cigre
For power system expertise

Paper 660 **Session 2022**
A3: Transmission & Distribution Equipment
PS 3 / Digitalisation of T&D Equipment

Field application of controlled switching & advanced digital monitoring techniques to mitigate switching transients for various power equipment connected with CBs with different drive technologies

Michael STANEK* [1], Urmil PARIKH[2], Mirko PALAZZO[1], Davide ZANON[3], Sebastiano SCARPACI[3], Patrik LINDFORS-DAHLIN[4], Mehulbhai SONAGRA[2]

[1] Hitachi Energy Switzerland Ltd
[2] Hitachi Energy India Ltd
[3] Hitachi Energy Italy Ltd
[4] Hitachi Energy Sweden AB

***michael.stanek@hitachienergy.com**

SUMMARY

Controlled switching has been applied since the 1990s for mitigating switching transients during energization and de-energization of various power equipment such as shunt reactors, capacitor banks, power transformers, power cables, and transmission lines. It is also used to reduce wear and tear of the internal components of high voltage circuit breakers (HVCBs) as well as generator circuit breakers (GCBs) during switching operations, thereby improving life cycle duration of the switchgear. A circuit breaker (CB) experiences electrical and mechanical aging during its service span based on number of off-load, on-load and fault operations. Therefore, it is very important to continuously monitor the performance of the controlled switching system (comprising CB and controller) to ensure its long-time performance in context to mitigation of switching transients. This functionality is based on detection of the actual switching instants of the CB. Consequently, the choice of adequate sensors and advanced monitoring algorithms is of utmost importance. The latest technology trend is integrating controlled switching devices into a digital substation control system via IEC 61850.
This paper presents experiences with application of controlled switching for various power system equipment to mitigate switching transients. The paper further elaborates application of advanced digital monitoring techniques for accurate detection of the actual switching instants, to assess transient mitigation performance and real-time condition monitoring of the CB as well as the power equipment. One installation with digital switchgear is described, wherein the primary voltage and current samples are distributed over redundant process bus through IEC 61850 to maximize reliability. Various case studies are presented to demonstrate successful application of controlled switching solutions for different power equipment with capacitive as well as inductive behaviour in diverse design & connection configurations. In this context, the first case study (Chapter 30 presents controlled de-energization of a 400kV solidly grounded

shunt reactor to reduce the wear and tear of CB components and the probability of unintentional re-ignitions. The case study is also supported by a Transient Recovery Voltage (TRV) simulation for this installation, and comparison of the simulation results with the reactor switching type testing standard IEC 62271-110. Another case study (Chapter 3b) illustrates controlled energization of an ungrounded capacitor bank at 150kV to minimize capacitive high-frequency inrush currents. The way to derive optimal switching targets for this case considering the load configuration and circuit breaker characteristics is also elaborated in the paper. Comparison of mitigation performance for non-optimum versus optimum targeting is explained. Both case studies include the usage of advanced filtering algorithms to compensate for unwanted signal components and, thereby, offer reliable performance monitoring. The last case study (Chapter 3c) includes performance of a controlled switching system during no-load energization of a coupled power transformer from 400kV winding side. The performance in repeated operations for mitigation of magnetizing inrush currents is presented in the paper with relevant field records. In this context, tracking the variation in operating time of the CB with the usage of a specially developed travel transducer is explained. The mechanical operating time errors and the variations in inrush currents for individual phases during successive live switching operations are also presented.
Lastly, the cases are selected in such a way to illustrate the application of controlled switching for different CB technologies viz. Live-tank breakers (LTB), Gas insulated switchgear (GIS), and Mixed-technology switchgear (MTS). The reactor switching case includes application of a GIS CB having spring operating mechanisms with hydraulic energy transfer. The transformer case study includes a live tank breaker with spring drive. The case of ungrounded capacitor bank includes application of controlled switching on MTS with motor drive, which is the latest innovation in drive technology.

KEYWORDS

Circuit breaker, controlled switching, digital monitoring, switching transients.

1. INTRODUCTION

Since the early 1990s, controlled switching has been becoming increasingly popular for minimizing switching transients related to major power system components such as transformer energization (magnetic inrush current reduction), capacitor bank energization (capacitive inrush current reduction), cable energization (minimization of charging currents and switching overvoltages), and energization and re-energization of transmission lines (reduction of switching overvoltages) [1][2][3]. For shunt reactors, controlled switching is used to minimize the probability of unwanted re-ignitions due to the steep TRV during de-energization. The high-frequency currents due to capacitive load energization as well as re-ignitions during de-energization of reactors may also lead to premature aging of arcing contacts and other internal components in the circuit breaker. With controlled switching, this electrical wear can be reduced and thereby the life cycle duration of the circuit breaker can be improved [1].
Implementation of controlled switching is not always straightforward due to technical as well as practical issues. The application of controlled switching to various power system equipment (capacitor banks, reactors, transformers, power cables, transmission lines) and the electrical & magnetic coupling along with type of connection configuration (isolated neutral, solidly grounded, or grounded through an impedance) demands a wide range of controlled de-energization and energization strategies which may vary from circuit breaker gap voltage zero to peak. In certain applications, the polarity of the gap voltage also needs to be considered while deciding the target points [1][2][3]. Therefore, to meet the controlled switching requirements for a large variety of equipment with different design philosophies and connection configurations, it

shall be possible to achieve electrical breaking and making at any point on the sinusoidal gap voltage for the individual poles of the circuit breaker. This, in turn, imposes certain requirements on the mechanical and dielectric properties of the CB: Most prominently, consistent mechanical operating times (low statistical scatter) and stable dielectric characteristics shall be ensured during both opening & closing for a large number of operations. Also, the impact of variations in external parameters such as temperature, auxiliary supply voltage, and others, on CB operating times must be considered. The said effects are largely intrinsic to the CB and drive technology. In this regard, controlled switching already has been successfully applied to various types of CBs viz. live tank, dead tank, gas insulated, and mixed technology (hybrid). Different drive technologies including spring operated, hydro-spring operated, and motor operated, have been widely used for the operating mechanisms of these CBs. Lastly, the long-term performance of a controlled switching system depends on reliable monitoring of the CB operating times. This is achieved by accurate detection of switching instants through advanced monitoring algorithms applied to the feedback signals from adequate current and voltage transformers, or through precision position sensors, which shall be able to accurately replicate the actual switching instants of the CB. Three different practical examples are presented below. Being implemented using digital microprocessors, controlled switching in principle lends itself to integration in a digital substation. This is explained in the last chapter.

2. CONTROLLED SWITCHING OF CBs WITH DIFFERENT TECHNOLOGIES

A controlled switching system is expected to reliably achieve the desired switching targets in each CB pole throughout its lifetime. This demands stable mechanical and dielectric properties of the CB for repeated operations. The stability is intrinsic to the design of the overall kinematic chain of the circuit breaker, which includes operating mechanism, linkage, and interrupting chamber. An international investigation showed that about 50% of all major failures in HVCBs and GCBs originated in the operating mechanism [6][7]. Therefore, to achieve highest operational reliability, circuit breakers need to be equipped with highly reliable operating mechanisms that also provide the stable mechanical properties for controlled switching [9]. Good results have been achieved with drives having the energy stored in a spring and with mechanical or hydraulic power transmission, and with electrical motor drives.

a) Spring operating mechanism

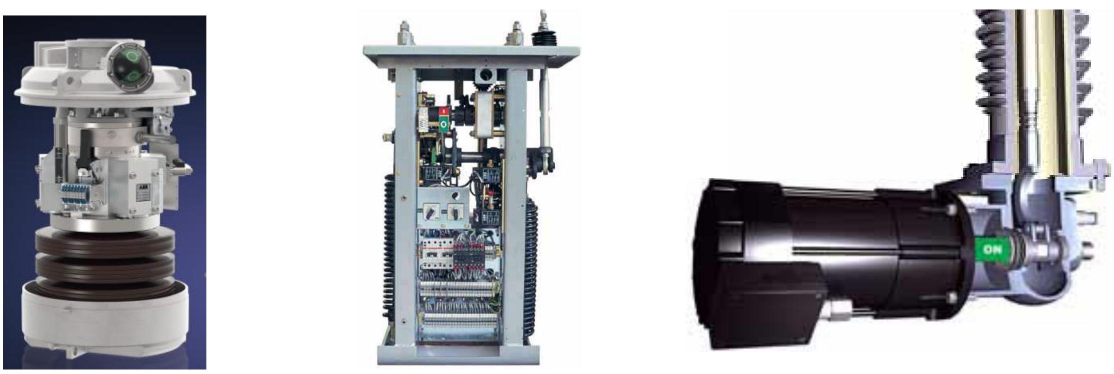
In a commonly used mechanism design, the closing springs generate the required driving force to both close the breaker and charge the opening spring. The opening springs are part of the circuit breaker’s mechanical linkage and are placed underneath the mechanism housing. This means that a closed CB is always prepared for immediate opening. A universal motor automatically winds up the closing springs immediately after CB closing operation. The springs are held in the charged state by a latch that is released when the breaker is being closed. This enables rapid reclosing of the breaker after a dead-time interval of 0.3s. The principle of the operating mechanism can be briefly described as follows: an endless chain links a cam disc and a set of springs. The chain, which is in two loops and runs over a motor-driven sprocket, transmits energy when the springs are being charged and drives the cam disc around when the circuit breaker is to be closed. During its rotation, the cam disc actuates a link that converts the rotating motion into a linear motion. The trip and closing latches are identical, fast acting, and vibration proof. Consistent operating times under all environmental conditions makes this type of operating mechanism suitable for controlled switching [9]. Figure 1 shows typical view of a spring operating mechanism used for LTBs in the voltage range of 245…765kV.

b) Spring operating mechanism with hydraulic power transmission

In this operating mechanism, the energy is stored in highly reliable disc springs. Operation is controlled by hydraulic valves widely used in industrial application and airplanes. After actuating the appropriate valve by an electrically driven solenoid, the energy is transmitted by hydraulic pistons. Damping at the end of the motion is integrated in the hydraulic system. By means of storage pistons, the mechanical energy components of spring force and spring travel are converted to the hydraulic energy components of pressure and volume. The fluid between the high-pressure system and the operating cylinder serves as a flexible linkage with a fast-acting control valve positioned in the flow path for closing and opening operations. Figure 1 shows an example of a typical hydro-mechanical spring operating mechanism applied in 1100kV GIS [9]. This type of operating mechanism offers stable operating characteristics and, hence, is suitable for controlled switching application [8].

c) Motor operating mechanism

A motor drive is a digitally controlled motor directly moving the circuit breaker contacts. On command, the motor is controlled to move the circuit breaker primary contacts according to the stored contact travel program. Energy charging, buffering, release, and transmission are essentially electrical and as such the mechanical system is reduced to a minimum of moving parts. The critical parts in the electrical operational chain are multiplied so that a redundant system is achieved. The mechanical simplicity of the motor drive provides advantages like elimination of wearing components, reduction in operating forces, substantial reduction of the noise level during operation, and increased reliability by elimination of multiple-interacting mechanical components. Being digital, it provides active feedback control of contact motion and can be directly interfaced to a digital substation control and monitoring system. Lastly, it also offers increased operational security and improved asset management through advanced on-line monitoring: During normal operation of the circuit breaker including idle state, the motor drive continuously runs diagnostic algorithms to check both its electrical and mechanical system. In the event of a problem, a warning or alarm signal will indicate to the substation control that service is needed. For further analysis purposes, the motor drive can also collect and store a wide array of data that can be retrieved either locally from the control board or remotely through a modem [9][10]. Being motor operated, this drive offers highly consistent operating times and, hence, is ideally suited for controlled switching applications [10].
Figure 1 shows typical views of the different types of mechanisms discussed above.



Hydro-mechanical spring drive — Spring drive — Motor drive

Figure 1: Typical views of different types of operating mechanism

Regardless of the CB and drive technologies, a controlled switching device (CSD) typically evaluates the actual CB operating times from the configured feedback signals and, therefore, provides intrinsic condition monitoring of the CB's switching behaviour.

3. FIELD EXPERIENCE FOR VARIOUS APPLICATIONS WITH DIFFERENT CB TECHNOLOGIES

To ensure reliable mitigation performance for repeated operations through controlled switching, the controlled switching device (CSD) needs to evaluate the deviation from the targets in every operation. This is achieved by monitoring suitable feedback signals based on the type of application. For reactor and capacitor bank application, the current into the load is normally used. For power transformers, the non-sinusoidal charging current is usually not suitable for feedback. Therefore, either transformer side voltage or mechanical CB position sensors need to be used to determine the actual switching instants. For coupled transformers (3-limb core design or having at least one delta connected winding), voltage start will be observed in all three phases as soon as the first phase is energized. This demands special connection arrangement of load voltages based on transformer design, connection configuration and side of charging. When mechanical position sensors such as CB auxiliary contacts are used for feedback, their correlation with main contact timing variation needs to be ensured [4]. In this section, the field experience of controlled switching for common applications, viz. reactor, capacitor bank, and transformer, are presented, when applied using CBs with different drive technologies.

a) Controlled switching of grounded reactor with GIS having hydro-mechanical spring drive

De-energization of a shunt reactor leads to voltage transients with very short rise time and frequency in the range of several kHz. Consequently, the TRV across the contact gap will vary in magnitude but it will have very short rise time, in the range of fractions of a millisecond. The fast-rising transients can lead to a breakdown of the contact gap and, hence, re-appearance of the current through arcing almost immediately post current zero, which is known as re-ignition. An unintentional re-ignition will lead to a steep voltage transient with high magnitude and frequency in the range of kilohertz, known as re-ignition overvoltage, which may affect the dielectric integrity and electrical lifetime of the circuit-breaker and/or the reactor [1]. Using controlled de-energization, the probability of unintentional re-ignitions, and thereby damage to the CB, can be minimized. The CSD aims at ensuring sufficient gap between CB contacts at the expected current zero on the sine wave, where the TRV is expected to appear. This is done by initiating contact separation several milliseconds before the expected current zero, depending on properties of the CB, the reactor, and the power system [1]. This time gap from arcing contacts' separation till current interruption is known as arcing time.

In this section, controlled de-energization of a 400kV, 80MVAR grounded reactor (no magnetic coupling between phases) by a GIS CB having hydro-mechanical spring operating mechanism is presented. The target arcing time for this reactor is set to 7.35ms based on results of reactor type testing as per IEC 62271-110 [5][12], on arcing time calculations as per IEEE Std C37.015, and on CB mechanical scatter of 1ms. Having a non-magnetically coupled core with star grounded connection configuration, the expected TRV and, hence, target arcing times for all three phases are the same. The simulation model together with interrupted current and TRV waveform for each phase is presented in Figure 2. For a non-coupled grounded reactor, the expected TRV for all three phases have the same peak of 646kV and rise time (t3) of 431μs. They are found within the IEC limit of 652kV peak with rate of rise less severe than the limit of 388μs [5]. Bushing capacitance, winding resistance, and winding capacitance were taken from the reactor routine test report. In this installation, the CSD uses reactor current as feedback signal for detecting the actual switching instants. As shown in Figure 2, high-frequency low-amplitude oscillatory current is observed from the reactor bushing CT post interruption. This is due to L-C oscillation of the reactor inductance with the capacitance of the bushing and the reactor windings. These oscillation signals need to be eliminated by advanced digital filtering as part of the monitoring algorithms to avoid false re-ignition detection, which otherwise may lead to unnecessary arcing time extension by the CSD.

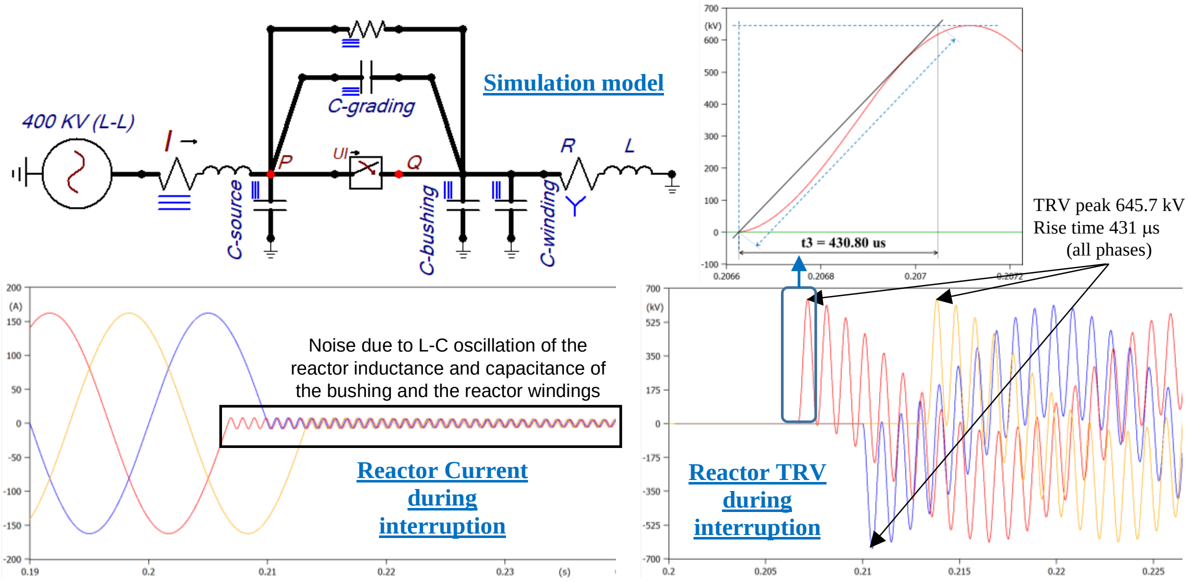


Figure 2: Simulation model and TRV waveform for 400kV, 80MVAR reactor

Table 1 shows the performance of controlled switching during de-energization of the said reactor with current feedback for repeated operations. It demonstrates that the target arcing times are well achieved for repeated operations, with very low monitoring errors as well.

Table 1:Accuracy of controlled de-energization of shunt reactor with current feedback

Operation No.	Actual arcing time (ms)			Electrical target error (ms) relative to target arcing time of 7.35ms		
	L1	L2	L3	L1	L2	L3
11	7.32	7.27	7.10	-0.03	-0.08	-0.25
13	7.29	7.25	7.12	-0.06	-0.10	-0.23
15	7.30	7.34	7.15	-0.05	-0.01	-0.20

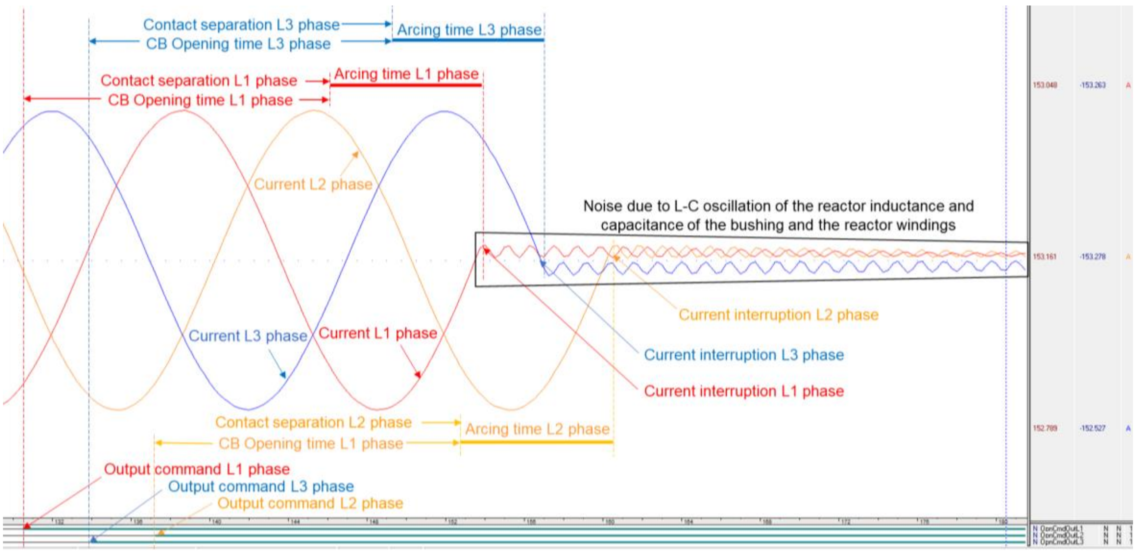


Figure 3: Waveform record of controlled de-energization operation no. 11

The waveform record for one of the controlled de-energization operations is shown in Figure 3. As usual, no voltage measurement was available on the reactor side of the CB, hence, the real TRV cannot be directly compared to the simulated one. Nevertheless, the fact that no re-ignitions were observed in any operation confirms the correct settings for target arcing time.

b) Controlled energization of ungrounded capacitor bank by MTS CB with motor drive

In this section, controlled energization of a 150kV, 26MVAR ungrounded capacitor bank through MTS CB having motor drive, to mitigate high-frequency inrush currents, is presented. Again, capacitor current is used as feedback signal to the CSD. The ideal energization targets for a capacitive load are in the vicinity of gap voltage zero across each CB pole. For an ungrounded load, current starts only when at least two poles are closed. Therefore, the first two poles need to be energized together in vicinity of line-to-line voltage zero, following a peak of 1.732pu. This will cause a neutral point potential shift by 0.5pu. Therefore, the third pole shall be energized in the vicinity of the respective pole gap voltage zero, following a peak of 1.5pu. As the first pole closing will not cause any current to flow, its target error shall be ignored, and any corrections need to be applied only to the second and third poles to close [1]. Figure 4 presents a comparison of controlled energization of an ungrounded capacitor bank with high target error, which led to high inrush currents, versus accurate targets leading to low inrush currents and target errors.

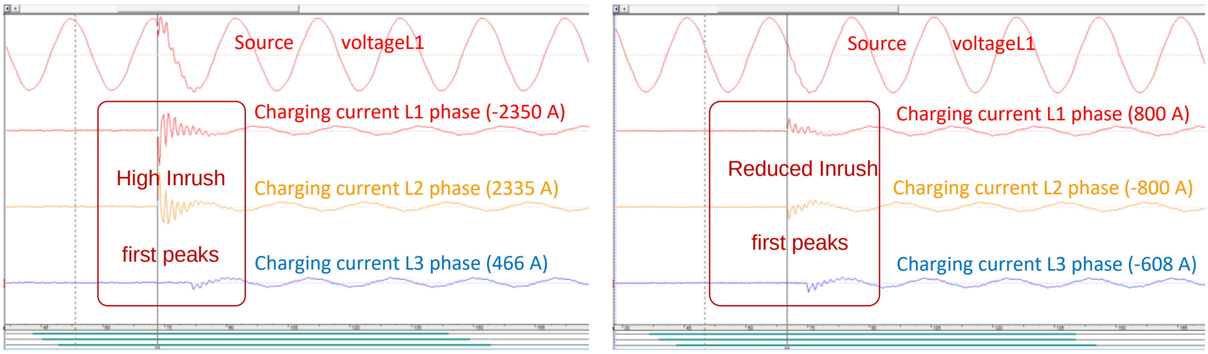


Figure 4: Controlled energization of an ungrounded capacitor bank

c) Controlled energization of coupled transformer by LTB with spring drive

During no-load energization of power transformers, controlled switching is used to mitigate magnetizing currents, which in turn may also lead to voltage instability on the grid. The optimal energization point is where the prospective dynamic flux matches the residual flux for each limb. In context to tracking the target errors, current feedback cannot be used due to the non-sinusoidal nature of the magnetizing currents. Furthermore, in transformers having a 3-limb core or at least one delta connected winding, energization of first phase will create fluxes in the other two phases even if they are not energized, which is known as inter-phase coupling effect [1]. This will cause voltage to appear in all three phases when being measured from star grounded side PTs. Hence, the said measured voltages need to be further processed to make them suitable as feedback signal for switching instant detection [13].

Application of this method to a 150/23kV YNd11 transformer with load PT connected on the 23kV side is shown in Figure 5. Controlled switching has been applied on the 150kV side by an LTB having spring operating mechanism. Without residual fluxes in the core, the "ideal" controlled making targets for an electrically coupled transformer would be energizing the first pole (L1) at its gap voltage peak, followed by the third pole (L3) a quarter cycle later, and the middle pole (L2) yet a little later (~1ms), to ensure L1-L3-L2 switching sequence. However, as the residual fluxes can generally not be neglected, controlled energization is preceded by controlled de-energization to establish a repeatable pattern of fairly low residual fluxes in the core ("flux locking method"). Consequently, controlled energization is performed at manually optimized making targets with reference to aforesaid "ideal" targets, based on the specific residual flux pattern obtained by controlled de-energization. The CSD disregards the non-zero load voltage signal seen in the later closing phases (L2 and L3) prior to actual energization through an advanced detection algorithm. Table 2 shows the performance of this method for repeated operations. Low target errors together with inrush current values less than 0.3pu of full load current peak, in successive operations, confirm the reliability of the approach.

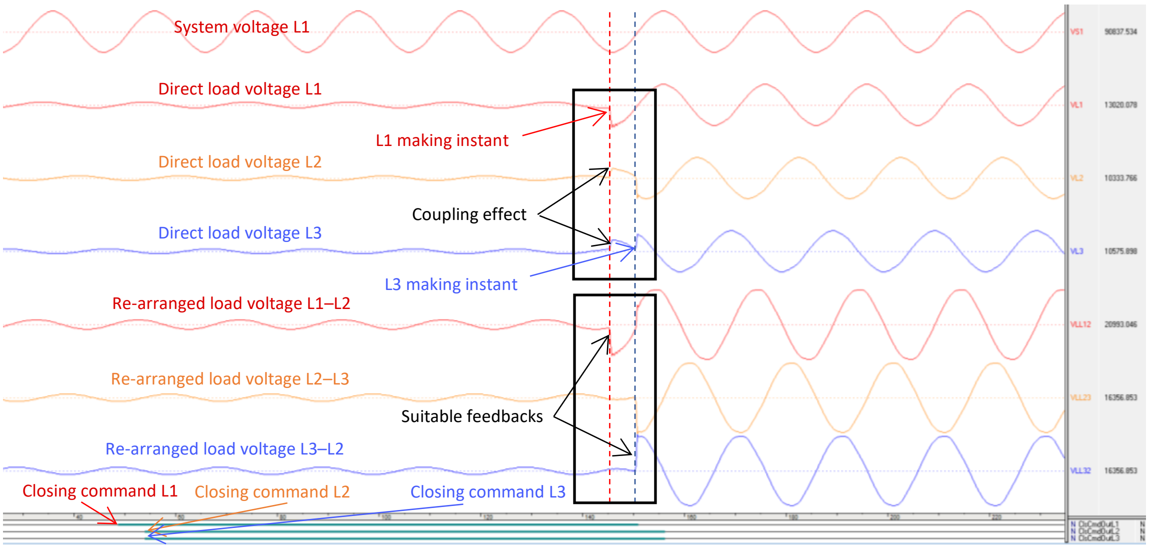


Figure 5: Special arrangement of transformer side PT for switching instant detection

Table 2: Results of controlled energization of YNd11 transformer with load PT feedback

DR No	Inrush current peak (A)			Electrical target error (ms)		
	L1	L2	L3	L1	L2	L3
8	-9.1	2.7	10.4	0.2	N/A	0.9
10	-8.9	-12.0	-8.6	-0.7	N/A	0.2
12	-10.0	-7.2	3.0	-0.6	N/A	0.3

In absence of transformer side voltage measurement, an auxiliary contact of the CB can be used for switching instant detection. However, this auxiliary contact shall have accurate correlation with variations in operating time of the main contact. Otherwise, a special precision position sensor needs to be employed.

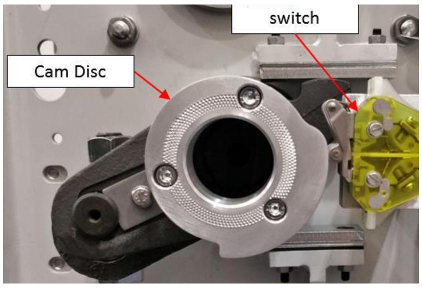


Figure 6: Special position sensor as feedback to CSD for switching instant detection

Figure 6 shows a specially designed operating-shaft mounted precision position sensor for such application on a live tank circuit breaker applied for a 400/220/11kV YNa0d11, 500MVA autotransformer, where controlled switching is applied to the grounded 400kV side [13]. Table 3 demonstrates successful implementation of the proposed method, wherein the target errors and inrush currents are found to be low for successive operations [13].

Table 3: Results during controlled energization of transformer with position sensor feedback

DR No	Inrush current peak (A)			Electrical target error (ms)		
	L1	L2	L3	L1	L2	L3
14	-9.1	2.7	10.4	0.2	N/A	0.9
16	-8.9	-12.0	-8.6	-0.7	N/A	0.2
18	-10.0	-7.2	3.0	-0.6	N/A	0.3

4. CONTROLLED SWITCHING IN DIGITAL SUBSTATION

Traditionally, a CSD is a stand-alone device. After commissioning, it is expected to perform its duty reliably without the need for user interaction. If any unexpected or unwanted condition should occur, it actively alerts the user through visual and/or electrical means such as LEDs or alarm contacts. This philosophy is still valid in a substation of conventional design, where every signal is transmitted via a dedicated pair of wires. Conversely, in a digital substation, each piece of primary equipment has its own little sensing or actuating module. These modules communicate with each other, with the control and protection devices, and with the SCADA – usually via optical fibres forming a redundant bus according to IEC 61850. In such a system, it makes sense to integrate the CSD in the digital communication scheme as well. As modern CSDs often include some CB monitoring functions based on the signals that are anyway needed for controlled switching, the user gets as additional benefits:

- Continuous monitoring information on the CSD and (to some degree) of the CB.
- Option to download stored records of switching operations and other data from remote.
- Trending of the operation data, which may help identify developing problems before they would cause a failure. These data may also be of interest for asset management.

IEC 61850 defines controlled switching as a logical node (LN) named CPOW [14] but does not specify where that functionality should physically reside. As controlled switching uses much of the same information as a bay controller or protection relay, it is expected that future CSDs will come as just a configurable software module in a control & protection device. Without losing functionality, this approach reduces the physical complexity of the installation, increasing reliability and saving costs.

The (presumably) first installation of a CSD in an IEC 61850 based digital substation is located in Eastern Australia [15]. The entire substation has only electronic instrument transformers (EITs), which transmit digital sampled voltage and current values to the receivers including CSDs. The trial installation, shown in Figure 7, was successfully completed in 2015 and has been in service without major problems since then.

Figure 7: Outdoor hybrid switchgear (MTS having spring-hydraulic drives) with redundant EITs and IEC 61850-9-2(LE) process bus for sampled values (blue). SC = Secondary Converter (on CB pole), MU = Merging Unit (in control house, same as CSD).

5. CONCLUSION

This paper presents application of controlled switching for various applications through different CB technologies, including LTB, DTB, GIS, and MTS. It also covers application using different types of operating mechanism including spring drive, hydro-mechanical spring drive, and motor drive. Field results of various applications such as grounded reactor de-energization, ungrounded capacitor energization, and coupled transformer energization have been presented with field DRs as well as results from repeated operations. Also, suitable feedback to evaluate target variations during successive operations for each application is explained in the paper. For reactor application, results of a simulation study show good agreement with field results. Finally, modern controlled switching devices are well suitable for integration in a digital substation, as demonstrated by a field installation that has been operating well for almost seven years.

BIBLIOGRAPHY

[1] CIGRE WG A3.35, "Guidelines and best practices for the commissioning and operation of controlled switching projects", CIGRE Technical Brochure 757, Feb. 2019.

[2] CIGRE WG A3.07, "Controlled switching of HVAC circuit breakers – Guide for application: Lines, reactors, capacitors, transformers", Part 1, ÉLECTRA No. 183, Apr. 1999.

[3] CIGRE WG A3.07, "Controlled switching of HVAC circuit breakers – Guide for application: Lines, reactors, capacitors, transformers", Part 2, ÉLECTRA No. 185, Aug. 1999.

[4] M. Stanek, "Analysis of Circuit Breaker Controlled Switching Operations – from Manual to Automatic." UPEC 2015 Conference, Staffordshire University, Stoke-on-Trent, UK, Sep. 2015.

[5] IEC 62271-110: "High-voltage switchgear and controlgear – Part 110: Inductive load switching", 2017.

[6] "Final Report of the 2004–2007 International Enquiry on Reliability of High Voltage Equipment: Part 2 - Reliability of High Voltage SF6 Circuit Breakers", CIGRE Technical Brochure 510, June 1994.

[7] M. Palazzo, D. Braun, G. Cavaliere, K. Dahinden, R. Eberle, W. Kiechl, M. Lakner, "Reliability analysis of generator circuit-breakers", CIGRE session 2012, paper A3-206.

[8] LIU Wei, XU Bing, YANG HuaYong, ZHAO HongFei, WU JunHui, "Hydraulic operating mechanisms for high voltage circuit breakers: Progress evolution and future trends", SCIENCE CHINA: Technological Sciences, Vol.54, No. 1, pp. 116–125, January 2011.

[9] L. Heinemann, H. Chi, "Technology Benchmark of Operating Mechanisms for High Voltage Switchgear", CEPSI 2010.

[10] A. Bosma, F.-J. Koerber, R. Cameroni, R. Thomas, "Motor Drive with Electronic Control for HVAC Circuit-Breakers", CIGRE session 2002, paper 13-203.

[11] CIGRE WG 13.02, "Interruption of small inductive currents", CIGRE Technical Brochure 050, 1995.

[12] "IEEE Guide for the Application of Shunt Reactor Switching - Redline," in IEEE Std C37.015-2009, pp.1-73, 12 Feb. 2010.

[13] U. Parikh, A. Fadadu, M. Sonagra, J. Bhanusali, N. Dubey, M. Stanek, "Accurate detection of actual switching instants in controlled switching of power transformers", e-SWICON 2021 – 10th International Conference on Switchgear and Controlgears, 2021.

[14] IEC 61850-5: "Communication networks and systems for power utility automation – Part 5: Communication requirements for functions and device models." Second edition, Jan. 2013.

[15] P. Schaub, A. Kenwrick, D. Ingram, "Australia Leads with Process Bus". T&D World, May 1, 2012.