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Mitigation of Switching Transients Using Point-on-Wave Controlled Circuit Breaker Closing

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Highlights

- Effects of switching transients caused by the connection of different loads are presented
- The technique of controlled circuit breaker switching is described
- The effects of applying the technique were tested on a real-time simulator
- Compared controller and conventional shunt reactor circuit breaker switching

Abstract

Transmission lines loaded below their surge impedance present a significant source of reactive power in the network, that can lead to local voltage increase. Transmission system operators around the world turn to shunt reactors in combination with a conventional high-voltage circuit breakers to cope with voltage issues. Implementation of such solution introduces a significant increase in the number of switching transients. Using controlled switching technology (Point-on-Wave), through individual switching of each breaker pole at optimal time, it is possible to limit reactor inrush current when shunt reactor is energized and the recovery voltage when it is de-energized. The paper presents the negative effects of uncontrolled switching of shunt reactor on transmission system. The technique of controlling the timing of circuit breaker switching is presented as a tool to mitigate the negative effects of switching transients. The algorithm for controlled switching of the circuit breaker has been tested in the laboratory. The test setup consists of a Point-on-Wave Intelligent Electronic Device (IED) and HIL (Hardware-in-the-Loop) device used to simulate 400 kV shunt reactor and circuit breaker. The devices exchange information using IEC 61850 Sampled Values and GOOSE protocol. Experimental results confirm limitation of inrush current magnitude when shunt reactor is energized by controlled switching device.

Keywords

Controlled switching, Hardware-in-the-Loop, Point-on-Wave, Reactor inrush, Shunt reactor

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1. INTRODUCTION

Switching transients are a leading cause of excessive stress on power system equipment. For instance, the energization of a shunt reactor may lead to voltage waveform distortion and the occurrence of high-amplitude inrush currents, whereas capacitor bank energization may be accompanied by excessive overvoltages. Point-on-Wave controlled switching of CBs is employed to mitigate or eliminate switching transients arising from the energization and de-energization of shunt reactors, power transformers, and capacitor banks. In recent years, the application of this technique has expanded to both high-voltage overhead transmission lines and cable systems.

The combination of high-voltage (HV) circuit breakers (CB) with stable operating characteristics and modern microprocessor-based devices has led to the refinement of CB controller algorithms, simplified their integration into primary and secondary circuits, and enabled their application across a wide range of load types. Owing to the substantial increase in its deployment over the past years, controlled switching has become recognized as a reliable means of mitigating the effects of switching transients.

The controller optimizes the operating instant of the HV circuit breaker by introducing an appropriate command delay depending on the type of load being switched. Consequently, the adverse effects of switching operations within the power system are reduced. The main advantages of modern controlled switching are [1]:

- increased power system reliability through reduced voltage variations and lower harmonic distortion;
- improved power quality;
- extended equipment service life;
- mitigation of switching overvoltages and transformer magnetizing inrush currents.

1.1 Shunt reactor circuit breaker closing

Busbar voltage levels, together with frequency and the degree of harmonic distortion, are the key indicators of power quality. In transmission lines loaded below their surge impedance, the capacitances of long high-voltage transmission lines become increasingly significant, acting as substantial sources of reactive power and consequently causing local voltage rises above allowed limits. The operation of 400 kV and 220 kV transmission lines below their surge impedance loading (SIL) is a common occurrence both in Serbia and throughout the region.

Across the power system, voltage conditions are local in nature and, in many cases, cannot be regulated on a system-wide basis without the use of additional reactive power compensation devices.

A wide range of reactive power compensation technologies is currently available. These include synchronous condensers, Shunt Reactors, Static VAR Compensators (SVC), Static Synchronous Compensators (STATCOM), combined series-shunt FACTS controllers such as the Unified Power Flow Controller (UPFC) and the Interline Power Flow Controller (IPFC), as well as FACTS controllers including the Thyristor Controlled Phase Shifting Transformer (TCPST) and the Thyristor Controlled Voltage Regulator (TCVR).

The shunt reactor is one of the most widely employed reactive power compensation devices used by transmission system operators worldwide. It is used at selected grid nodes to maintain the desired voltage profile within the power system. Shunt reactors are manufactured as either single-phase or three-phase units, with or without tap changers (variable or fixed reactors). They are connected either directly to the HV substation busbar system through conventional CBs (Fig. 1) or to the tertiary winding of power transformers.

During periods of heavy power system loading and increased power transfer over high-voltage transmission lines, shunt reactors are typically disconnected from the network. Depending on voltage variations and the frequency of switching operations performed by shunt reactor CBs, a significant increase in the number of switching transients may occur at the point of connection. Such transients are one of the major sources of excessive stress on transmission system equipment, particularly on CBs. Furthermore, they adversely affect power quality and may lead to unnecessary responses of protective relays.

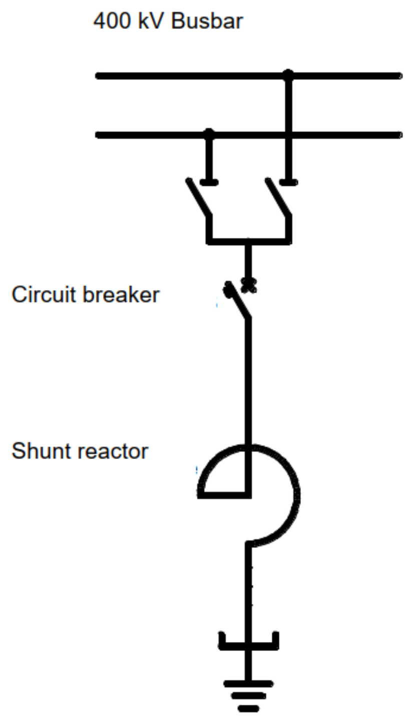

Figure 1. Direct connection of the shunt reactor to HV substation busbars

1.2 Power transformer circuit breaker closing

Power transformers are key components in ensuring the reliable operation of power systems. Owing to the significant increase in the demand for uninterrupted electricity supply over recent decades, high reliability requirements have been imposed on power transformers (hereinafter referred to as transformers).

Transformer magnetizing inrush current (Fig. 2), [2] is a phenomenon that occurs during the energization of an unloaded transformer. Under certain conditions, it may approach fault-current levels [3]. Although its impact is less severe than that of a fault current, the frequency of its occurrence and its duration may adversely affect the service life of HV equipment. In addition to the high magnitude of the inrush current, transformer energization may generate higher-order harmonics, adversely affect power quality, and lead to unnecessary responses of protection relays.

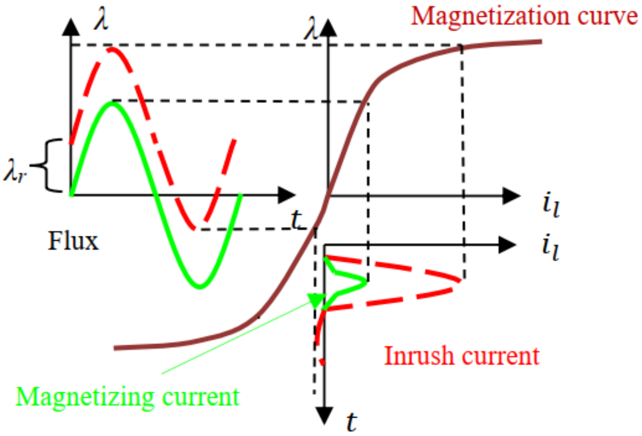

Figure 2. Transformer magnetizing current

Under steady-state no-load conditions, the flux is confined to the transformer magnetic core. Consequently, only a small magnetizing current is required, as shown in Fig. 2. It typically amounts to 1–2% of the transformer's rated current. For economic reasons, transformers are designed with the operating flux value close to the knee point of the magnetization curve.

Conventional energization of a transformer at a random instant may result in an asymmetric magnetic flux and core saturation. It is important to note that, following transformer de-energization, a portion of the magnetic flux remains in the core. This flux, referred to as remanent or residual flux (λ_r), may affect the amplitude of the magnetizing inrush current during subsequent transformer energization, depending on the voltage value at the instant of energization.

As transformers are an important component of the power system and their outage may be harmful during periods of heavy system loading, controlled switching can make a significant contribution to extending transformer service life.

1.3 Capacitor bank circuit breaker closing

When a capacitor bank or harmonic filter is de-energized, a certain amount of time is required for the residual energy stored in the bank to be discharged. In order to prevent re-energization of the capacitor bank before its complete discharge, a time-delay relay is typically applied to block the CB mechanism for a specified period. The built-in discharge resistors ensure that the capacitor bank is fully discharged before the blocking interval expires. A typical relay setting is 10 minutes from the instant of CB opening to the earliest possible subsequent closing operation.

A discharged capacitor bank effectively appears as a short circuit at the instant voltage is applied to its terminals, i.e., during CB closing. If energization occurs at voltage peak, voltage and current variations may be significant.

Depending on the grid configuration, overvoltages during capacitor bank energization may result in damage or even insulation failure of individual power system components such as transformers, insulators, cables, etc. For certain capacitor bank configurations, energization may lead to high-amplitude and high-frequency currents, which in extreme cases may compromise the mechanical integrity of both the capacitor bank and the CB.

These transients can be significantly mitigated by controlled switching of capacitor bank CBs such that energization occurs at a voltage zero crossing (Fig. 3), [4].

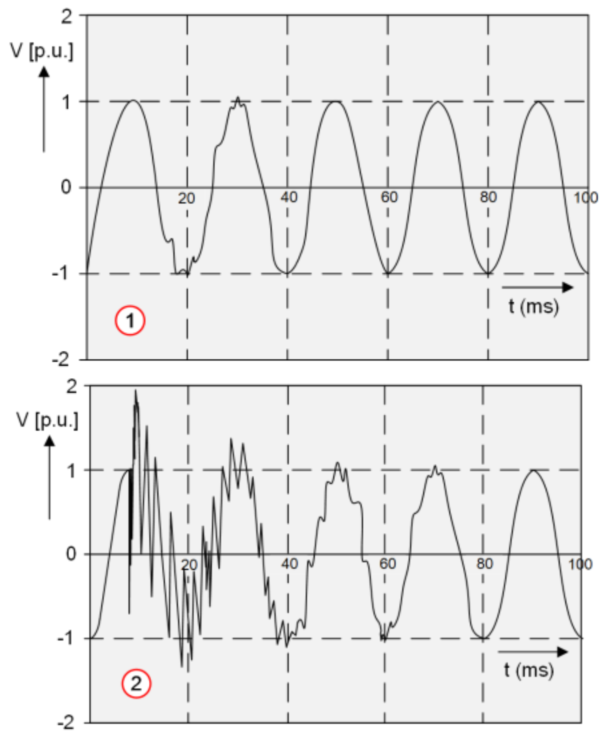

Figure 3. Voltage waveforms during controlled (top) and uncontrolled (bottom) capacitor bank switching

2. POINT-ON-WAVE CONTROLLED SWITCHING

One of the most widely used CB control techniques is based on selecting the optimum instant on the voltage waveform (Point-on-Wave). Such controlled switching can significantly reduce the adverse effects of switching transients that may occur during conventional random switching. The algorithm that determines the optimal switching instant for each phase based on the input parameters is implemented in the CB controller. The CB controller's characteristics are similar to those of modern microprocessor-based protection and control devices.

Upon receiving a CB closing command, the controller evaluates the optimum switching instant based on the measured voltage waveform and accordingly calculates the required command execution delay. In this way, each breaker pole closes independently at the optimum instant. The expected controller repeatability and the accuracy of current establishment relative to the optimum point on the voltage waveform are within ±1 ms. The controller monitors variations in the reference voltage frequency by detecting voltage zero crossings and, based on this information, determines the execution instant.

The principle of controlled closing, including all key time instants, is illustrated in Fig. 4, [5]. It can be observed that, before mechanical closing occurs, dielectric breakdown of the insulating medium occurs as the CB contacts approach one another, resulting in the establishment of an electric arc. This corresponds to the establishment of electrical contact between the CB poles, i.e., the electrical closing of the CB. The mechanical closing time ($T_{CLOSING}$) is a characteristic of the CB and can be measured. Arc initiation time (T_m) is an input parameter of the controller used to calculate the total time interval between issuing the command and establishing current, i.e., the electrical closing of the CB (T_{MAKING}).

The total delay introduced by the controller between the detection of the closing command and its execution (T_{total}) is equal to the sum of the voltage zero-crossing detection time (T_W) and the synchronization delay calculated by the controller (T_{cont}). The synchronization delay is used to ensure that current is established at the optimum instant on the voltage waveform, taking into account the calculated electrical closing time of the CB (T_{MAKING}).

Accordingly, the controller is designed to ensure the establishment of electrical rather than mechanical contact between the CB poles at the optimum instant, which is calculated as (1):

$$T_{MAKING} = T_{CLOSING} - T_m \quad (1).$$

The effectiveness of controlled switching is strongly influenced by the consistency of the CB's mechanical performance and its dielectric properties. Another significant factor is the controller's ability to accurately predict CB behavior throughout its service life.

Required CB characteristics for application in controlled switching schemes are:

- independent pole operation;
- stable closing time with high mechanical reliability;
- excellent dielectric properties, i.e., a steep Rate of Decrease of Dielectric Strength (RDDS).

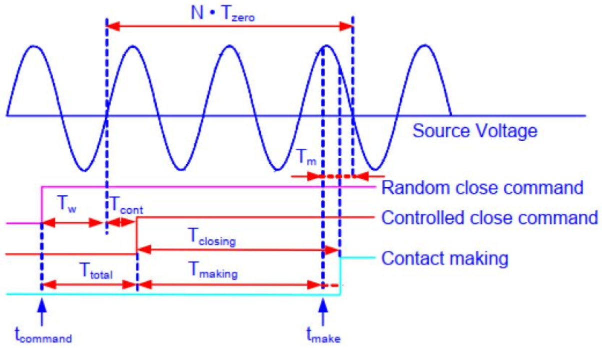

Figure 4. Key time instants of controlled circuit breaker switching

The operating times of CBs vary considerably depending on the breaker type as well as operating and ambient conditions. A portion of the total variation in CB operating time can be predicted. In addition to predictable variations, there are also variations that cannot be predicted because they are purely statistical in nature. The CB operating time can be expressed as (2):

$$T_{Oper} = T_{Nom} + \Delta T_{Comp} + \Delta T_{Drift} + \Delta T_{Statistic} \quad (2),$$

where:

- T_{Oper} – CB operating time;
- T_{Nom} – CB operating time under nominal conditions;
- ΔT_{Comp} – predictable variation that can be compensated for by the controller;
- ΔT_{Drift} – variation caused by CB aging and wear throughout its service life;
- $\Delta T_{Statistic}$ – statistical variation.

Therefore, there is a variable component of the CB operating time that can be predicted and accounted for within the controller (ΔT_{Comp}). Variations in CB operating time are caused by changes in control voltage and ambient temperature and, in the case of pneumatic CBs, by variations in pressure. Consequently, these variations can be predicted and their impact on CB operating time can be compensated for using sensor data available to the controller.

3. CONTROLLED CLOSING STRATEGIES FOR DIFFERENT LOAD TYPES

The following sections provide an overview of CB closure control strategies for the three principal load types. Depending on user requirements and the available controller functionalities, the controller can be configured for one of the standard load types and, if required, for both operating modes – closing and opening.

3.1 Controlled closing of shunt reactor circuit breakers

For an ideal shunt reactor, the current waveform lags the voltage at its terminals by approximately 90° [6]. Consequently, the instantaneous voltage reaches its maximum value when the current passes through zero, as shown in Fig. 5.

The magnitude of the reactor inrush current and the degree of voltage waveform distortion depend on the value of the system voltage at the instant the closing command is issued, as well as on the CB operating time.

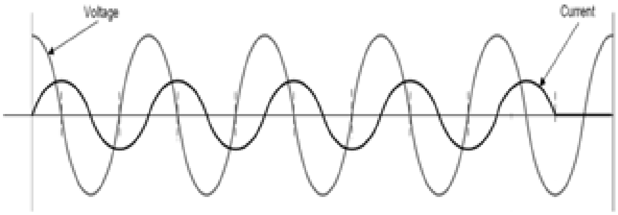

Figure 5. Shunt reactor current and voltage waveforms

Conventional shunt reactor energization at a random instant results in asymmetric currents and increased electromechanical stresses on both the CB and the reactor windings. In extreme cases, it may lead to saturation of current transformers and unnecessary trip of the earth-fault protection (50N/51N), which operates based on the current measured in the reactor neutral grounding conductor. If energization occurs when the voltage of one phase is close to zero, the switching transient will be most pronounced.

In three-phase systems, the phase-voltage peaks always occur in the inverse sequence (L1–L3–L2) relative to the phase sequence of the system voltages (L1–L2–L3) and are displaced by one-third of a cycle, corresponding to 6.66 ms in a 50 Hz system (Fig. 6).

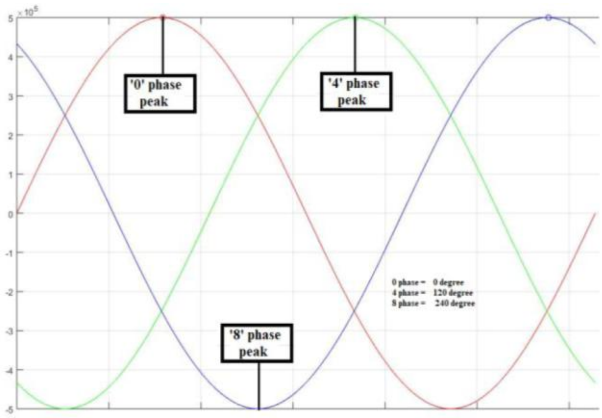

Figure 6. Three-phase voltage waveforms and their peak values

The optimal reactor energization strategy is based on closing each CB pole at voltage peak. Since the reactor is an inductive element, closing at voltage peak theoretically results in the minimum magnetic flux and, consequently, minimizes the inrush current. The reference instant is defined as the zero crossing of the phase L1 voltage waveform. The controller is designed to close the L1 pole with a phase shift of 90° relative to the reference instant, i.e., when the phase L1 voltage reaches its peak [7].

Phase L3 reaches its negative peak value next, at 90° + 60° = 150°, corresponding to a delay of 3.33 ms relative to phase L1. The final step is the closing of phase L2, with a theoretical delay of 90° + 120° = 210°, corresponding to 6.66 ms.

Although beyond the scope of this paper, it should be noted that shunt reactor CB opening may also be challenging. The difficulty arises not from the magnitude of the interrupted current, but from the energy stored in the reactor. Current chopping before the natural current zero crossing may result in pronounced high-frequency oscillations due to the energy stored in the reactor as an inductive element, together with the effect of parasitic capacitances. A sudden rise in the transient recovery voltage across the CB contacts may lead to arc re-ignition. It should be emphasized that modern SF_6 CBs are designed such that the probability of current chopping is minimal.

During shunt reactor de-energization, the controller initiates mechanical separation of the CB contacts immediately after current zero crossing. Following contact separation, the arc is stretched and current continues to flow until the dielectric strength becomes sufficient to extinguish the arc at the next current zero crossing. Once the arc is extinguished, the contact gap should be large enough for the dielectric strength to withstand the transient recovery voltage and prevent arc re-ignition.

3.2 Controlled closing of power transformer circuit breakers

In three-phase transformers assembled from three single-phase units, there is no magnetic coupling between the phases of a given winding. Consequently, from the perspective of the closing strategy, such transformers can be treated similarly to shunt reactors, with each phase being energized at the maximum value of its respective phase voltage.

Three-phase transformers with a common magnetic core and tank are commonly used throughout the region. Their primary and secondary windings may be connected in either wye (with grounded or isolated neutral) or delta configuration. In some cases, transformers are also equipped with a tertiary winding. When a transformer is equipped with a tertiary winding or is constructed as a three-phase unit with a common magnetic core, magnetic coupling exists between its phases, which affects the optimal energization strategy.

Table I presents the optimum closing instants of individual transformer CB phases depending on the winding connection and neutral grounding arrangement of the primary winding. The desired closing instant is expressed as the phase angle of each individual phase relative to the reference instant, or by the zero crossing of the phase L1 voltage waveform. The energization strategy specifies that the winding listed first in Table I is energized first.

The described closing technique is based on measurement of the reference voltage and does not take the transformer remanent flux into account.

Table I Optimum closing instant depending on the transformer winding connection

Winding connection	Phase L1 [°]	Phase L2 [°]	Phase L3 [°]
YNd; YNyn	90	180	180
Yd; Yy; Dd; Dyn; Dy	60	60	150

3.2.1 Transformer with grounded neutral (YNd; YNyn). The following strategy applies to transformers whose energized winding is wye-connected with a grounded neutral point. In this configuration, phase L1 is energized first at the voltage peak, when the flux reaches its minimum value. Magnetizing current is established in this phase and flows through the grounded neutral of the winding. The magnetizing current in phase L1 induces a symmetrical flux in phases L2 and L3, whose magnitude is equal to one half of the flux in phase L1 and has the opposite polarity. As a result, the magnetizing current established in phase L1 is 1.5 times higher than the steady-state magnetizing current when all three phases are energized.

The remaining two phases should be energized simultaneously with a 90° phase shift relative to the first phase. At this instant, the magnetic flux in phase L1 reaches its maximum value, while the flux induced in phases L2 and L3 reaches the level corresponding to the flux that would be produced in those phases by the system voltage at that instant. Although phases L2 and L3 are not energized at the peak of their respective system voltages, the switching instant corresponds to the maximum magnetic flux induced in those phases by phase L1.

3.2.2 Transformer with isolated neutral (Yd; Yy; Dd; Dyn; Dy). For transformers with an isolated neutral point, energizing a single phase cannot establish magnetizing current due to the isolated neutral or the delta-connected winding configuration (D). Therefore, phases L1 and L2 are energized simultaneously at the maximum value of the phase-to-phase voltage $U_{L1\text{-}L2}$, corresponding to a 60° phase shift relative to the reference instant (the zero crossing of phase L1 voltage).

At the instant of energization, the flux amplitude in phases L1 and L2 is zero. The voltage of phase L3 reaches its peak with a 90° delay (60° + 90° = 150° relative to the reference instant). Energizing phase L3 at this instant ensures that switching occurs at minimum flux.

3.3 Controlled closing of capacitor bank circuit breakers

When voltage is applied to a discharged capacitor bank, which is a low-impedance element, at the instant of voltage maximum, a pronounced transient process occurs, which is characterized by overvoltages and high-amplitude inrush currents.

To minimize the potential difference during controlled closing, energization should take place as close as possible to the voltage zero crossing of each phase. Table II presents the optimal closing instants of the individual CB poles depending on the grounding arrangement of the capacitor bank neutral point.

Table II Optimum closing instant depending on the capacitor bank grounding

Capacitor bank neutral point	Phase L1 [°]	Phase L2 [°]	Phase L3 [°]
Grounded	0	120	60
Isolated	180	90	90

3.3.1 Capacitor bank with grounded neutral. For capacitor banks with a grounded neutral point, each phase is energized independently at its respective voltage zero crossing (Fig. 7). The zero crossing instants of the phase-voltage waveforms are mutually displaced by 60°.

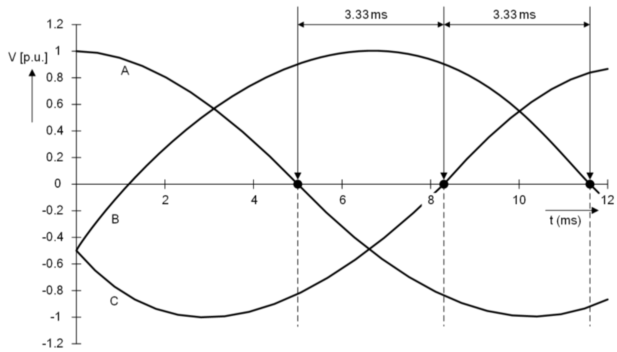

Figure 7. Optimal switching instants for a capacitor bank with grounded neutral

The closing sequence of the CB poles shown in Fig. 7 is L1–L3–L2, with a time shift of 3.33 ms for a 50 Hz system and 2.77 ms for 60 Hz systems.

3.3.2 Capacitor bank with isolated neutral. For capacitor banks with an isolated neutral point, zero-voltage closing is interpreted differently from that used for capacitor banks with a grounded neutral point. Instead of energizing each phase independently at its phase-voltage zero crossing, two phases are energized simultaneously (Fig. 8) at the instant when their phase voltages are equal. This corresponds to the instant when the phase-to-phase voltage $U_{L2\text{–}L3}$ is equal to zero, resulting in zero-voltage energization of phases L2 and L3. A quarter of a cycle later, phase L1 is energized at the instant its phase voltage passes through zero.

The key instants identified in Fig. 8 are:

1. controller reference instant – zero crossing of the phase L1 voltage;
2. energization instant of phases L2 and L3;
3. energization instant of phase L1.

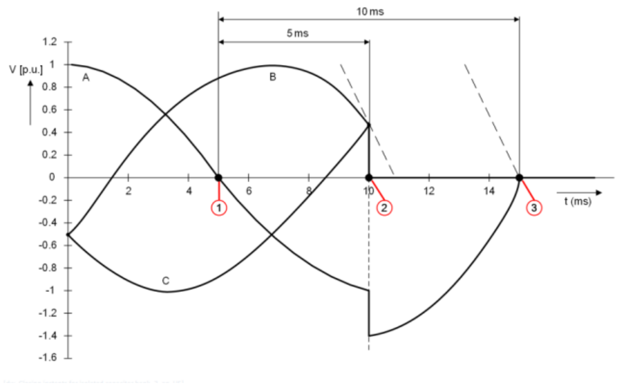

Figure 8. Optimal switching instants for a capacitor bank with isolated neutral

4. LABORATORY SETUP

The effects of controlled CB closing were tested under laboratory conditions using a 400 kV shunt reactor as a case study. A laboratory setup (Fig. 9) was assembled for this purpose, consisting of a microprocessor-based protection and control device acting as the CB controller, a network communication switch, and a Hardware-in-the-Loop (HIL) device implementing models of a 400 kV shunt reactor, a high-voltage (HV) circuit breaker, and a portion of the surrounding power system.

The process bus network (implemented in accordance with the IEC 61850 standard) was simplified and configured using a star topology with a single network switch. In addition to the information exchange function, the switch provides time synchronization via the IEEE 1588 Precision Time Protocol (PTP). which is required for generating valid Sampled Values.

4.1 Shunt reactor model

Within the HIL device, a 400 kV bay was modeled, comprising a shunt reactor, a CB, current transformers, and other relevant HV equipment. The shunt reactor is a nonlinear, wye-connected unit with a solidly grounded neutral. Its technical characteristics are summarized in Table III. The magnetic circuit is of a five-limb design and incorporates an air gap.

Table III Shunt reactor technical characteristics

Rated voltage	420 kV
Rated frequency	50 Hz
Rated power	250 Mvar
Rated current	343.66 A
Winding connection	Yn
Winding inductance	2.25 H (per phase)

The reactor CB was modeled as a switching device with independently controlled poles. Its technical characteristics are provided in Table IV.

Table IV Circuit breaker technical characteristics

Mechanical closing time of the circuit breaker	50 ms
Mechanical opening time of the circuit breaker	30 ms

The network was modeled as a Thevenin equivalent derived from the short-circuit power at the reactor point of connection. The magnitude and damping of reactor inrush currents are primarily determined by the reactor parameters and the CB closing instant. By contrast, network strength and electrical distance to the source are secondary and mainly affect the overvoltage magnitude rather than the effectiveness of controlled closing.

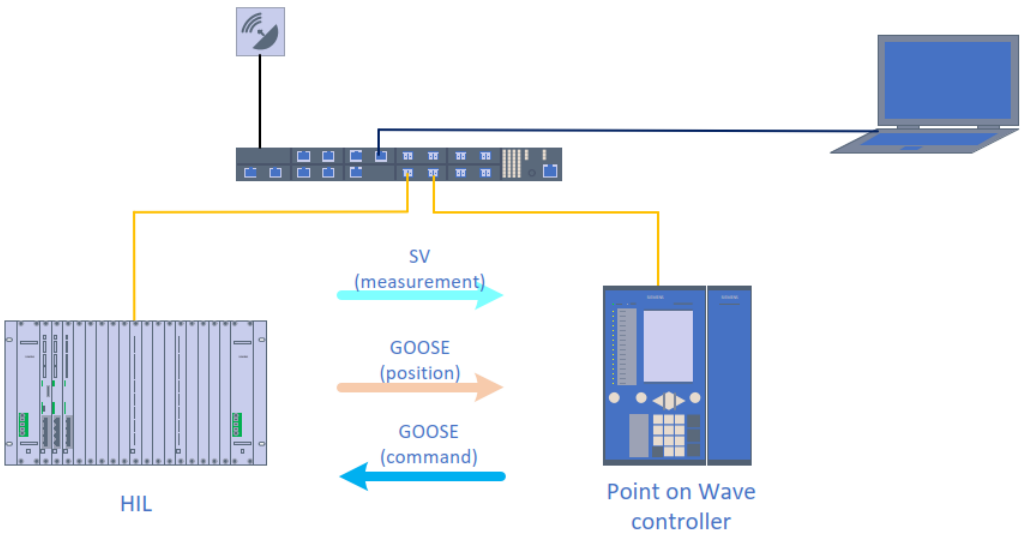

Figure 9. Block diagram of the laboratory setup

Including circuit resistance introduces additional transient damping and a slight shift of the optimum closing instant. However, it has no significant impact on the controlled switching strategy, nor does it significantly increase the error in determining the optimum closing instant.

The primary equipment model implemented on the HIL device was developed subject to the following limitations:

- there are no variations in operating times between individual CB poles, they always correspond to the predefined values in all three phases;
- a communication delay exists between the instant a command is issued by the controller and its reception by the HIL device. Since information exchange between the controller and the HIL device is performed via GOOSE messages, the maximum delay is limited to 1 ms;
- there is no time delay between electrical and mechanical contact establishment of the CB poles, as confirmed by the absence of arcing in the oscillographic records.

4.2 Circuit breaker controller

The controller functionality was implemented within a microprocessor-based protection and control device (Fig. 10). By analyzing the reference voltage waveform and taking into account configured parameters, such as the selected switching strategy and CB timing characteristics, the controller calculates and applies the optimum delay for energizing the CB closing coil.

The reference signal is obtained from a voltage transformer connected to the 400 kV busbars. It is generated by the HIL platform acting as an SV publisher, while the controller receives it as an SV subscriber through the process bus network. Instantaneous voltage values are transmitted as IEC 61850-9-2 Sampled Values (SV) streams.

Table V summarizes the SV stream contents. Each measurement stream contains samples of the three phase voltages and the residual voltage, together with the phase currents measured at the shunt reactor terminals and the calculated neutral current.

Information regarding the status of the switching equipment is generated by the HIL device in the form of GOOSE messages, while the controller transmits GOOSE messages to the HIL device containing commands for individual CB poles.

Table V Content of Sampled Values stream

IEC 61850-9-2 Sampled Value stream							
Busbar voltage				Shunt reactor current			
U_{L1}	U_{L2}	U_{L3}	$3U_0$	I_{L1}	I_{L2}	I_{L3}	$3I_0$
Pos 1	Pos 2	Pos 3	Pos 4	Pos 5	Pos 6	Pos 7	Pos 8

Monitoring functions are enabled in the controller. Following each closing operation, the controller collects and analyzes the recorded data and issues an alarm if abnormal conditions are detected. The following functions have been implemented:

- recording the measured inrush current and comparing it against a predefined threshold, which in this case is set to twice the rated current of the reactor;
- measuring the mechanical closing time of the CB using information from the breaker auxiliary contacts modeled in the HIL device and recording any deviation from the configured value;
- measuring the electrical CB closing time by detecting current establishment and recording any deviation from the calculated value.

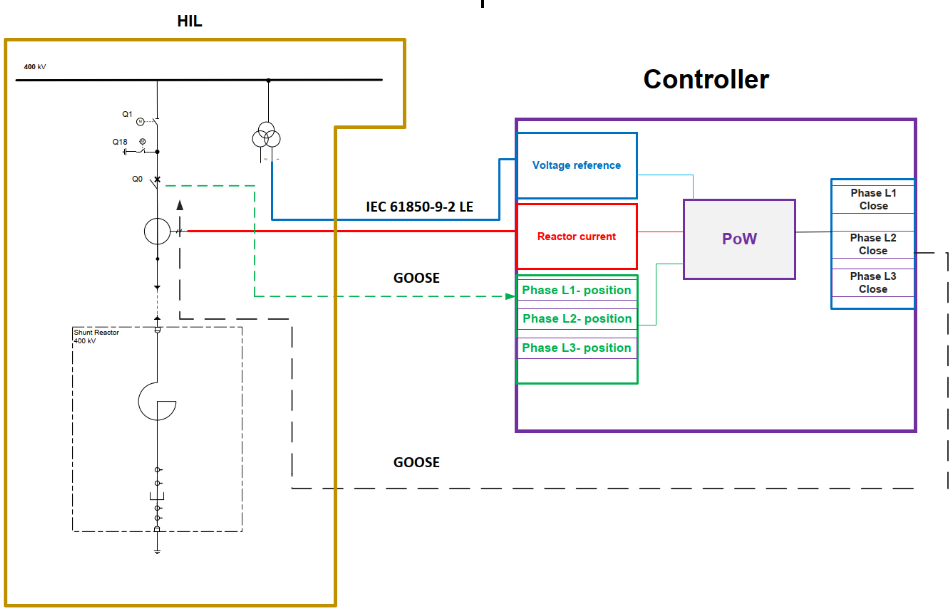

Figure 10. Logical diagram of information exchange between the HIL device and the controller

5. TEST RESULTS

The effectiveness of the proposed technique was evaluated by comparing three different shunt reactor CB closing strategies using the laboratory model:

1. Conventional closing – simultaneous random closing of all three CB poles;
2. Controlled closing with each pole closed at the most unfavorable instant;
3. Controlled closing with each pole closed at the optimum instant.

Following each closing, oscillographic records and event logs were retrieved from the controller. These data were used to evaluate and compare the voltage and current waveforms of the shunt reactor, as well as the status indications of the CB auxiliary contacts.

5.1 Conventional circuit breaker closing

Conventional closing is characterized by the simultaneous issuance of closing commands to all three CB poles. In this case, the controller acts as a passive element and introduces no intentional delay between the receipt of a closing command from the control system and its execution. Since the command may be issued at any point, both the degree of asymmetry and the magnitude of the inrush currents depend on the instant at which the command is issued, as well as on the CB operating time. The oscillographic record (Fig. 11) confirms the simultaneous closing of all three CB poles.

The record clearly shows the dependence of the inrush current value on the instantaneous value of the system voltage at the moment of closing. A pronounced inrush transient of long duration is observed. This leads to noticeable distortion of voltage and current waveforms, as well as high inrush currents.

In this case, the peak values were $I_{L1} = 1.63\ kA$, $I_{L2} = 2.88\ kA$ and $I_{L3} = 955\ A$. The peak current value in the reactor neutral conductor was $I_N = 1.86\ kA$.

5.2 Controlled closing of each circuit breaker pole at the most unfavorable instant

Since the shunt reactor is an inductive element, controlled closing of each CB pole at the voltage zero crossing in each phase represents the most unfavorable case. Under these circumstances, waveform distortion is most pronounced.

Although the controller aims to mitigate energization transients, improper parameter settings may lead to closing conditions under which adverse effects are maximized.

The voltage waveforms are shown in Fig. 15, while the current waveforms are presented in Fig. 16.

This switching condition produces exceptionally high peak inrush currents of $I_{L1} = 3.47\ kA$, $I_{L2} = 3.64\ kA$ and $I_{L3} = 3.80\ kA$. The asymmetry of the inrush currents becomes particularly pronounced, causing the reactor grounding conductor current to reach a peak value of $I_N = 3.33\ kA$ (Fig. 12).

Due to the duration of the inrush transient, unnecessary responses of the earth-fault protection may occur, depending on its operating time delay.

In addition, the high X/R ratio causes the DC component of the current to decay slowly, increasing the likelihood of current transformer saturation.

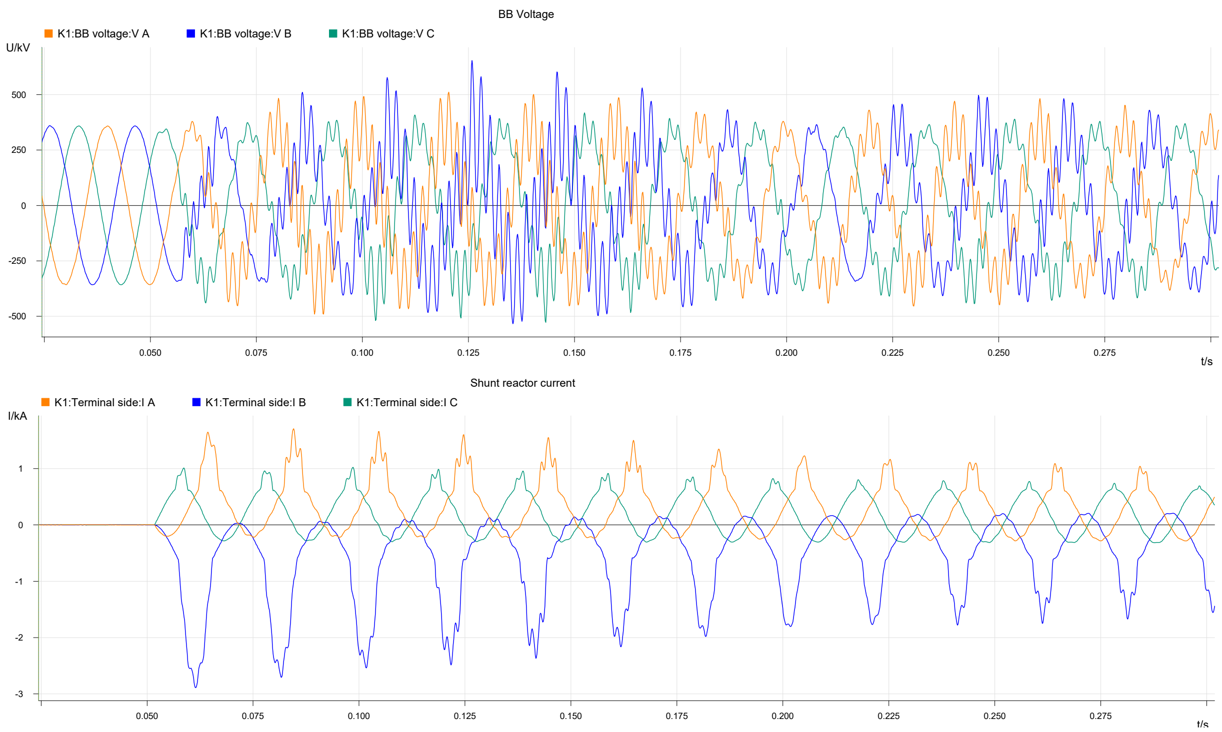

Figure 11. Voltage and current waveforms during conventional switching

5.3 Optimum circuit breaker closing

The optimum shunt reactor energization strategy is based on closing each CB pole at the voltage peak. The reference instant is defined as the zero crossing of the phase L1 voltage waveform. The controller is intended to close the L1 pole with a phase shift of 90° relative to the reference instant, i.e., when the phase L1 voltage reaches its maximum value.

The next voltage peak is reached by phase L3, with negative polarity, at 90˚ + 60˚ = 150˚, with a delay of 3.33 ms relative to phase L1. The final step is the closing of phase L2 with a theoretical delay of 90º + 120º = 210º, corresponding to 6.66 ms.

Fig. 13 shows the sequential issuance of pole-closing commands. Analysis of the event records confirms that no deviations from the theoretically calculated controller operating times were observed.

Analysis of the oscillographic records shows timely closing of each pole. This is illustrated by the phase L1 record shown in Fig. 14, where current establishment occurs at the voltage peak.

By comparing the voltage waveforms (Fig. 15) and current waveforms (Fig. 16), it can be concluded that controlled switching completely eliminates the inrush transient. With optimum switching, voltage waveform distortion is hardly noticeable, while higher harmonics are effectively eliminated.

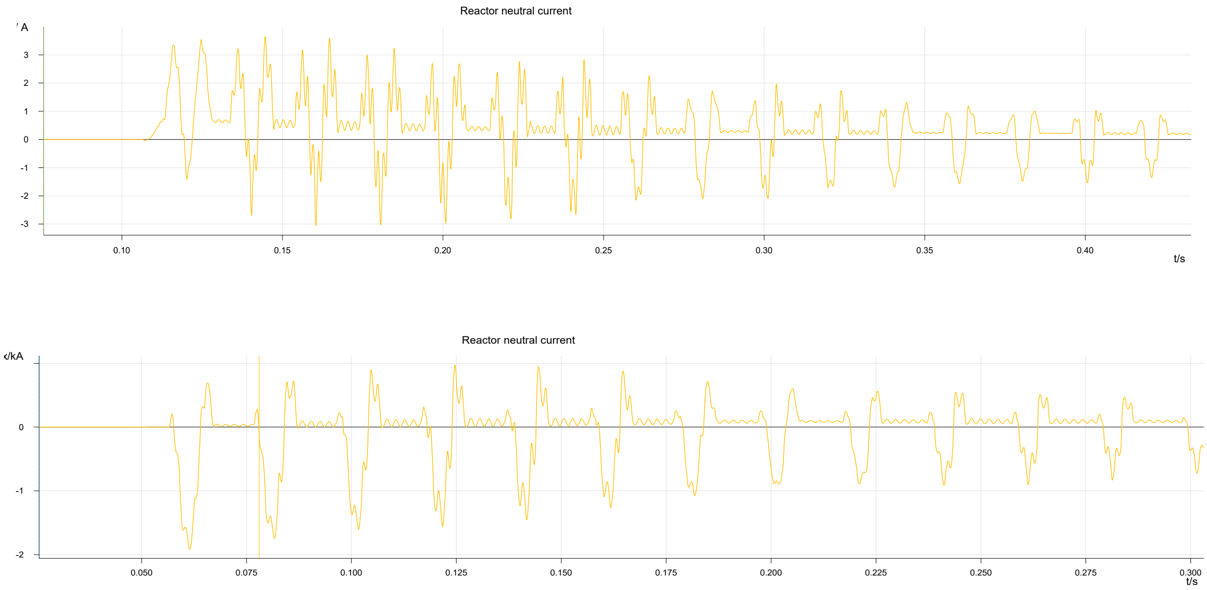

Figure 12. Reactor neutral current waveform under the most unfavorable (top) and conventional (bottom) switching conditions

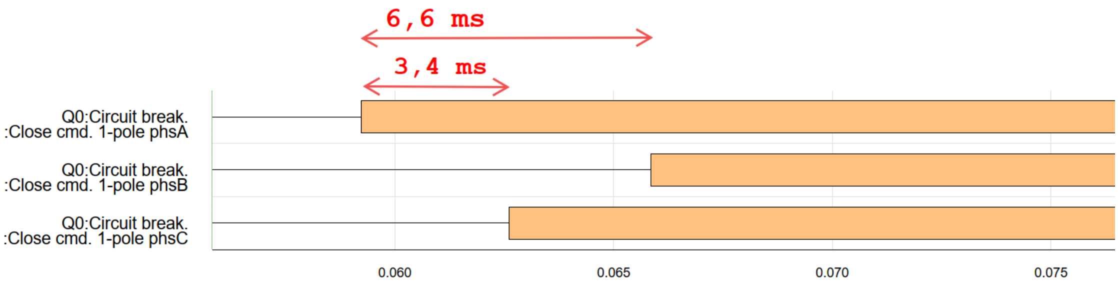

Figure 13. Sequence of circuit breaker pole closing commands

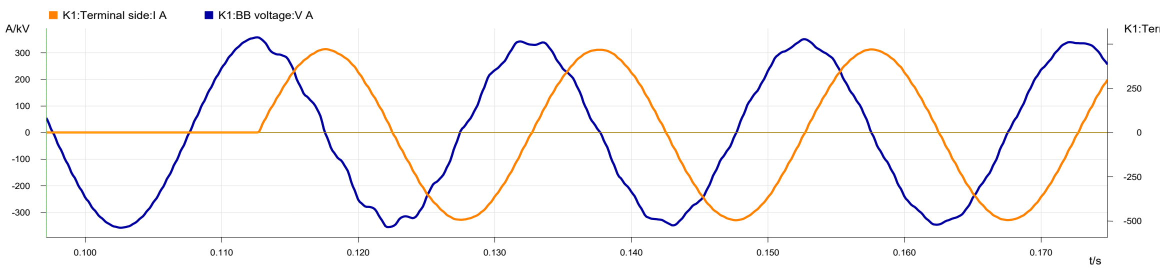

Figure 14. Current establishment instant relative to the voltage waveform

Controlled closing limits the peak inrush currents to $I_{L1} = 469\ A$, $I_{L2} = 523\ A$ and $I_{L3} = 488\ A$. The RMS current during the first cycle is approximately 340 A, corresponding to the rated current of the shunt reactor.

The controlled-closing results exhibit symmetrical current waveforms and no observable DC component. By eliminating the transient period, the peak current in the reactor grounding conductor is limited to $I_N = 358\ A$ (Fig. 17).

The oscillographic records indicate that the transient impulse of the neutral current lasted approximately 6 ms under optimum switching conditions, whereas in the most unfavorable case it exceeded 500 ms. The exact duration could not be determined because the recording window was limited.

The effectiveness of controlled closing in limiting reactor inrush currents can be evaluated by comparing the measured results obtained for all three switching strategies investigated on the laboratory model (Table VI).

The maximum measured inrush current was 3.80 kA, while controlled closing limited this value to a maximum measured current of 0.52 kA. Similarly, the suppression of current asymmetry reduced the peak current in the reactor grounding conductor from $I_N = 3.33$ kA to $I_N = 0.36$ kA.

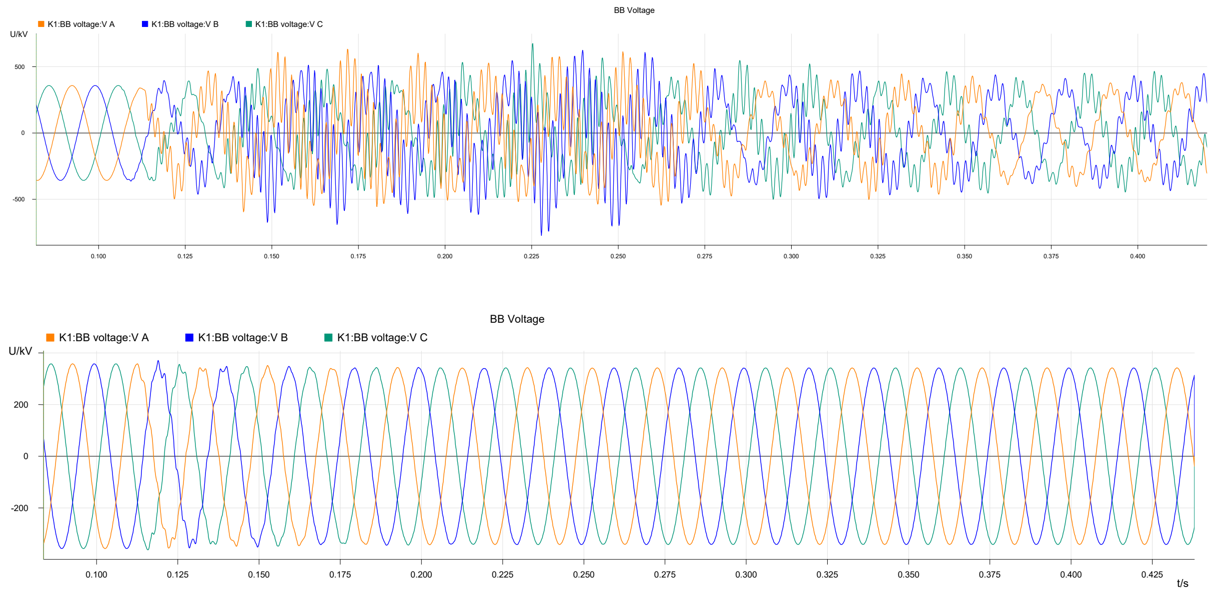

Figure 15. Voltage waveforms under the most unfavorable (top) and optimum (bottom) reactor switching conditions

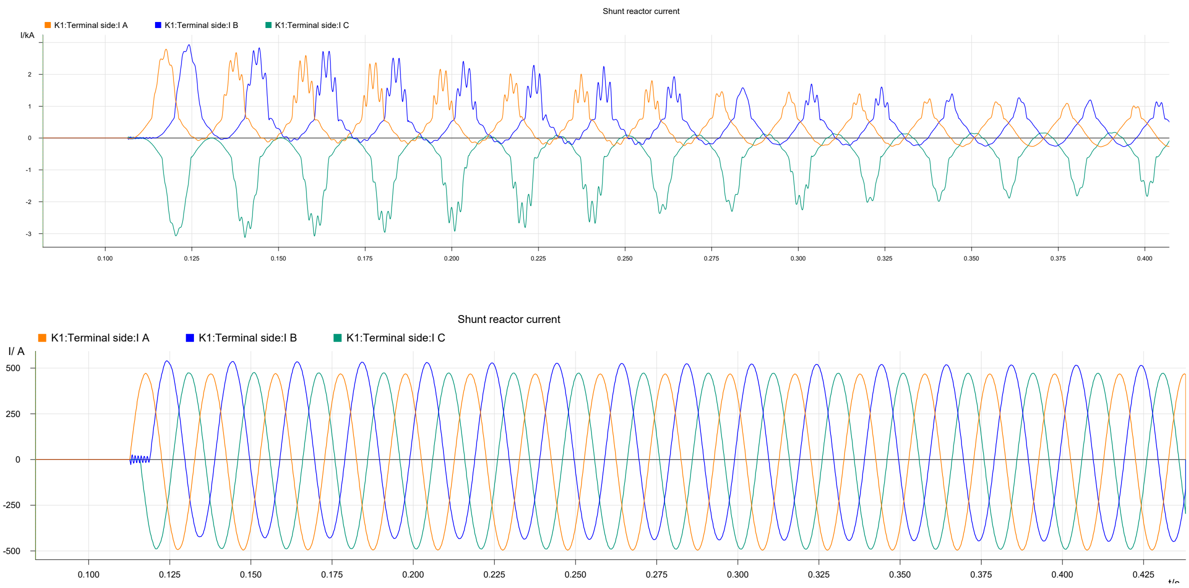

Figure 16. Current waveforms under the most unfavorable (top) and optimum (bottom) reactor switching conditions

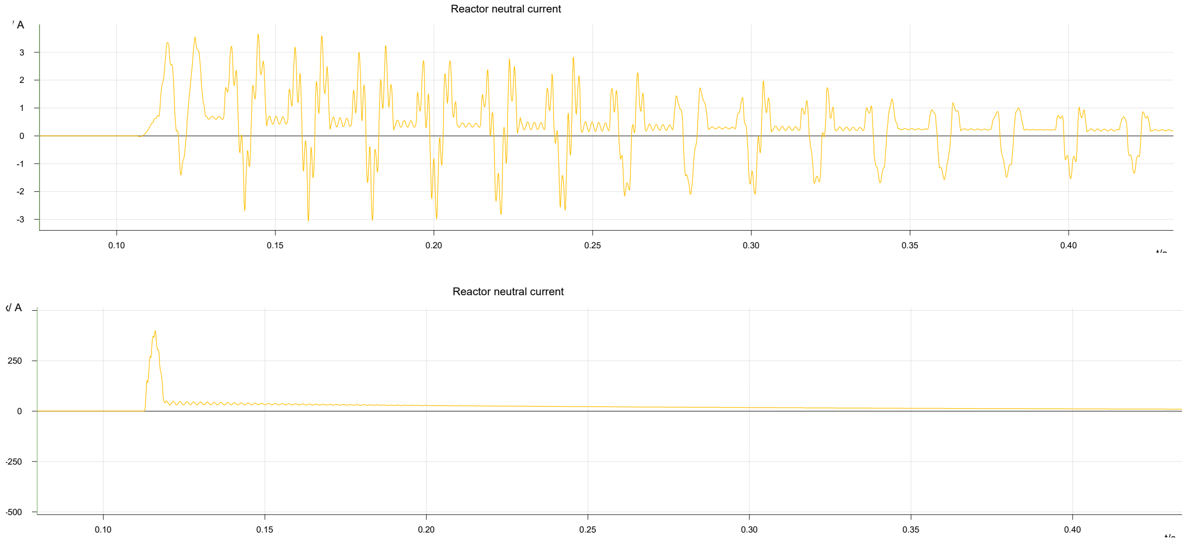

Figure 17. Reactor neutral current waveform under the most unfavorable (top) and optimum (bottom) switching conditions

Table VI Shunt reactor inrush current

Shunt reactor inrush current	Phase L1 [kA]	Phase L2 [kA]	Phase L3 [kA]	I_N [kA]
Conventional – uncontrolled circuit breaker closing	1.63	2.88	0.95	1.86
Controlled - closing at the most unfavorable instant	3.47	3.64	3.80	3.33
Controlled - closing at optimal instant	0.47	0.52	0.42	0.36

6. CONCLUSION

Conventional (uncontrolled) CB closing is inherently random, meaning that the waveforms depend on the voltage at the moment of closing. In general, uncontrolled closing results in significant voltage waveform distortion accompanied by a long-lasting transient process and high inrush currents, which may reach up to ten times the rated current. Neutral grounding conductor currents of up to 1.86 kA were observed and, due to the prolonged duration of the inrush transient, may lead to unwanted operation of protection functions.

Testing controlled switching at the most unfavorable instant proved particularly valuable. This approach provided consistent results, enabling an assessment of the benefits of optimum Point-on-Wave switching. The test results enabled the authors to gain insight into the critical importance of accurate coordination between controller parameters and CB timing. Each 1 ms deviation between the set and actual CB closing time corresponds to approximately 18° deviation from the optimum switching instant. The use of a controller with incorrectly configured parameters results in more severe switching transients compared to those resulting from random closing.

Analysis of the oscillographic records obtained for the three investigated 400 kV shunt reactor CB closing strategies, including a comparison of current and voltage waveforms as well as measured inrush current values, confirmed that controlled switching can completely eliminate the inrush transient.

Continued technological advances are increasing the flexibility, reliability, and ease of application of controlled switching systems while simultaneously reducing implementation costs. This enables their broader deployment across power systems.

Finally, it should be noted that shunt reactor de-energization also presents several technical challenges, including current chopping, transient recovery voltage control, and arc re-ignition. These issues will be addressed in the authors' future research.

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BIOGRAPHIES

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Ograničenje sklopnih tranzijenata primenom tehnike kontrolisanog uključenja prekidača (Point-on-Wave)

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Originalni naučno-istraživački rad

Ključne poruke

- Predstavljeni efekti sklopnih tranzijenata usled priključenja različitih vrsta opterećenja
- Opisana tehnika kontrolisanog uključenja prekidača
- Efekti primene tehnike testirani na simulatoru u realnom vremenu
- Izvršeno poređenje sa konvencionalnim uključenjem prekidača kompenzacione prigušnice

Kratak sadržaj

Podopterećena prenosna mreža, odnosno vodovi opterećeni ispod svoje prirodne snage, značajan su izvor reaktivne snage sa posledicom lokalnog povećanja napona. Kao sredstvo regulacije naponskih prilika operatorima prenosnog sistema širom sveta nametnula se upotreba paralelno priključene prigušnice (engl. Shunt Reactor) u kombinaciji sa konvencionalnim visokonaponskim prekidačem. Implementacija ovakvog rešenja dovodi do značajnog porasta broja sklopnih tranzijenata. Primenom tehnike kontrolisanih operacija prekidača (Point-on-Wave), kroz pojedinačno uključenje/isključenje svakog pola prekidača u najpovoljnijem trenutku, u velikoj meri se mogu ograničiti vrednosti udarne struje uključenja prigušnice i povratnog napona pri isključenju. U radu su predstavljeni negativni efekti nekontrolisanog priključenja paralelnih prigušnica na prenosni sistem. Opisana je tehnika kontrole trenutka uključenja prekidača kao mera ograničavanja negativnih uticaja sklopnih tranzijenata. Funkcija kontrole prekidača i potencijalni efekti primene u prenosnoj mreži su testirani u laboratorijskim uslovima. Laboratorijska postavka se sastoji od mikroprocesorskog uređaja za zaštitu i upravljanje kao kontrolera i simulatora u realnom vremenu (HIL – Hardware-in-the-Loop) na kome je realizovan model 400 kV paralelne prigušnice i prekidača. Uređaji komuniciraju korišćenjem IEC 61850 Sampled Values i GOOSE protokola. Dobijeni rezultati potvrđuju skoro potpunu eliminaciju udarnog perioda prilikom uključenja kompenzacione prigušnice.

Ključne reči

Kompenzaciona prigušnica, kontrolisano uključenje prekidača, simulacija *Hardware-in-the-Loop*, udarna struja prigušnice

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