of idle time is revealed: the curves are not superposed and are shifted vertically upward when the idle time increases.

Beside the friction force changes between hydraulic CB moving parts, another reason could explain the influence of the idle time on the CB operating time: the dissolved air in the hydraulic fluid can agglomerate temporally into bubbles when pressure is released during an operation; these bubbles in a hydraulic fluid will delay the response of the hydraulic piston movement for the next operation.

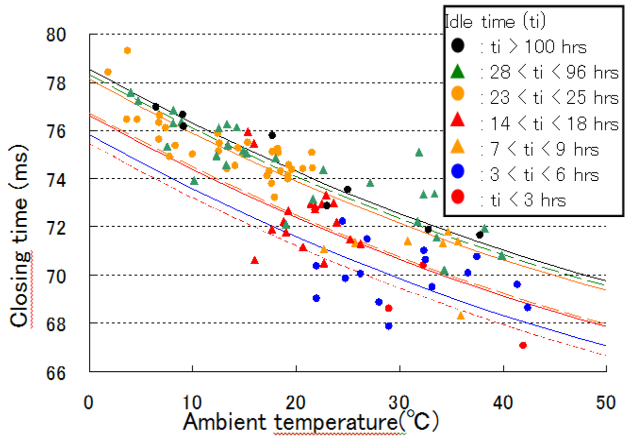


Figure 2: Example of idle time influence

By way of comparison, Figure 3 shows the idle-time dependence of a 145-kV-362-kV CB spring-operated mechanism [8] and a conventional 300-kV CB with a hydraulically operated mechanism. These characteristics were evaluated using C-O operating cycles after idle times of 2, 4, 8, 16, 64, 128, 256 and 720 h repeatedly. The spring operating mechanism has lubricating coating on its main sliding parts and shows a significantly small idle-time dependence up to 1000 h. Conversely, the test results with a conventional hydraulic drive reveal that the increase in closing time is observed after several hours of idle time and saturated to the maximum delay of about 2.0 ms if the idle time exceeds 72 h. Despite the difference in their CB timing behavior, both CSSs would have similar performances with an adequate configuration of the CSD taking into account the influence of the idle time.

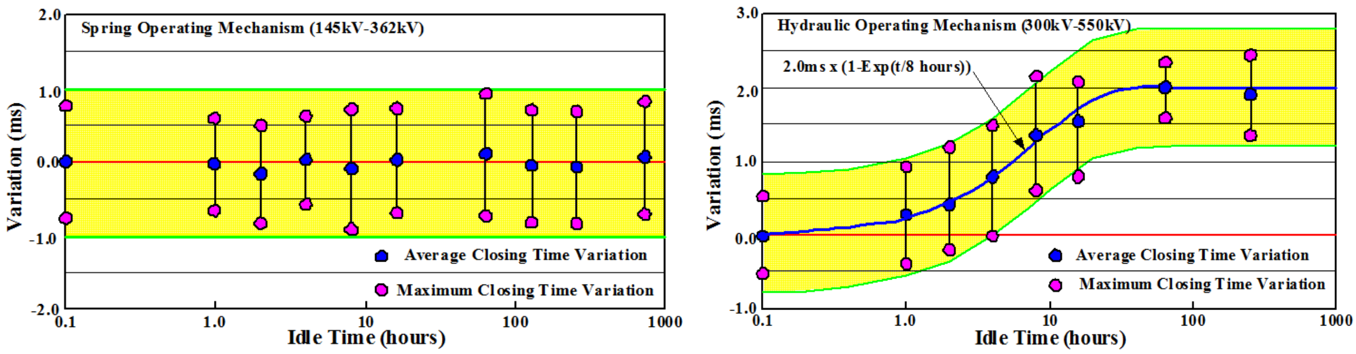
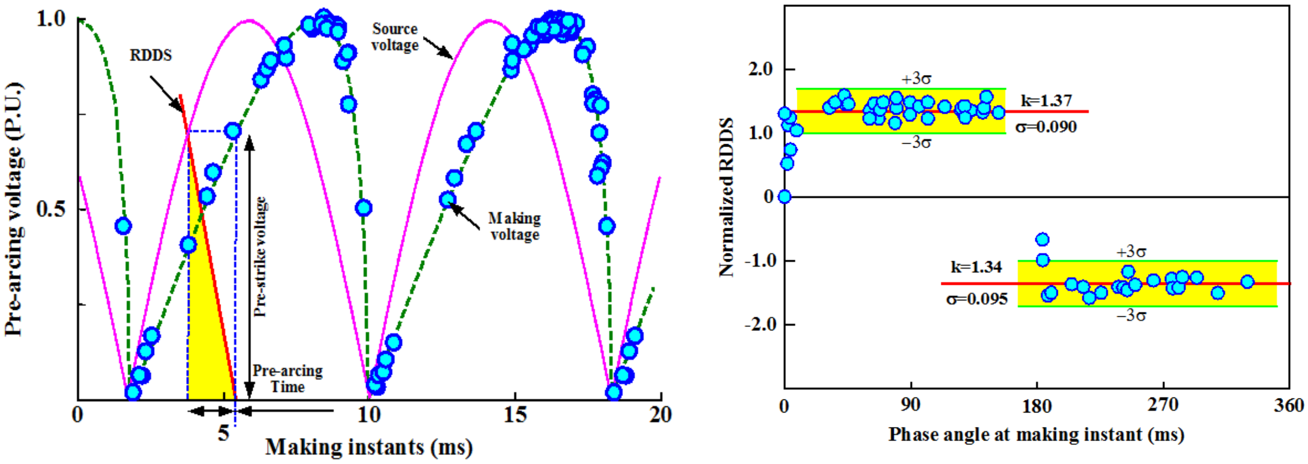


Figure 3: Idle time influence: comparison between spring and hydraulic operating mechanisms

2.2 CB electrical performance

Knowledge of a CB's electrical performance is also of the utmost importance for an optimum CSS. Testing procedures have already been published by CIGRE to obtain the CB electrical characteristics. For example, Figure 4-a shows the time of arc appearance at different mechanical targets taking as reference the absolute voltage across the CB. Figure 4-b [9] shows the CB's calculated RDDS (Rate of Decrease of the Dielectric Slope) value of each operation: each dot is the inverse-tangent value of a pre-strike voltage divided by a pre-arcing time (from the instant of pre-strike to contact touching). The resulting RDDS values (in p.u.) are normalized to the gradient of the system voltage at the zero crossing point. In this example, the normalized RDDS shows little dependence on the polarity because the average value is almost the same (1.37 for positive polarity and 1.34 for negative polarity).



a) Time of arc appearance vs mechanical target **b) Calculated RDDS values**

Figure 4: RDDS evaluation

The CSD can only control the CB to make/separate the main contacts at a programed instant (mechanical target). Therefore, the RDDS value must be calculated properly and configured in the CSD to enable it to work optimally by converting the required electrical target (i.e. what the system and the engineer need) into a mechanical target (i.e. what is needed by the CB control coil).

3. Commissioning

As previously described, the operating time of a CB may be influenced by many operating conditions, including control voltage, temperature, idle time, etc.. Although the dependence on these parameters can be evaluated from factory tests (especially for new CBs), a number of commissioning tests are required because the CB operating times may vary after its installation and over its operating life. Therefore the values to set in the CSD must be those validated or obtained during commissioning at the site. In addition to this, the actual system and load conditions can only be determined during the commissioning process, where the CSS is interconnected to the grid.

During CSS commissioning, a modern CSD will usually capture and provide sufficient information to assess its performance [10]. The waveform time resolution should be 80 samples minimum per power cycle (which is one of the data rates specified by IEC 61850-9-2 "Lite Edition" [11]), i.e. 4000 S/s at 50 Hz or 4800 S/s at 60 Hz. As a minimum, the following signals (*curves in blue in Figure 5*) need to be recorded in each phase:

- reference voltage (usually busbar voltage)
- breaker current and/or load voltage, depending on the application
- command output of CSD

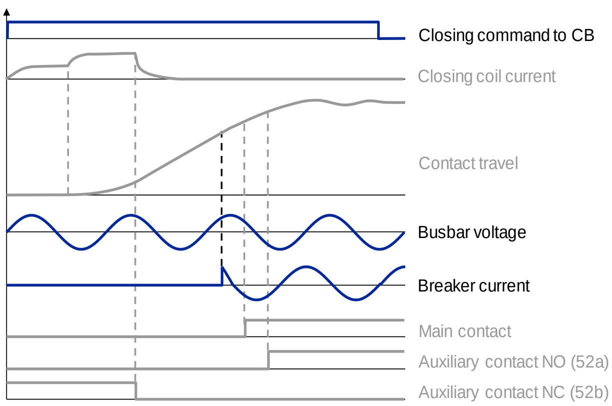


Figure 5: Typical recorded signals during commissioning

From these signals, the electrical switching instants can be derived, i.e. current inception (CB closing) or current interruption (CB opening), and their phase angles with respect to the reference signal. When an adequate number of tests are performed under different conditions, this is sufficient to ascertain that the CSS is working properly. However, if controlled switching operations are not initially optimal [10], further information may be needed to identify the cause. Some CSDs facilitate the investigations by supporting one or more of the extra monitoring sensors and signals displayed in Figure 5. However, the signals from stable auxiliary contacts in the CB drive will usually provide valuable information on the mechanical behavior of the CB.

The final performance test of the CSS always involves several “live” switching operations. These commissioning tests should be minimized in order 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.

While there are similarities in the processes and procedures for commissioning a CSS, CIGRÉ SC A3 has identified a need for updated guidelines in support of the best commissioning practices. These must reflect the recent field experience of various manufacturers and utilities world-wide, including pitfalls to avoid. For this purpose, CIGRÉ WG A3.35 is currently investigating, for different applications, all the aspects that will have an influence on the future commissioning practice, namely:

a) updated or new control strategies
b) new data analysis tools
c) improvement based on field experience

Their work will result in recommendations for the improvement of relevant standards and in the publication of a detailed guide for CSS commissioning and follow-up. The following sections provide hints on WG A3.35's recent findings.

4. Some updated or new CSD strategies and/or functionalities

4.1 Idle-time compensation

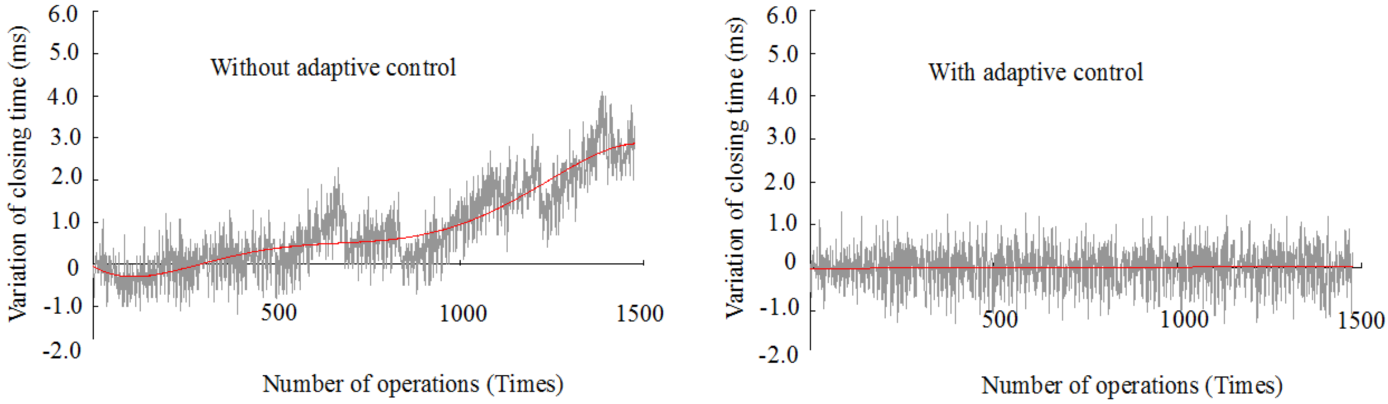
Most of the controllers have conditional compensation functions that can adjust the variation in the closing/opening times depending on the ambient temperature, the control voltage and the hydraulic pressure. The idle-time dependence of the drive (if of significant importance) is one of the major causes of controlled target misses in case of the controller without the idle-time compensation function.

The test procedure (especially for retrofitting projects) must be defined more clearly to measure the influence of this parameter on the CB timing operation and on the required CSD specifications. In this case, the adaptive function is not a solution to adopt blindly.

4.2 Adaptive function

Gas CBs are commonly designed using several sliding parts such as contacts and a sliding seal between metal surfaces during closing and opening operations. As a result, 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, an adaptive control can effectively compensate for the drifts in 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 ontained by detailed investigations of a series of mechanical endurance tests.

Figure 6 [9] shows typical drifts in the closing time measured with and without adaptive control over 1500 operations of a 145-kV spring-operated gas circuit breaker. The variation in the closing time is given by the difference between the predicted closing time and the result. Although the closing time becomes longer (Figure 6-a) with the increase in the number of operations, the closing time could be effectively compensated with good accuracy by the adaptive control. When the controller is able to detect the making instant directly by measuring the load current, the RDDS characteristics can also be compensated to the actual value with this adaptive control. In this case, the width of deviation was decreased from +4.1/-1.2 ms to +1.2/-1.2 ms (Figure 6-b).



a) without adaptive control **b) with adaptive control**

Figure 6: Typical drifts of the closing time measured with and without adaptive control

However, this adaptive function that could simplify the CSD configuration will make the follow-up analysis more complex. It is therefore recommended to activate it only when necessary and when all the known variable influences are mastered and configured in the CSD.

4.3 Coupling voltage consideration before closing (transformer application)

Since the 2004 CIGRE publications, controlled switching for the energization of power transformers is better known and more often applied. Unlike the shunt capacitor bank, which accounts for 70% of the total installation number of CSSs, and shunt reactor applications that use a specific target for all operations, an optimal transformer application calculates a different target from one CB operation to the other. In this calculation, determining the residual flux at the last opening is the key factor [12].

Most EHV and UHV CBs have multiple interrupting chambers in series along with grading capacitors to ensure a uniform voltage distribution across all contact points during normal (CB open position) and switching-system operations. Although these grading capacitors increase the switching capacity of the breaker, they have a side effect that sometimes is not negligible: part of the network voltage is transmitted with a phase shift to the load by the interaction of the grading capacitors which forms a capacitive voltage divider with the equivalent load impedance.

To obtain a rough picture of the values seen on a single HV network, measurements were taken on 15 installations (315 kV and 735 kV). The analysis of this initial, relatively small, survey showed that:

- the coupling voltage amplitudes are not the same for all installations (in some, the amplitude is less than 5%, while in others the amplitude is more than 30% as shown in Figure 7)
- the phase shift is different from one installation to the other and not the same for each phase (the minimum value was around 10°, while the maximum was more than 110°)

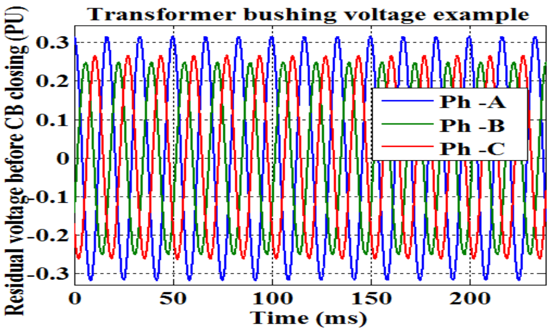


Figure 7: Example of coupling voltage on the transformer due to capacitive voltage divider formed by the grading capacitors and the load

This coupling voltage if not taken into account will produce two types of errors during calculation:

- missed electrical target (because the voltage across the CB main contacts is not as expected)
- erroneous residual flux evaluation at the electrical target moment (this coupling voltage also generates a dynamic AC magnetic flux that adds to the DC value measured at the opening)

To cater for this effect, a new function must be implemented in the CSD for an optimal transformer control strategy [13].

4.4 Delayed third-phase energization (transformer application)

A common strategy for energizing a Y-connected transformer or autotransformer with its tertiary windings delta-connected, taking into account the residual magnetic flux in the transformer, is to firstly energize the phase with the highest flux value. The two last phases are then closed simultaneously at the zero-voltage crossing of the first phase after a limited number of half-cycles. At this intersection, the absolute voltage of the second phase is increasing, while decreasing for the third phase. Table 2 shows the phases involved for three different scenarios where the first phase differs.

Table 2: Closing scenarios

Scenario #	Phase to close		
	1^{st}	2^{nd}	3^{rd}
1	A	B	C
2	B	C	A
3	C	A	B

Using this strategy, a problem arises in the commissioning and follow-up analysis process when trying to validate whether the electrical targets for the last two phases were reached. In fact, as soon as the arc is initiated on one of these phases, a voltage will appear on the other as if the arc was also initiated (due to delta windings). Another factor contributing to the two latter target uncertainties comes from the third phase where the combined effect of a decreasing absolute voltage, the RDDS value and the timing scatter amplify an observed target deviation on both of the last two phases. Sufficiently delaying the third phase will shorten the commissioning period by enabling the analysis tool to extract with greater precision more information for the three phases from each single CB operation.

4.5 Stress reduction strategy (transformer application)

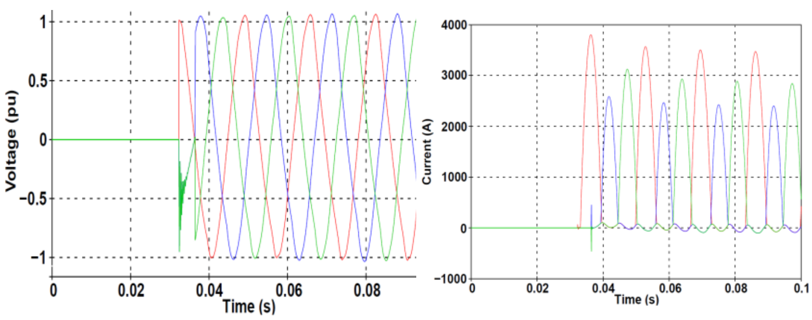
Since the beginning of CIGRE WG A3.07 in 2000, a question was raised which has still not received a convincing answer: *"When energizing a power transformer, which of the inrush current and of the dielectric stress is more damageable to the transformer?"* Meanwhile, the tendencies of all these strategies converge to eliminate or reduce the inrush current, especially for the worst scenario where the residual flux is not known. But with the arrival of EHV and UHV power transformers, an answer leading to a consensus should be obtained more clearly, mainly from manufacturers.

Until then, simulation studies are under way to validate other strategies to mitigate only the dielectric stress or to compromise by minimizing both stresses at the same time. Other rare situations are also studied, like the first energization of three newly installed single-phase transformers whose the summation of their individual residual flux is not necessarily zero and could be very far from that value [14]. Some preliminary simulation results already show that using a particular controlled energization strategy for any unknown residual fluxes in each transformer core could allow a significant reduction in the inrush current (from 5 p.u. to 2 p.u. in the simulated example where In is 1832A peak). Table 3 shows a case of the obtained inrush current in relation to the making instant on the voltage wave of the first phase being energized: the lowest inrush current is reached when making at peak voltage as expected.

Table 3: Simulation case study

Making voltage (p.u.)	Inrush current (p.u.)
0	4.97
0.5	4.58
0.75	3.99
0.85	3.6
1.0	2.07

Table 3 shows also that inrush current could reach a maximum value of nearly 5 p.u. in case of random energization. Figure 8 displays a simulated case of energization of a 735/315/12.5 kV, 1650 MVA autotransformer with a residual flux of +0.85, +0.55 and +0.65 p.u. respectively. In this case, the "first phase" is energised at peak voltage while the last two phases at the next "first phase" zero voltage crossing.



a) Voltage (p.u.) b) Inrsuh current (A)

Figure 8: Simulation case study

The resulting conclusions to be published in the forthcoming TB may have an impact on commissioning procedures for normal and special cases.

4.6 New data analysis and/or commissioning tools

New software tools or CSD functionalities could be used to help accelerate the commissioning process of all controlled-switching applications. As an example, Figure 8 shows some results obtained from such a tool during a 735-kV transformer controlled-switching commissioning. The CSD used at that time did not have the coupling-voltage compensation functionality, with the result that the electrical target was missed by 1 ms even though the configured CB timing value and RDDS were adequate. The reason for this was that the CSD expected the arc to occur when the network voltage reached a specific value and the CB main contacts were sufficiently close to each other. But at that time the voltage across the CB main contacts was lower than expected and instead it was the network voltage minus the coupling voltage. In this case, the tool was able to offer a temporary compromise with the apparent RDDS and timing values to be set in the CSD.

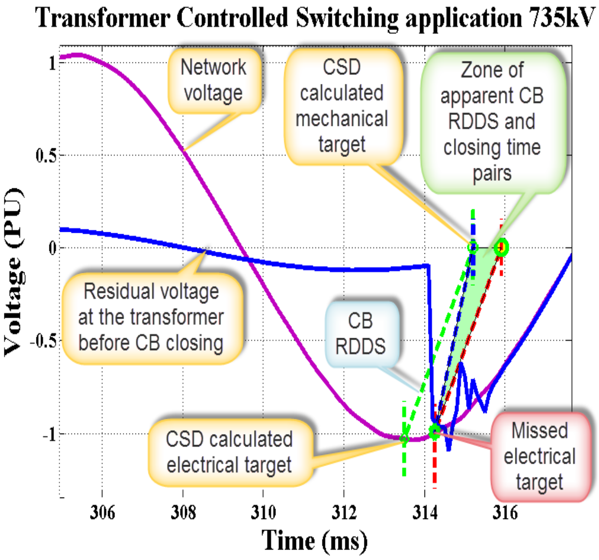


Figure 8: Commissioning tool result

5. Field experience and follow-up examples

Follow-up (or post-commissioning) is an extension of the CSS commissioning process. It is easily done using the inherent low-cost, efficient monitoring functions offered by a CSD. The CB status and stress accumulation on related equipment can be monitored in order to prompt preventive maintenance tasks if needed. Most of the CSS problems are related to timing deviations of the CB or unexpected configurations uncovered in the planning stage. CSD alarms are then of the upmost importance as they indicate that inappropriate behavior has occurred and that action must be taken quickly, starting with analysis of the alarm. The following subsections present partially the actual experience of different utilities on the subject.

5.1 Controlled Capacitor Switching

At one utility, a 121-kV capacitor bank switched using a CB with an independent pole-operated spring mechanism has been successfully commissioned. In addition to the type and routine tests performed at the factory, the commissioning on site was completed within 10 C-O live operations of the load. The programed closing target was set at 8 electrical degrees after source voltage zero in order to have a making voltage as low as possible no matter the CB timing uncertainties. This value was determined by the characteristics of the CB's RDDS and mechanical scatter plus a small safety factor. The target for the opening operation was set to obtain a maximum arcing time before current zero. The analysis concluded that the CSS behavior was satisfactory, so the system was approved and left operating daily in the field.

Having the CSD measuring and storing the operating conditions and results was found useful not only for CB maintenance but also for a complete knowledge of the CSS behavior. More than 1000 operations were successfully conducted in the field and no restrikes were observed. The targets obtained were analyzed along with the corresponding influencing parameters. The deviations observed fall within the specification. Figure 9 summarizes the field performance of closing instants [9]: normal distribution around the target instant of 8 electrical degrees, standard deviation of less than 0.3 ms and a maximum making voltage of 0.25 p.u..

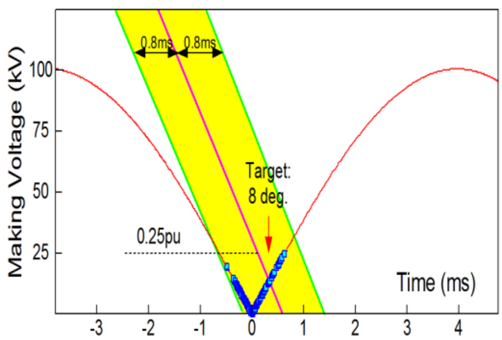


Figure 9: Observed target distribution

5.2 Controlled Reactor Switching

Besides mainly preventing restrike at CB opening for the shunt reactor application, the same CSS can also be used to reduce the inrush current or the transient stresses at CB closing. The making target that minimizes the reactor inrush current is the voltage peak. The associated switching overvoltage in this case is generally low but a steep voltage wave-front may stress the reactor insulation. Since it is impossible to achieve the reduction of both inrush current and transient stresses on the reactor energization with the same target, a compromise solution must be reached.

Taking as an example [15] a commissioned 204-kV CB with a hydraulic mechanism for a controlled reactor switching application, a follow-up of the CSS was performed over a one-year period. The CB timing scatter taking into account the idle-time characteristics was found to be within ±1.2 ms for the closing operation and ±0.2 ms for the opening operation, respectively. Figure 10 summarizes the field performance of closing instants that shows a normal distribution around the target of 79 electrical degrees with a standard deviation of less than 0.5 ms, the minimum making voltage being 0.8 p.u.. The maximum inrush current of 1270 A observed by random closing was then reduced to below 50 A.

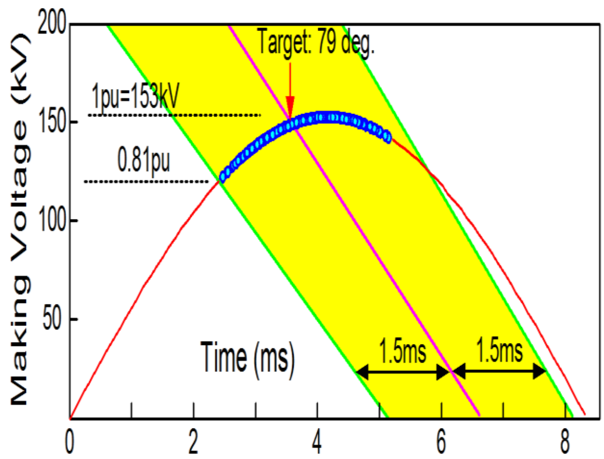


Figure 10: Observed electrical targets

For the same period, measurements were taken for the opening operations. Figure 11 shows the distribution of the observed opening instants. The resulting deviations were small (0.21ms) and the de-energization was carried out entirely within the re-ignition free window.

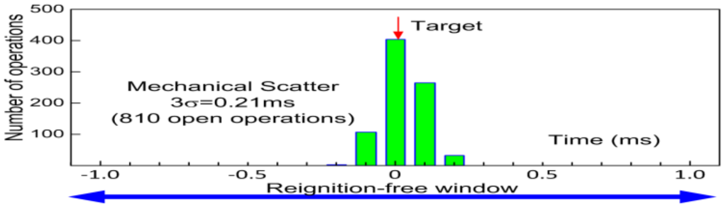


Figure 11: Distribution of opening targets

5.3 Alarm implementation example

The effectiveness and reliability of CSS over a long- term period is very dependent on the follow-up done over the years. Taking a shunt reactor CS application by way of example, one way to verify whether or not the CB reignites after a CB opening is by validating either that the reactor voltage does not exceed a pre-set threshold (re-ignition threshold)) or that no more current is flowing after the initially targeted interruption instant; otherwise an alarm should be generated. CB closing operations should be monitored also in order to minimize the stresses on the shunt reactor. These stresses can be twofold:

- mechanical stresses on the windings due to asymmetrical currents;
- dielectric stresses due to fast transient voltages applied to the insulation system of the shunt reactor (including the bushings).

Depending on the closing strategy adopted, one of the stresses can be greatly reduced. Closing on a zero source voltage will create the largest current asymmetry and the smallest transient voltage whereas closing on a source voltage peak will produce the worst voltage transients but theoretically no current asymmetry. Closing in between, i.e. at half the source voltage, will avoid the worst-case scenarios in terms of current and voltage transients. To make sure the target has been reached, the current amplitude should be monitored. The alarm threshold level could be easily set when the pre-set target is at peak source voltage and when considering a normal mechanical scatter of ± 1 ms on the CB closing time.

However if the strategy is to close at half the source voltage, the same alarm strategy cannot be used because the threshold level would have to be set too high to avoid unwanted alarms.

5.4 Unfortunate experience

Even if most CSS installations went smoothly, sometimes it is not the case [16]. For example, in 2013 one utility had two unfortunate and unexpected mishaps with shunt-reactor-controlled switching applications. This type of application has long been recognized as a source of current and voltage transients. During the de-energization of shunt reactors, overvoltages that are damageable to all surrounding equipment may be generated by two different causes: current chopping or re-ignitions. Since re-ignition overvoltages are normally more severe in peak value than chopping overvoltages, the use of CS to increase arcing times is commonly used in order to always be in the re-ignition-free arcing time window at contact separation.

Two unfortunate mishaps that led to a complete breakdown of the CBs occurred in a two-month interval time after around 1100 operations in two different substations, on the same type of 420-kV live tank CB where a CSD was installed and energized in 2009. Figure 12 shows the result of one failure. Analysis showed that during the CSD commissioning, wrong CB opening times were provided.

The configuration parameter was set at 27 ms while the CB was in fact opening in 19.2 ms with a specified minimum arcing time of 117 electrical degrees (6.5 ms on a 50-Hz basis). This difference resulted in having a shorter arcing time than expected of 77.4° (4.3 ms) for one station and 86.4° (4.8 ms) for the second, which led to re-ignition at almost every open operation creating cumulative wear on the isolating materials of the CB breaking chamber. Not surprisingly, a failure occurred on the first installation, followed two months later by the other.

Figure 12: Unfortunate experience

Reactor switching is an operation where small differences in circuit parameters (such as CB technology and models, inductance and capacitance values of the reactor and the surrounding network, etc.) can produce large differences in the severity of the duty. Despite passing the test according to IEC 62271-110, which is intended to cover the interruption of different kinds of inductive load by evaluating the risk of creating dangerous overvoltages, only field tests with a specific reactor can fully demonstrate the switching performance of a CB under real conditions. If the settings are not correctly programmed, consistent switching at wrong instants may have severe consequences on the equipment and/or the power system. Therefore it is very important during shunt reactor CS commissioning to take the time to verify the settings and limits of re-ignition. Technologies such as UHF or passive antenna have been developed and yield good results for measurement [14, 17, 18]. Guided setting tools for entering application specific data can prove very helpful to achieve optimal controlled switching performance.

5.5 Extensive and detailed pre-commissioning case

For a successful CSS commissioning [19], a detailed procedure must be followed to ensure a proper behavior of the CSS for a long period of working under various conditions. The commissioning should start by checking the system without HV or connected load (i.e. off-load commissioning or pre-commissioning) in order to minimize the subsequent real HV test operations.

The following suggestions serve as a basis for further discussion on this pre-commissioning procedure to be included as a complete chapter in the WG A3.35 technical brochure:

- Validation of technical data and comparison with project definition (well-known CB characteristics that fit the CS application, CSD selection with adequate functionalities, CB pole match with phase, technical data on the load, grounding conditions of the load, correspondence of voltage reference (if needed), technical data on the instrument transformers (CT and VT), etc.)
- Checking the wiring and sensor functionality (wiring and correct connection to the CSD, grounding of the CSD housing and wiring screens, VT and CT wiring, comparison of the CSD measured values with external measurements performed by other devices, signal and alarm check, etc.)
- Checking that the CSD configuration is in accordance with the actual application
- Testing operations (no HV) with validation of (CB) timing and correct wiring (correlation of CSD command output signals with the CB release coils, correspondence of auxiliary contact signals, validation of CB operating times (CLOSE and OPEN time), reference voltage behavior, CSD behavior during operation with injected VT and CT signals, etc.)
- Proper preparation and planning of the subsequent HV live tests to avoid excessive disturbance on the power system

Real-case examples will be provided in the annexes of the technical brochure to confirm that the proposed pre-conditioning procedure is complete. Already by following the above simplified recommendation list, many recorded mistakes have been detected and corrected in time in different utility installations.

Conclusion

There is a growing need to transmit large blocks of energy to distant main consumption centers, within countries with large territories or from one country to another. This leads to long-distance transmission systems at ever higher voltage (EHV-AC and UHV-AC). In order to maintain high quality, stability and reliability levels for these networks, with longer and higher loaded transmission lines, series and parallel reactive compensation must be installed at certain points of the network. Due to the daily load variation, switching operations must be performed to control the reactive-power levels. These operations can result in even higher switching overvoltages and their undesirable consequences for the equipment and the network as a whole. To help avoid these problems, which multiply as the network voltage rises, an efficient mitigation technique is needed like the one used by CSS which has been deployed now for more than two decades.

Initially designed for shunt-reactor and capacitor-bank applications, the CS technology is presently used for more complex applications, such as the energization of power lines and unloaded power transformers. This technology also offers a unique solution for low-cost, efficient monitoring of CB status and stress accumulation on related equipment, which can be used to prompt preventive maintenance tasks as they are required. Its performance depends greatly on the consistency of the CB mechanical and dielectric behavior under various operating condition variations, a proper strategy for implementing the controlled switching device (CSD), and the ability of the CSD to accurately predict the CB operating time during its lifetime.

Most important, all the gains of this mitigation technique can be obtained and maintained for a long period only if a proper and rigorous commissioning is performed. To ease and accelerate CSS installations and avoid misunderstandings that lead eventually to failure, WG A3.35 has been created to clearly define and explain all the steps of this task, mainly:

- ➢ Pre-commissioning (factory tests and on-site tests without HV or load)
- ➢ Commissioning (on-site HV tests with load)
- ➢ Post-commissioning (actual operation follow-up)

Their findings, supported by the analysis of an on-going international survey, will be compiled in a technical brochure to be published in the next two years. Until then, experts are encouraged to contribute their own findings.

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