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> Advanced sensors, non-conventional instrument transformers, monitoring and condition assessment

Application of controlled switching for a 500 kV switchable line reactor connected to 600 MW solar power generating plant to reduce probability of unintentional re-ignitions and life cycle enhancement – A field case study

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SUMMARY

Shunt reactors are employed on transmission lines to manage voltage profile during light load conditions. De-energization of a shunt reactor is a challenging duty for a high voltage (HV) circuit breaker (CB) due to the nature of transient recovery voltage (TRV) imposed post the current interruption. Even though the magnitude of TRV may not be always very high, it has quite steep rise time resulting into TRV frequency in range of few kHz. The magnitude and waveshape of the TRV depends upon reactor specification, its design & grounding configuration and on the surrounding site conditions in terms of inductance and capacitance offered by the substation. Many times, the CB may fail to interrupt such a fast-rising high frequency TRV at very first natural current zero after the arcing contact separation and will result into re-breakdown in a very short time post current zero, generally, within quarter cycle post natural current zero, known as re-ignition. These unintended re-ignitions can increase the aging of CB and also in some cases, may result into permanent damage of the internal components of the interrupting chamber. Controlled switching can be used to reduce probability of unintentional re-ignitions during de-energization operation. Thereby, it also assists in improving life cycle of the CB as well as the shunt reactor.

This paper presents application of controlled switching of the Live Tank Breaker for a 500 kV, 50 Hz switchable line reactor connected to a 600 MW solar power generating plant to reduce probability of unintentional re-ignitions and life cycle enhancement of the CB and the line reactor. Being solar power plant, during islanding mode with light generation, the voltage may rise on the transmission line. This is compensated by pulling in the aforesaid reactor on the transmission line. When the voltage profile on the line goes down, this reactor is pulled off from the transmission line. The commissioning experience in terms of handling wiring errors and compensating external noise with advanced digital monitoring algorithms has been discussed. Asset health monitoring for CB and reactor is achieved by detection of un-intentional re-ignitions & monitoring electrical target errors. Same is also presented in this paper. The paper further elaborates calculation of settings for the controlled switching device (CSD) to reduce probability of unintended re-ignitions as per IEC 62271-306. The way to achieve real-time condition and asset health monitoring using fully digitized IEC61850 enabled CSD is also explained. To validate the feasibility of CSD settings for the expected over-voltage, simulations have performed using ATP software, and are presented in this paper. On request from the user, reactor is also equipped with surge capacitor for each phase, to reduce the steepness and peak value of the over-voltage due to current chopping. Consequently, the simulation cases also include the comparison of over-voltage with and without surge capacitor. Nevertheless, from type test results and simulation study it has been validated that the CB can interrupt the current even without the presence of surge capacitor. Therefore, the calculated arcing time from reactor switching type test results which has been performed without the surge capacitor, has been applied for setting of the CSD to be on safer side.

As the reactor is grounded with the neutral grounding reactor (NGR), the peak value of over-voltage may attain further high value compared to the solidly grounded reactor. This is avoided by bypassing the NGR during reactor de-energization. The needed interlocking scheme to ensure this condition during reactor de-energization is also explained in the paper. Being one and a half CB scheme having separate CB for line reactor with CSD, the switching of transmission line together with reactor is performed with main or tie CB associated with the line bay. These CBs are not provided with controlled switching system. Therefore, in the event of line being disconnected through the dedicated lineside isolator, there exists possibility for main or tie CB de-energizing the reactor, which can result into unintentional re-ignition or even damage to these CBs. Needed interlocking scheme has been implemented to avoid this risk and is discussed in this paper.

KEYWORDS

“Asset health monitoring, IEC 62271-306, life cycle enhancement, re-ignition, transient recovery voltage”

1. INTRODUCTION

Switching operations on a power equipment like reactors, capacitor banks, long cables and transmission lines lead to switching transients. Energization of capacitor banks or long cables result into high frequency inrush currents which can create power quality issues on the grid. These high frequency currents can also increase wear of the arcing contacts of the CB [1][2][3]. De-energization of a shunt reactor leads to steep switching over-voltage and may result into faster contact wear or even in worst cases, damage to the internal components of the interrupting chamber of the CB [1][3]. No load energization of the power transformer creates high magnetizing inrush currents which, in turn, may lead to temporary over-voltages (TOV) on the grid. (Re)energization of transmission lines may result into high switching over-voltages and may impact insulation co-ordination of the transmission lines. In some cases, this may even cause flashovers on lines [1][2][3]. Therefore, these switching transients are one of the important concerns for the power system when it comes to healthiness of the equipment, it’s insulation coordination or lifetime of the CB as well as the power equipment. Consequently, the CB undergoes severe thermal as well as dielectric stresses and, is subjected to mechanical and electrical aging over its life span, based on number of no-load operations and number of live operations under different switching conditions [1][2]. Furthermore, increased penetration of distributed energy resources (DERs) and renewables on the main grid, result into power quality issues. For very sensitive grids, high switching transients may lead to protection maloperation and hence, nuisance tripping of connected equipment on the same grid.

Controlled switching (also known as point on wave switching or synchronous switching) is used to mitigate the aforesaid switching transients by controlling switching instant of the CB. In this way it minimizes power quality issues on the grid and minimizes the probability of protection maloperation [1][2]. It also helps in reducing the dielectric and thermal stresses and thereby, improves life cycle duration of both CB and the power equipment. The controlled switching target depends upon type, design, and connection configuration of the power equipment to be switched. The desired controlled switching targets varies in a wide range of gap voltage zero to peak and may be dissimilar for individual phases[1]. Controlled switching is achieved by a controlled switching device (CSD, popularly known as point-on-wave controller). The key role of CSD is basically to investigate the primary voltage and current signals received from the substation voltage transformers (VTs) and current transformers (CTs) to achieve the desired controlled switching targets [1]. The accuracy in achieving desired targets largely depends on mechanical and dielectric properties of the CB. This includes statistical variation in operating time of the CB (mechanical scatter) and the electrical characteristics– rate of rise of dielectric strength (RRDS) & rate of decay of dielectric strength (RDDS) of the CB. To achieve successful mitigation of the switching transients for repeated operations, CBs shall have stable mechanical and electrical characteristics. Also, variations in operating times due to the external parameters like control voltage, gas pressure, temperature, idle time etc. needs to be considered. The systematic variation in operating time due to electrical and mechanical aging of the CB shall be evaluated for every operation and necessary corrections in operating time needs to be applied during next operation. Controlled switching has been successfully applied for CBs having different technologies like live tank breaker (LTB), dead tank breaker (DTB), Gas insulated switchgear (GIS) and mixed technology switchgear (MTS) Furthermore, CBs having different types of operating mechanism like spring operated, hydro-mechanical and motor operated have been successfully used for controlled switching.

2. SHUNT REACTOR SWITCHING

Shunt reactors are generally employed on long transmission lines to maintain the voltage profile during light load conditions. These reactors are generally connected to station busbars or to the overhead lines. Many times, line reactors have dedicated CBs and hence, can be switched ON or OFF based on the voltage profile on the line. The line reactors are mostly employed with neutral grounded reactor (NGR) to have successful secondary arc quenching during auto-reclosure operation. In this case, over-voltage seen by the CB contacts will be higher than that of the non-coupled grounded reactor due to higher first pole to clear factor. Moreover, the pole who will experience the highest over-voltage and its magnitude will depend upon reactor core design and ratio of reactor to NGR impedance. Among all switching duties, reactor de-energization is considered to be challenging duty for a CB. The internal component of CB interrupting chamber as well as the reactor insulation are exposed to steep over-voltage, both in terms of magnitude and the time to reach its peak, post current interruption. The interaction between reactor's inductance and stray capacitance, leads to multi-fold oscillations post the current interruption. Generally, in modern alternating current (AC) CBs with SF_6 as dielectric medium, the current is interrupted in the vicinity of a natural current zero with very low value of chopping currents. Consequently, the voltage transient across the breaker (TRV) may not always have too high magnitude but will have a very short rise time. This can lead to re-breakdown inside the arcing chamber of the CB after first time interruption of the current in vicinity of natural current zero. This will cause re-establishment of the current through arcing, known as re-ignition. Although CBs can withstand re-ignitions, some re-ignitions may be harmful to both shunt reactor and CB depending on CB design, reactor specification, and power system configuration, and should be avoided [1][4]. In context to severity, both TRV peak as well as it's rise time can risk the CB. This means, TRV having comparatively lower peak, but very short rise times can lead to unintentional re-ignitions. The unintentional re-ignition may not lead to immediate damage to the internal components of CB but may cause higher contact wear and nozzle burning. This can lead to permanent damage of the CB as well as the reactor insulation after repeated current interruption operations through the CB [1][4].

Here controlled switching finds its pathway and serves as an important technology which can not only reduce the probability of unintentional re-ignitions during its de-energization operation but also assists in improving the life cycle of the CB as well as the shunt reactor. This is accomplished by ensuring sufficient gap between contacts and hence, the dielectric strength; at the time of current interruption when the steep over-voltage is expected to be appeared across the CB contacts. To achieve this, arcing contacts are separated well before the natural current zero where arc is expected to be quenched. The time difference between arcing contact separation till the natural current zero where arc is expected to be quenched is known as arcing time. Some CBs may require arcing times longer than the half cycle for very small reactor currents or the reactors having NGRs. However, such re-ignitions are controlled in a way, wherein the re-establishment of arc always happens between arcing contacts after very first natural current zero post the arcing contact separation, known as "Forced re-ignition".

Such re-ignitions will not result into damage of internal components of the CB provided the arcing times are not targeted in re-ignition prone zone [1] [5].

The needed minimum arcing time for re-ignition free operation shall be derived phase wise, based on specifications of the reactor as per chopping number (λ) calculations described in IEC 62271-306 and IEEE C37.015 [6][7], taking reference from the results of the reactor switching type test report as per IEC62271-110 [5]. The calculation results may also be validated with over-voltage simulation study. The arcing time setting shall always be higher than the calculated minimum arcing time. The range of arcing time for which probability of unintentional re-ignitions is minimum is known as re-ignition free window. To cater for the variations in the over-voltage due to configuration of the reactor, mechanical & dielectric characteristics of the CB and site conditions, centre of re-ignition free window is chosen as target arcing time for controlled switching. Figure I shows re-ignition free window for a non-coupled grounded reactor [1][2].

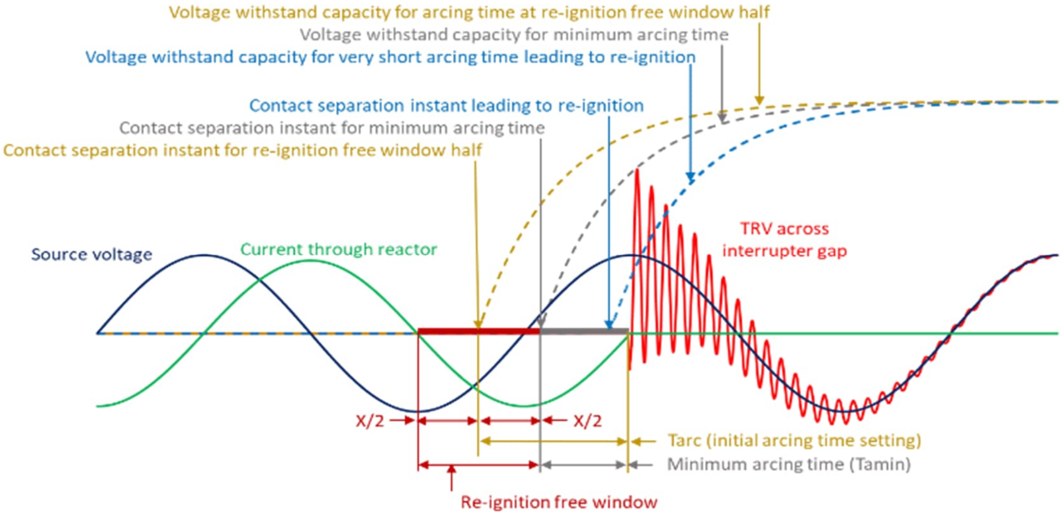
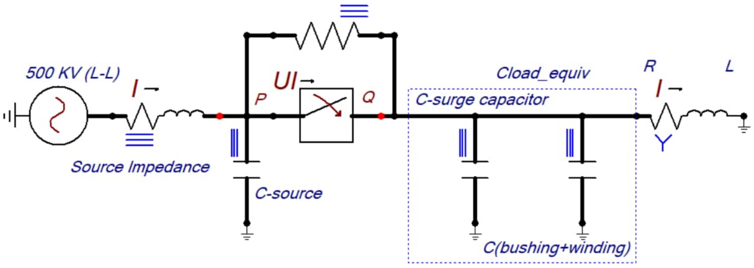


Figure I : Re-ignition free window for a non – coupled grounded reactor

With increasing usage of renewable generation and their integration with the conventional grids, compensating devices like shunt reactors and capacitor banks are becoming popular. The shunt reactor applications might lead to re-ignitions due to higher TRV and (rate of rise of restriking voltage) RRRV, which increase the probability of damage to the CB and to the insulation of the reactors. In this paper, application of controlled switching of the LTB for a 500 kV, 50 Hz, 60 MVAR switchable line reactor connected to 600 MW solar power generating plant to reduce probability of unintentional re-ignitions and life cycle enhancement of the CB is presented. The evaluation of arcing time using TRV simulation study, calculations as per IEC 62271-306 & IEEE C37.015 [6][7] and results from the reactor switching type test, is well elaborated in the paper. The field implementation of the controlled switching system and results from live switching operations have also been discussed in detail. The troubleshooting in context to wiring errors and compensating for external noise in the waveforms is explained with experience during commissioning of controlled switching system. To avoid exposure of CB to more severe TRV due to higher first pole to clear factor, bypass CB has been provided with the NGR when line reactor needs to be de-energized. Furthermore, the line reactor CB only has provided with controlled switching whereas line main CBs doesn't have CSD. Hence, to avoid risk of reactor de-energization operation without CSD, the recommendations regarding necessary interlocking scheme to be implemented, is also described at end of the paper.

3. TRV SIMULATION ANALYSIS

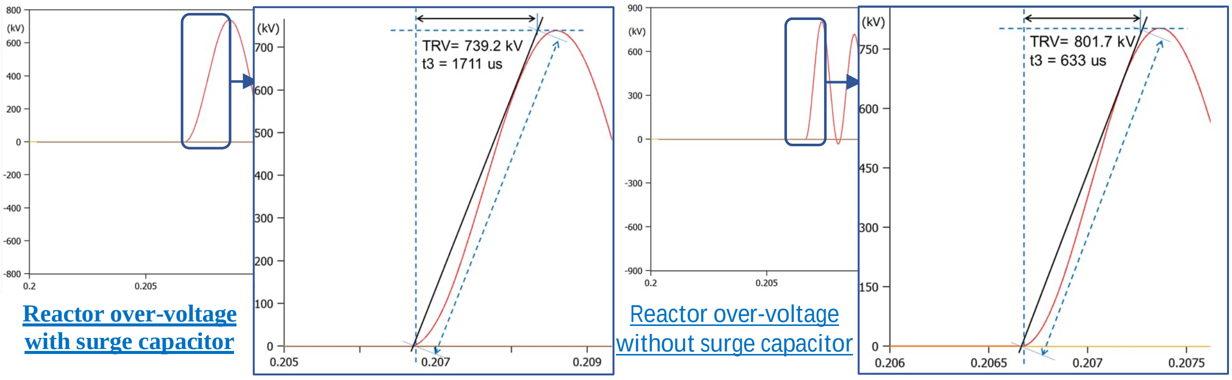
This Section presents TRV simulation analysis for the line reactor. To correctly estimate the TRV and its rise time, accurate modelling of overall system is necessary. The important components are bushing and winding to ground capacitances of the reactor, inductance of the reactor and source side stray capacitance. These parameters can be easily found out from routine test report of the reactor. The model & parameters of reactor used for performing the simulations are given in Figure II. As shown in Figure II, the reactor is equipped with the surge capacitor which will reduce the steepness of TRV during de-energization (the adoption of surge capacitor was requested by the user to minimize the risk of over-voltage especially in conjunction with shunt reactor switching). Source side capacitance can be considered ten times of the total capacitance to ground on the reactor side, as a good approximation [5]. System short circuit level and X/R ratio needs to be supplied by power system regulator. As the NGR of the line reactor is bypassed during line reactor de-energized, need not be considered in modelling. The simulations need to be performed with different values of chopping currents, which can be derived from results of reactor switching type test report as per IEC 62271-110 [5] and the calculation as per IEC 62271-306 and IEEE C37.015 [6][7].



Specifications of line reactor	
Source voltage	500 KV
KVAr rating	60 MVAr
Voltage rating (reactor)	500 KV
Current rating (reactor)	69.50 A
Z-reactor	7.75+ j4153.12 ohms
L-reactor	13.226 H
Bushing capacitance	525 pF/ph
Interwinding capacitance	3313.33 pF/ph
Surge suppressor	27000 pF/ph

Figure II - Simulation model for the TRV studies along with the parameters

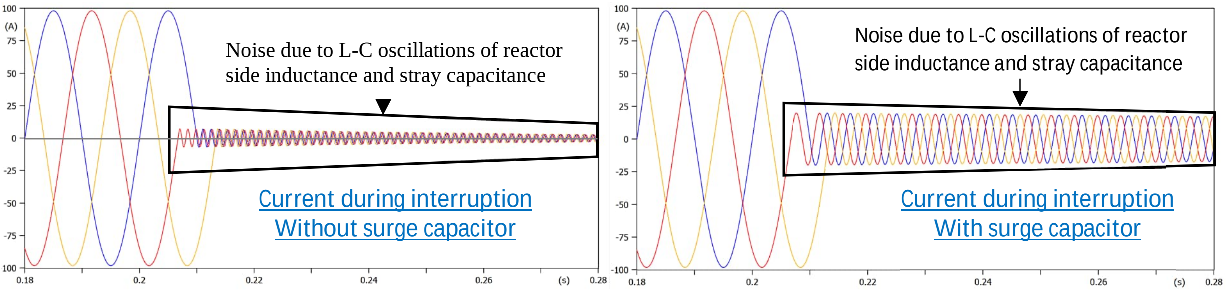
The TRV waveforms in the absence and presence of surge capacitor are shown in Figure III. The simulations have been performed for all levels of current chopping with surge capacitor and without surge capacitor for comparing the TRV severity. Figure IV shows currents of all three phases at the time of interruption measured through bushing CT of the reactor. As seen in that Figure, oscillatory noise is observed in the current waveform post its interruption if reactor bushing CT is used. This is due to L-C oscillation of the reactor inductance and capacitance of the bushing and the reactor windings. Also, the noise is increased in case of surge capacitor, as the overall capacitance on load side has increased causing oscillations with higher magnitude as well as decaying at slower rate, compared to the case without surge capacitor. The same are compensated with advanced digital filtering algorithms to avoid false re-ignition detection, which otherwise, may lead to unnecessary arcing time extinction by the controlled switching device (CSD).



Reactor over-voltage with surge capacitor

Reactor over-voltage without surge capacitor

Figure III - Over-Voltage during de-energization, with and without surge capacitor



Current during interruption
Without surge capacitor

Current during interruption
With surge capacitor

Figure IV - Current through busing CT during de-energization with & without surge capacitor

The LTB is rated for 550 kV with two interrupters per pole without grading capacitors, and one full pole has been tested for reactor switching type test report as per IEC 62271-110 [5]. Consequently, the chopping characteristics of the CB is derived, and the simulations have been performed for various chopping current levels for both cases: with and without surge capacitor. In Section 4 calculations related to chopping characteristics of this CB and arcing time required for the specific reactor application are presented.

Table *I* summarizes the results of the simulations. The highest chopping current chosen in simulations is based on the maximum chopping current derived from reactor switching test results. The type test for the reactor is performed without any additional surge capacitor. The initial arcing time setting for controlled switching of the LTB for this specific reactor configuration is found to be ~9.0 ms from the calculation results as well as TRV simulations, without considering surge capacitor. The evaluation of this arcing time is explained in the Section 4. Furthermore, it has also been observed that, for the cases without surge capacitor for all the analysed chopping currents, the over-voltage value is found to be less than the highest TRV observed during reactor switching type test. Therefore, the CB will be able to successfully interrupt the current with proper arcing time setting of CSD (refer Section 4) even without surge capacitor. Moreover, the adoption of surge capacitor was requested by the user to minimize the risk of over-voltage especially in conjunction with shunt reactor switching. Nevertheless, to be on safer side and the CB being capable to handle expected TRV, the arcing time setting of 9.0 ms, without consideration of surge capacitor is adapted for controlled switching system implementation.

Table I: Maximum over-voltage vs different chopping currents

Sr. No	**Chopping current (A)**	**With surge capacitor**		**Without surge capacitor**	
		Over-voltage peak (kV)	**Rise time (t3) (µs)**	**Over-voltage peak (kV)**	**Rise time (t3) (µs)**
1	0	739.19	1710.9	801.70	633.00
2	3	743.56	1608.0	839.55	525.00
3	5	751.83	1527.6	899.83	460.51
4	10	793.91	1350.4	1100.9	369.95

4. CHOPPING NUMBER AND RECOMMENDED ARCING TIME CALCULATION

This Section presents step by step evaluation of arcing time for specific line reactor without any surge capacitor, based on calculations as per IEC 62271-306 and IEEE C37.015, from the results of the reactor switching type test performed on full one pole of the CB as per IEC 62271-110 [5][6][7]. Generally, the chopping number varies based on the type of the circuit breaker. For SF6 puffer type CB the chopping number typically varies in range of 40000 to 200000 [4]. It may not be essentially constant but may vary with the arcing time. The maximum chopping number based on the type test report is found also to fall in this range. The CB has been successfully tested as per IEC 62271-110, for TRV peak with a margin of more than 25 %. Figure V presents the chopping characteristics of the CB pole under test.

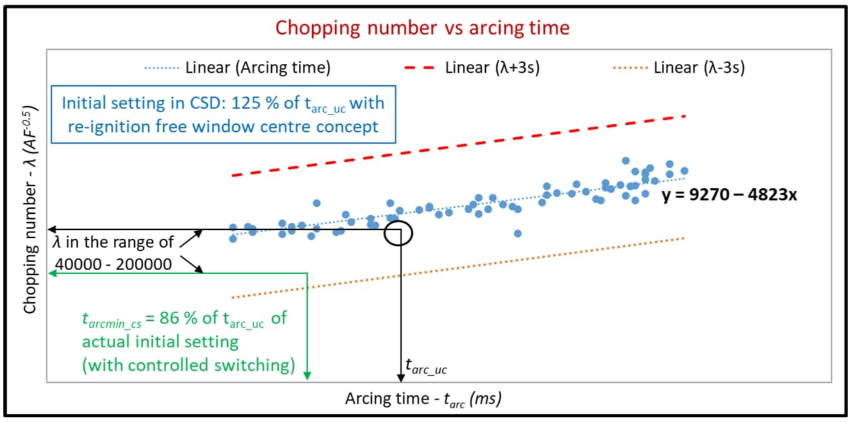


Figure V – Chopping characteristics of the CB

Step 1: The value λ and its statistical distribution is calculated from formulas shown below [7].

$$\lambda = A + Bt_{arc} + 2Se. \text{ Where, } A = \frac{1}{n}\sum_{i=1}^{n}\lambda_i - \left(\frac{B}{n}\right)\left(\sum_{1}^{n} t_{ai}\right) \;\&\; B = \frac{S_{xy}}{S_{xx}}$$

$$Sxx = n\sum_{i=1}^{n} t_{ai}{}^2 - \left(\sum_{i=1}^{n} t_{ai}\right)^2, Syy = n\sum_{i=1}^{n}\lambda_i{}^2 - \left(\sum_{i=1}^{n}\lambda_i\right)^2$$

$$Sxy = n\sum_{i=1}^{n} t_{ai}\lambda_i - \left(\sum_{i=1}^{n} t_{ai}\right)\left(\sum_{i=1}^{n}\lambda_i\right) \;\&\; Se^2 = \frac{1}{n(n-2)}\left(S_{yy} - B^2 S_{xx}\right);$$

Here, *Se* is Standard error of estimate

Consequently, parameter values are found as $A = -4823$, $t_{amax} = 13$, $B = 9270$ and $Se = 21555.34$
Here, maximum arcing time (t_{amax}) observed during type test among all four test duties is used to determine maximum value of chopping number λ_{max}..

Step 2: The value of RDDS is evaluated using the maximum of minimum arcing time for test duty 1 & 2 and corresponding peak recovery voltage using below equation.

$$RRDS = \frac{Ur}{t_{max}+t_p} = 0.38\,pu$$

Where, U_r is the peak recovery voltage from the type test duties
t_{max} is the min arcing time, with max U_r for operations without re-ignitions
t_p is the rise time from the type test.

Step 3: Using λ_{max}, overvoltage parameters k_{a_uc} (*pu*) and k_{rv_uc} (*pu*) without any overvoltage mitigation technique are computed.

$$k_{a_{uc}} = (1 + K) \times \left[\sqrt{1 + \frac{3N\lambda^2}{2\omega Q(1+K)}}\right] - K = 1.73\,pu \;\&\; k_{rv} = 1 + k_a = 2.73 \text{ pu}$$

Where, k_a = Suppression peak over-voltage across the reactor
k_{rv} = Peak recovery voltage across the CB.
N = Number of interrupters per phase used during testing = 1
K = Neutral shift factor = 0 for grounded reactor
ω = Angular frequency in rad/sec
Q = Three phase reactive power of the reactor in Var

Step 4: From the overvoltage parameters, minimum arcing time (t_{arc_uc}) required without any overvoltage mitigation techniques is calculated as shown below.

$$t_{arc\_uc} = \frac{k_{rv}}{RRDS_{pu}} = \frac{2.73}{0.38} = 7.2 \text{ ms}$$

Step 5: For this arcing time, the corresponding λ and corresponding overvoltage parameters are re-evaluated from the formulas of *Step 1* and *Step 3*, for the specific CB dielectric characteristics if controlled switching is employed as overvoltage mitigation technique.
This gives values of k_{a_cs} = 1.37 pu and k_{rv_cs} = 2.37 pu with controlled switching mitigation technique. Consequently, minimum arcing time for controlled switching (t_{arcmin_cs}) is found out…

$$t_{arcmin\_cs} = \frac{k_{rv_{cs}}}{RRDS_{pu}} = 86\,\% \text{ of } t_{arc\_uc}$$

Step 6: Using concept of re-ignition free window centre as described in Section 2 the arcing time setting for controlled switching device is found out as…

$$t_{arc\_cs} = t_{arcmin_{cs}} + \frac{Half\ cycle - t_{arcmin_{cs}}}{2} = 125\,\% \text{ of } t_{arc\_uc}$$

Considering above equation of t_{arc_cs} with safely margin and statistical variations in mechanical and dielectric characteristics of the CB, Arcing time setting (t_{arc_cs}) of 9 ms has been used as an initial setting in the CSD for the given reactor rating.

5. FIELD EXPERIENCE

In this Section, field experience during energization of the 60 MVAR, 500 kV line reactor, with NGR bypassed is discussed. As discussed in sections 3 & 4 the arcing time setting for the LTB connected to this reactor is set to 9.0 ms for all three phases and is compared with achieved arcing time for repeated operations. The controlled energization is aimed at phase wise voltage peak. Both controlled closing and opening operations are targeted for reverse phase sequence L1-L3-L2][1][2].

a) Interlocking logics to avoid reactor de-energization with NGR in system and operation with main CBs without controlled switching

Figure VI shows the overall SLD of the Line with Reactor Bay. As discussed in earlier sections, the controlled de-energization targets are derived considering the NGR bypassed, which otherwise will lead to higher TRV. Consequently, interlocking scheme needs to be implemented to ensure the de-energization always happens with NGR bypassed. Furthermore, the Main CB1 and Main CB2 (marked in BLUE) doesn't have controlled switching system (CSS). Only, the Reactor CB (marked in RED) is equipped with CSS. Therefore, the reactor de-energization needs to be always performed through the Reactor CB. Consequently, interlocking scheme must be implemented to avoid de-energization of reactor in deadline condition. This, otherwise, may lead to higher electrical wear due to un-intentional re-ignitions in the CB interrupting chamber.

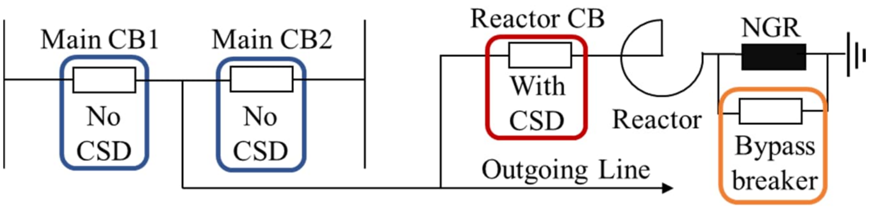


Figure VI : Overall SLD of the line with reactor bay

b) Troubleshooting for wiring error during commissioning

During very first live energization and de-energization operations, the switching sequence achieved was L3-L1-L2, even though output commands were in correct sequence of L1-L3-L2; as shown in Figure *VII*. During further investigation, the CT wiring was found to be erroneous. CT connections for phases L1 and L3 were found to be swapped, which later on had been corrected, and operations were repeated.

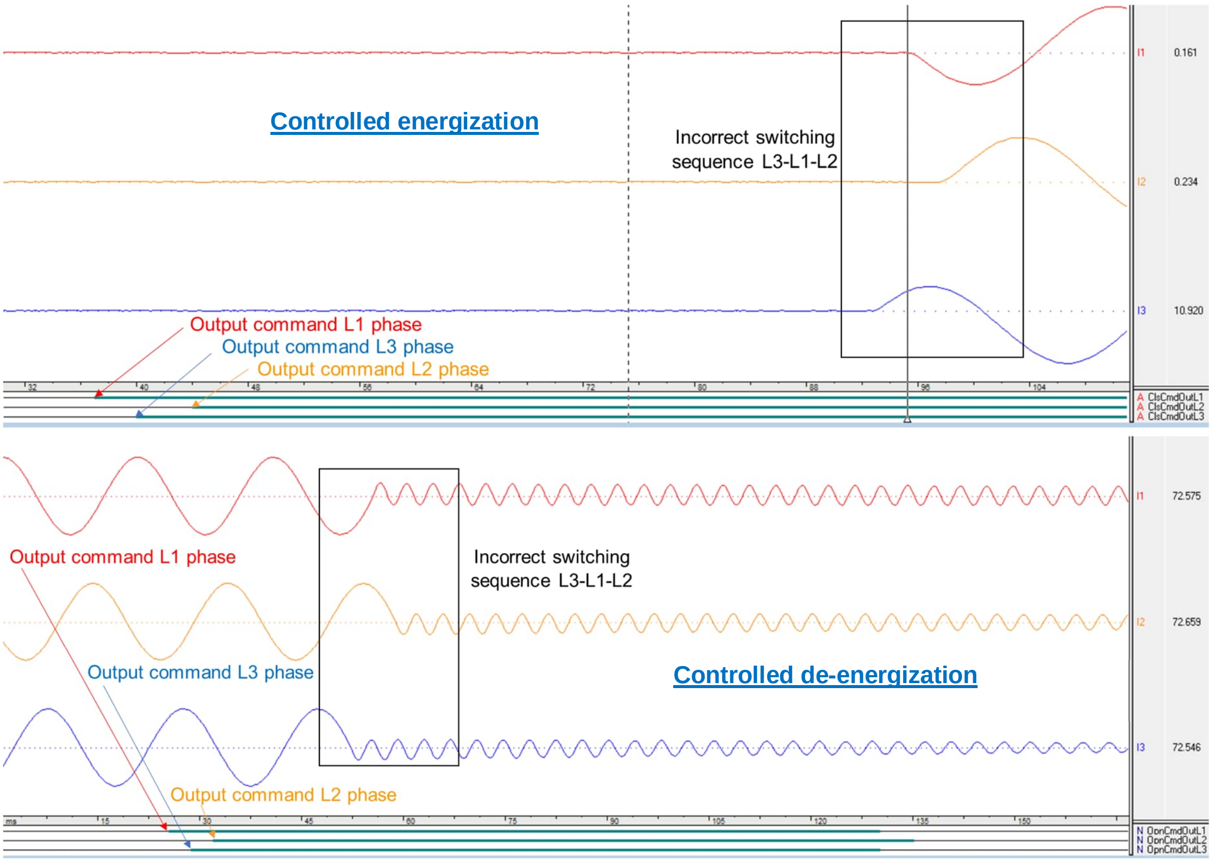
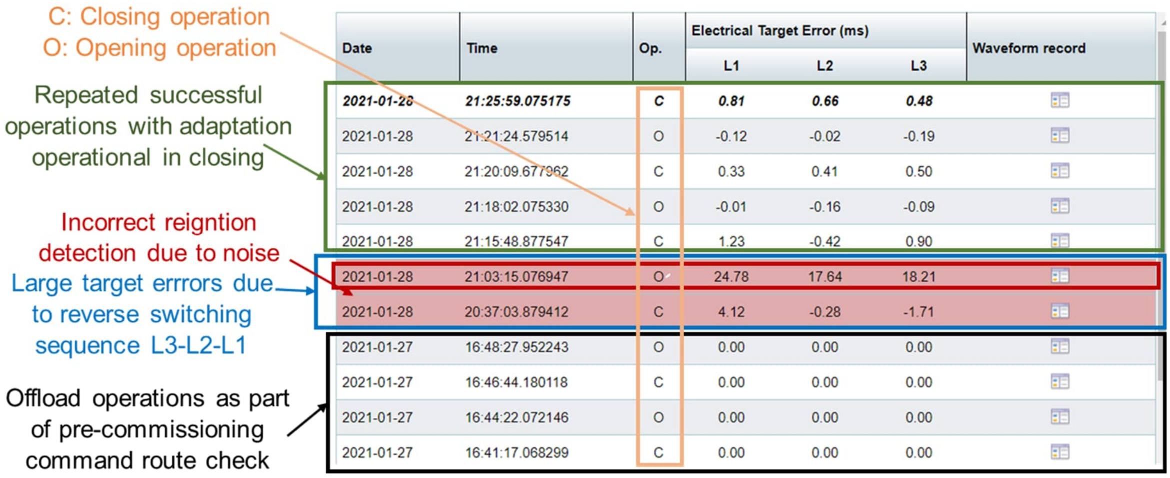


Figure VII : Operation with incorrect switching sequence L3-L1-L2

c) Correction for incorrect re-ignition detection due to noise

With change in wiring as explained in previous Section, the correct switching sequence L1-L3-L2 was obtained both in opening and closing. Moreover, current feedback from reactor bushing CT detected re-ignition incorrectly due to the noise interference formed by L-C oscillations of inductance of the reactor and reactor side stray capacitances. This was corrected by increasing the current detection threshold to eliminate the noise interference. Figure VIII shows the incorrect re-ignition detection (marked by RED) which also resulted into large target errors observed by CSD. After applying mentioned correction in detention threshold, this issue had been sorted out and the incorrect re-ignition detection had stopped. Consequently, target errors had also reduced to very low value in next operations. The offload operations (as part of pre-commissioning command route checks), successful controlled closing & opening operations with low target errors are marked in the Figure VIII. The adaptation function in closing has been achieved through current feedback in the CSS.



Date	Time	Op.	Electrical Target Error (ms)			Waveform record
			L1	L2	L3	
2021-01-28	***21:25:59.075175***	**C**	***0.81***	***0.66***	***0.48***	▤
2021-01-28	21:21:24.579514	O	-0.12	-0.02	-0.19	▤
2021-01-28	21:20:09.677962	C	0.33	0.41	0.50	▤
2021-01-28	21:18:02.075330	O	-0.01	-0.16	-0.09	▤
2021-01-28	21:15:48.877547	C	1.23	-0.42	0.90	▤
2021-01-28	21:03:15.076947	O	24.78	17.64	18.21	▤
2021-01-28	20:37:03.879412	C	4.12	-0.28	-1.71	▤
2021-01-27	16:48:27.952243	O	0.00	0.00	0.00	▤
2021-01-27	16:46:44.180118	C	0.00	0.00	0.00	▤
2021-01-27	16:44:22.072146	O	0.00	0.00	0.00	▤
2021-01-27	16:41:17.068299	C	0.00	0.00	0.00	▤

Figure VIII : Target errors in successive operations

Table II shows making targets and arcing times achieved for successive operations. Figure *IX* and Figure X show waveform records for the last successful controlled energization and de-energization operations respectively.

Table II: Performance during repeated operations

Controlled switching performance	Type	DR No	Phase 1	Phase 2	Phase 3
Achieved arcing times (ms) (Target: 9.0 ms for each phase)	Open	35	8.88	8.98	8.81
		33	8.99	8.84	8.91
Achieved making angles (deg°) (Target: 90° for each phase)	Close	36	102.26°	99.64°	96.63°
		34	93.67°	95.13°	96.43°

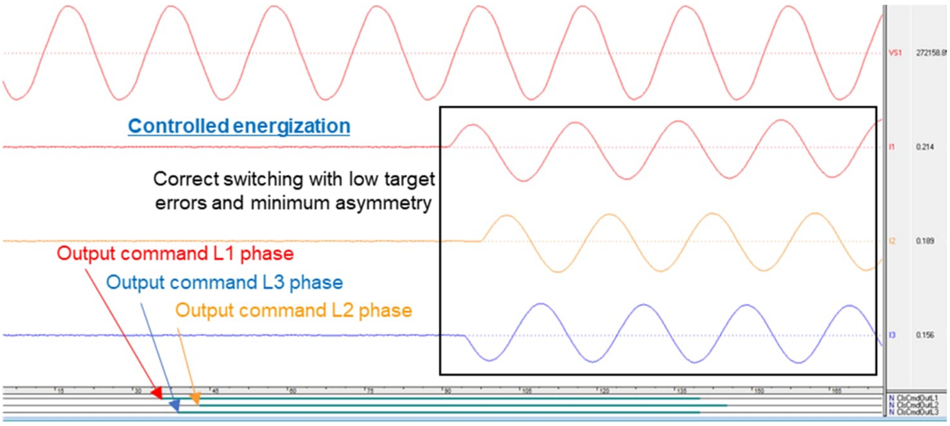


Figure IX: Controlled opening operation with incorrect switching sequence L1-L3-L2

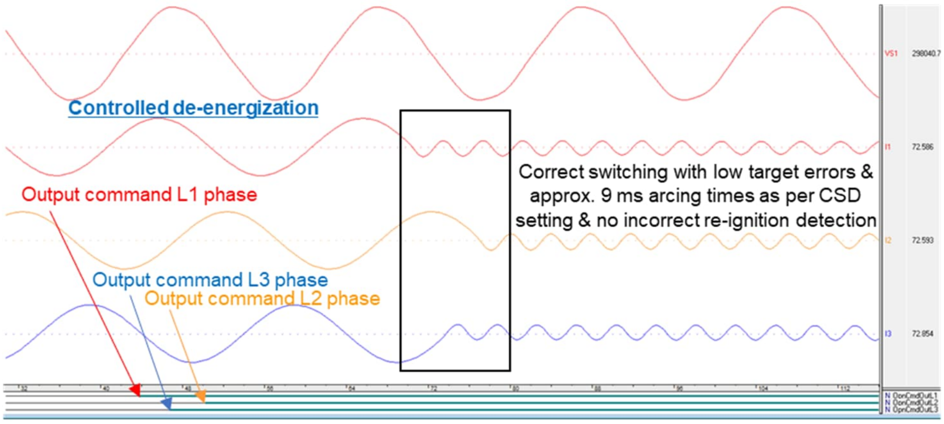


Figure X: Controlled opening operation with incorrect switching sequence L1-L3-L2

6. CONCLUSION

This paper presents controlled switching of the LTB for a 60 MVAR, 500 kV, 50 Hz line reactor, connected to 600 MW solar power generating plant. The controlled switching system is employed to reduce probability of unintentional re-ignitions and life cycle enhancement of the CB and the line reactor. The paper well elaborates the commissioning experience to troubleshoot wiring errors, settings adjustment to avoid incorrect detection of re-ignitions due to external noise with advanced digital monitoring algorithms. The switching performance for repeated operations during controlled energization and de-energization is presented with target errors and achieved arcing time for each operation. The method to derive arcing times settings for CSD using TRV simulations for different chopping currents, results from reactor switching type test report as per IEC 62271-110 and calculations as per IEEE C37.015 is explained for the specific line reactor. A surge capacitor has been provided on request from the user to minimize the risk of over-voltage especially in conjunction with shunt reactor switching. Consequently, the comparison of simulation results with and without surge capacitor is presented in the paper. Nevertheless, from type test results and simulation study it has been validated that the CB can interrupt the current even without the presence of surge capacitor. Therefore, the calculated arcing time from reactor switching type test results which has been performed without the surge capacitor, has been applied for setting of the CSD to be on safer side. The controlled switching is implemented only for dedicated CB of the line reactor, whereas the main CBs are without controlled switching. Also, the line reactor is provided with NGR which is bypassed during controlled de-energization of reactor through its dedicated CB. Necessary interlocking scheme to ensure the bypassing of NGR and avoiding purely reactive current interruption through main CB, have been presented at last.

7. BIBLIOGRAPHY

[1] CIGRE Technical Brochure 757, Guidelines and best practices for the commissioning and operation of controlled switching projects, Feb 2019.
[2] Controlled switching of HVAC circuit breakers, Guide for application lines, reactors, capacitors, transformers, Part 1, ÉLECTRA No. 183, April 1999.
[3] Controlled switching of HVAC circuit breakers, Guide for application lines, reactors, capacitors, transformers, Part 2, ÉLECTRA No. 183, August 1999.
[4] D.F. Peelo, R.P.P. Smeets and B.S. Sunga, “Shunt Reactor Stresses due to Switching”, Paper No. A2-304, Cigre 2008 Session.
[5] IEC 62271-110: High-voltage switchgear and controlgear – Part 110: Inductive load switching, 2017.
[6] IEC TR 62271-306:2012 High-voltage switchgear and controlgear - Part 306: Guide to IEC 62271-100, IEC 62271-1 and other IEC standards related to alternating current circuit-breakers.
[7] "IEEE Guide for the Application of Shunt Reactor Switching," in IEEE Std C37.015- 2017 (Revision of IEEE Std C37.015-2009, vol., no., pp.1-63, 16 March 2018, doi: 10.1109/IEEESTD.2018.8320990.