FACTORY AND FIELD VERIFICATION TESTS OF CONTROLLED SWITCHING SYSTEM

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SUMMARY

Controlled switching systems (CSS) with 145kV, 245kV, 362kV and 550kV independent-pole-operated gas circuit breakers and the controller have been developed and have demonstrated their performance. The circuit breakers, sensors and controller, and the integrated systems were verified according to CIGRE recommendations for development, routine and type tests. The CSS applied to a capacitor bank and a reactor bank was tested in the field. Complete system performance checks also have been conducted according to CIGRE recommendations during the commissioning test.

The characteristics of circuit breakers such as the rate of decrease of dielectric strength, the mechanical scatter of the operating times and the idle time dependence are essential to the success of a CSS. A practical approach of determining the optimum close target is proposed based on the circuit-breaker characteristics identified in the type tests. Any drift in operating times associated with the past operations and the delay caused by the idle time of the mechanism should be included in the compensation algorithm along with the variation of the operating times due to the operating conditions. Innovative mechanisms such as stable high-pressure hydraulic operating mechanisms and low-friction spring operating mechanisms have been developed and shown to minimize the delay of the operating time of the first operation after a long idle time. The proposed method of determining the optimum close targets can be applied for the CSS. Its effectiveness was demonstrated by the controlled switching tests at site.

The paper describes the results of evaluation tests and field verification tests related to a CSS.

Keywords: Controlled switching, Gas circuit breaker, Testing, Commissioning test, Operating time, Idle time, Rate of decrease of dielectric strength, Compensation, Capacitor switching

1. Introduction

Controlled switching systems (CSS) have become an economical solution and are commonly applied to reduce switching surges for all switching cases. The number of installations has increased rapidly due to satisfactory service performance since the late 1990's [1]. CIGRE WG13.07 published an application guide [2] based on an international survey of the field experience and proposed testing requirements and their procedure [3].

The guide emphasizes the importance of compensation for the variations of the operating time because a CSS requires accurate operation consistency during the lifetime of a circuit breaker. Variations of the operating times due to operating conditions such as ambient temperature, control voltage and stored energy of the drives can be compensated by the controller using the measured dependence of variations of the operating times for these conditions. The operating time should also be compensated to account for the deviations of the operating time caused by consecutive operations and the first operation after a long idle time.

Recent research reveals that the closing time for some hydraulic operating mechanisms was significantly delayed after idle times of only a few hours [3]. Accordingly, the idle time compensation is essential for even a daily-operated CSS.

This paper presents typical results of factory evaluation tests as well as field verification tests required for the components and the integrated system. This scenario is based on the complete CSS produced by one manufacturer. CIGRE WG13.07 also proposed the method of determining the optimum close targets based on the pre-strike characteristic of a gas circuit breaker measured for different closing angles at rated voltage. The optimum close targets can be also determined using the measured RDDS and the mechanical scatter of the operating time characterized in the type tests [4] [5].

Table 1 CIGRE WG13.07 Recommendation for Evaluation Tests

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

2. Testing Requirements

CIGRE WG13.07 recommended evaluation and verification tests required for the individual components, i.e. the circuit breakers, the sensors and the controller, as well as the integrated system. The testing items are summarized in the Table 1.

Basic characteristics of the circuit breaker including the rate of decrease of dielectric strength (RDDS), the rate of rise of dielectric strength (RRDS) and the mechanical scatter of operating times should be evaluated with the existing type tests specified by IEC62271 / ANSI C37.04. A daily-operated circuit breaker applied to capacitor bank or reactor bank switching should have extended mechanical endurance of class M2. Long-term (idle time up to 1000 hours) tests demonstrating the idle time dependence of circuit breakers are also required.

The necessary type tests for the controllers and the sensors can be classified into two main categories: functional performance tests and hardware conformance tests. These tests should be performed according to IEC61000 / ANSI C37.90 specified for relay systems.

Finally, field verification tests are required to ensure satisfactory in-service performance of the complete CSS. Since the commissioning tests are limited to the minimum possible in order to avoid inconvenience in the utility's network, the tests consist of a limited number of point-on-wave operations of the circuit breaker by means of the controller.

All the testing requirements for a CSS were successfully completed according to the CIGRE recommendations. Minimum requirements and procedures of the CIGRE recommended tests were evaluated by reviewing typical testing results obtained in the development, routine, and type tests.

3. Individual Component Testing

The components are normally tested in the factory as a part of the routine and type tests. CSS requires some additional tests to measure RDDS, RRDS, variations of operating time on the operating conditions, idle-time dependence of the operating time, etc. The characteristics of the individual components that determine the CSS performance are described.

These measurements of RDDS, RRDS and the mechanical scatter of the operating time provide important information for considering the suitability and the close target for any switching application. Especially, the optimum close targets for the CSS should be determined by factory evaluation tests in order to avoid inconveniences to network operation, because the switching tests can cause significant voltage disturbance for the system.

A determination method for the optimum close target using the characteristics of the RDDS and the mechanical scatter of the closing times is more convenient when considering switching applications for different voltages. The effectiveness of the method was demonstrated using several gas circuit breakers.

3.1 Variation of Operating Times on Conditions

Most controllers have conditional compensation functions that can adjust for the variation of the operating time depending on ambient temperature, control voltage and mechanism pressure. The variations of closing and opening times from the average values at standard conditions and their deviations were investigated in detail for different control voltages and different ambient temperatures using several spring operated gas circuit breakers.

The control voltage and temperature dependence of the closing and opening times for 40 operations are evaluated. Figure 1 shows the average closing and opening times, and their deviations using a 145kV gas circuit breaker. It can be seen that conditional compensation can control the switching instants within ±1.0ms deviations around the targets.

The driving force of the open and close coils varies with the control voltage and the ambient temperature. The friction of the moving parts of the circuit breaker mainly varies with the ambient temperature. The dimensional difference within the circuit breaker design allowance causes a slight change for the average operating time. However, variations of the operating times caused by

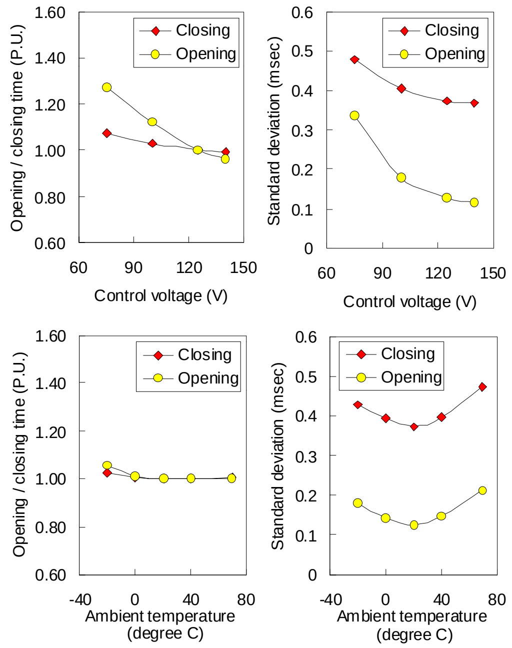


Fig.1 Variations of the closing and opening times from the average values at standard conditions and their deviations

operating conditions were confirmed to have the same trend in values among different units. Therefore the controller using the measured dependence of the operating times on these conditions can compensate these variations. In the case of hydraulic or pneumatic operating mechanisms, variations of the operating times caused by changes of the mechanism pressure can also be compensated in a similar way.

Figure 2 shows the difference from the standard operating time plotted in the form of a mesh map. The mesh map can be programmed into the controller as a set of common characteristics for the same type of breaker, which will have a slightly different average operating time due to the design tolerances.

3.2 Measurements of RDDS

The mean value of the decrease of the withstand voltage during the closing stroke can be approximated by a linear function of time when the contacts are close to touching. The slope is proportional to the mean value of the closing velocity and to the gas pressure of the circuit breaker. Therefore, the RDDS can be obtained by the measurement of the pre-strike voltages and the pre-arcing times for different closing instants (electrical phase angles from 0 to 360 degrees) at the rated voltage.

Figure 3 shows a typical measurement of pre-strike characteristic plotted with a cycle of power frequency for a 145kV gas circuit breaker at rated control voltage and rated operating pressure. The pre-arcing time is the duration from the instant of pre-strike to contact touch. Each gradient is calculated by the inverse-tangent value of the pre-strike voltage divided by the pre-arcing time, which gives the RDDS value of the circuit breaker.

Figure 4 shows the experimental results of the RDDS measurement normalized by the gradient of the system voltage at the zero crossing point. The normalized RDDS shows an average value of 1.37 for positive polarity and 1.34 for negative polarity, except for the instants around voltage zero where the error becomes relatively large due to the difficulty of obtaining a precise measurement of the short pre-arcing time. The normalized RDDS shows little dependence on the polarity of voltage.

CIGRE WG13.07 proposed a test sequence for evaluating RDDS by conducting closing tests every four points with a step of 15 electrical degrees. However, the results show that the random closing test is adequate for this evaluation.

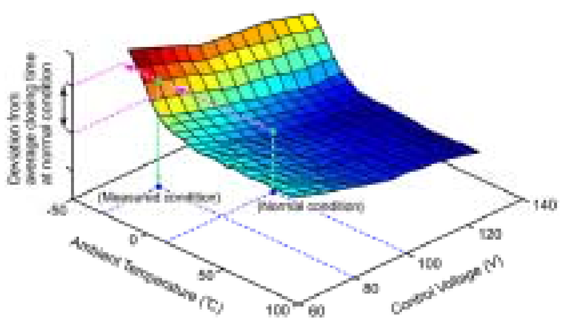


Fig.2 Deviation from the average closing time at the standard conditions plotted as functions of the ambient temperature and the control voltage.

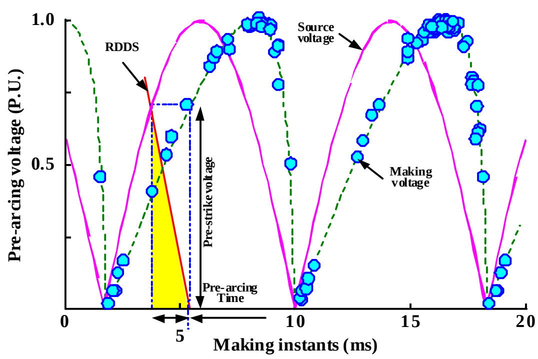


Fig.3 Typical pre-strike voltage against closing instant

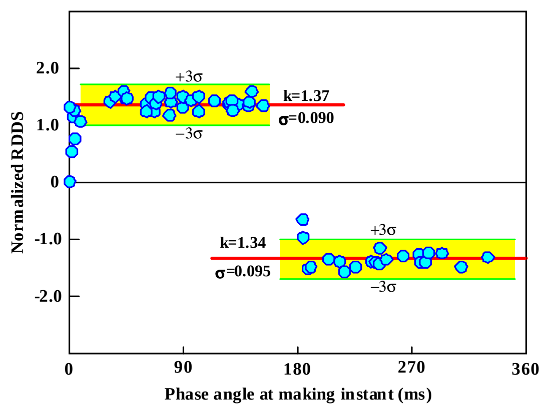


Fig.4 RDDS measurement obtained by pre-strike test

3.3 Determination of Optimum Close Targets

The optimum close targets for voltage zero are calculated in Figure 5 when the RDDS and the mechanical scatter of the closing time are known. The close targets for voltage zero provide the instants when the maximum making voltage becomes the minimum value considering the scatter of the closing time. On the contrary, the close targets for voltage peak provide the instants when the minimum making voltage becomes the maximum value. The close target should be moved forward from voltage zero instants with an increase of the mechanical scatter and with a decrease of the RDDS. When the measured mechanical scatter is 0.9 ms (three times its standard deviation) and the normalized RDDS is 1.35, the optimum close target of 16 electrical degree of the phase angle for voltage zero is obtained from the figure 5.

Figure 6 shows the maximum making voltage for voltage zero targets as functions of the RDDS and the mechanical scatter. The maximum making voltage becomes higher as the RDDS becomes smaller or the mechanical scatter becomes larger. A making voltage less than 0.5 P.U. cannot be realized by the CSS when the standard deviation of the mechanical scatter is larger than 1.2ms. Accordingly, the information shown in figure 6 is particularly important for the switching applications whose close target is voltage zero. The maximum making voltage is estimated as 0.4 P.U. when a circuit breaker

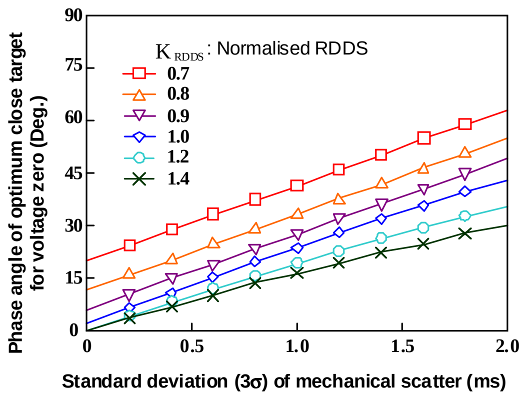


Fig.5 Optimum close target for voltage zero calculated as functions of RDDS and Mechanical scatters

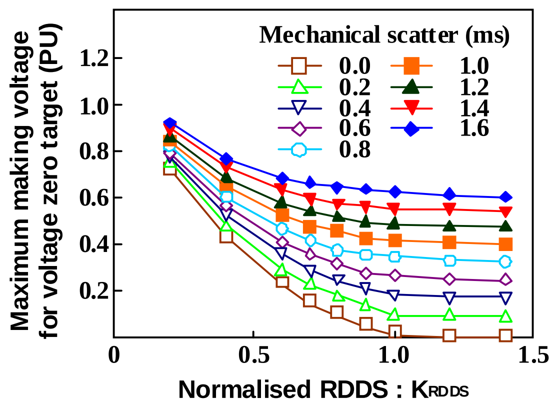


Fig.6 Dependence of maximum making voltage on RDDS and mechanical scatters in case of voltage zero targets

with the normalized RDDS of 1.35 and a standard deviation of 0.3ms is applied to the switching applications for voltage zero targets.

3.4 Measurements of RRDS

Circuit breakers applied to controlled reactor opening are required to be reignition-free within a half cycle before interruption. Similarly, the mean value of the increase of the withstand voltage during the opening stroke can be approximated by a linear function of time when the contacts are separating from each other at the average opening velocity. The RRDS can be roughly given by (RRDS value) = (RDDS value) x (Opening velocity) / (Closing velocity). However, the minimum arcing times for both voltage polarities should be evaluated by small inductive interruption tests.

The reignition behavior of circuit breakers was evaluated according to the procedure of the small inductive switching test described in IEC61233. Figure 7 shows the cold recovery characteristic of a 550kV one-break gas circuit breaker with a pneumatic operating mechanism. The plots show the breakdown voltage obtained from inductive switching tests at breaking current of 315A. Thermal restrikes were observed at very short arcing times when the contacts were separated just after the current zero. A capacitive current switching test was also performed and confirmed the circuit breaker to be restrike-free for the transient recovery voltage equal to the rated phase voltage multiplied by 1.4 under minimum operating air pressure (1.18MPa) and minimum SF_6 gas pressure (0.5MPa). The cold recovery reignition-free window for a high pressure at rated gas density of 0.6MPa and a high speed at rated operating air pressure 1.47MPa, is evaluated as shown in figure 7 based on these tests. Since the minimum arcing time shows a slight difference for the polarity of the voltage, the controlled arcing time should be longer than 5ms.

3.5 Determination of Optimum Open Targets

Since reignition overvoltages are normally more severe than chopping overvoltage in the case of reactor opening, the use of controlled opening increases the arcing times within the window allowing reignition-free operations with a certain safety margin. Conclusively, the

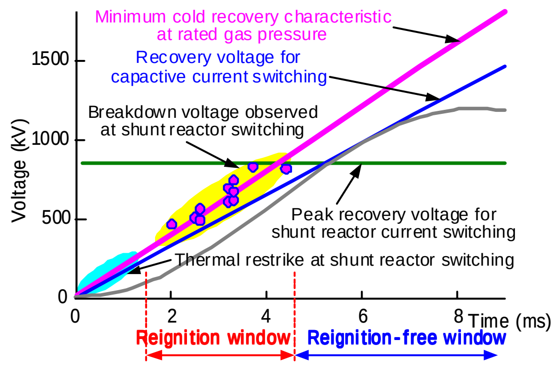


Fig.7 Dielectric recovery (RRDS) characteristic of the 550kV one-break GCB

optimum open target is normally in the middle of the minimum and maximum arcing times. The thermal restrike region, which varies with the breaking current and the circuit conditions, can be included in the open targets.

3.6 Idle Time Dependence

Idle time dependence of the drive is one of the major causes for controlled switching failure reported in [3]. A few milliseconds delay of the closing time resulted after only a few hours of idle time since the last opening operation [3]. This indicates that even a daily-operated circuit breaker requires idle time compensation if the circuit breaker shows this dependence. Since the idle time behavior is of prime importance, CIGRE WG13.07 proposed a detailed test procedure for the determination of the relationship between the idle time and the operating times and also provided some typical results.

Figure 8 shows the idle time dependence of close operations with spring operated mechanisms for 145kV-362kV rating breakers and a conventional hydraulic operated mechanism for 300kV. These characteristics were evaluated for operating cycles of C-O-C-O after idles times of 2, 4, 8, 16, 64, 128, 256, 720 hours.

The spring operating mechanisms showed significantly smaller idle time dependence up to 1000 hours because they have a lubricating coating on their main sliding parts. The lubrication minimizes the change of friction and reduces the sticking force on the surfaces. The friction force between these parts generally varies with the change of the properties of the lubricant due to long-term aging and evaporation. It can be seen that idle time compensation is not required when these spring mechanisms are applied to the CSS.

On the other hand, the test results with a conventional hydraulic drive showed that the increase of closing time is

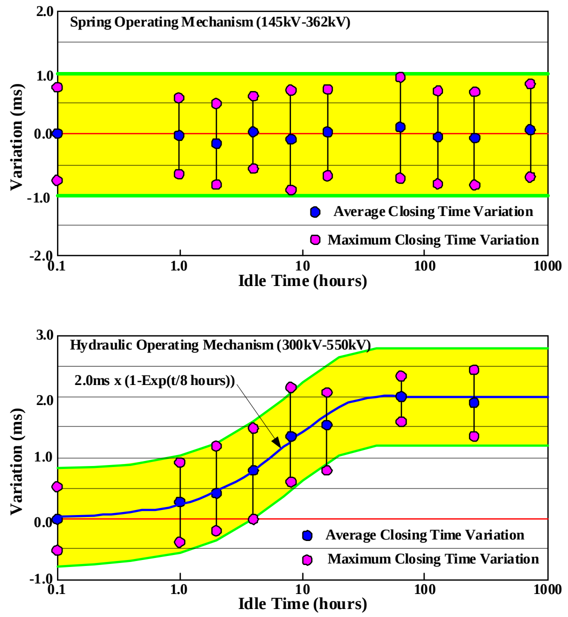


Fig.8 Idle time dependence of the circuit breakers with spring operating mechanisms and a conventional hydraulic operating mechanism

observed from several hours of idle time and saturated to the maximum delay of about 2.0ms if the idle time exceeds 72 hours. The main reason for the delay in hydraulic drives is ascribed to the dissolved air in the hydraulic fluid that can appear as bubbles when pressure is released during operation. Bubbles in the hydraulic fluid may delay the response of hydraulic piston movement at the next operation. Innovative stable high-pressure hydraulic drives have been developed and their effectiveness verified to solve this problem [6].

From investigations of the hydraulic mechanism idle time characteristics, it can be concluded that the delay is observed for the closing operation after only a few hours of idle time and saturated at a certain value if the idle time exceeds about 100 hours. The delay for drives that show significantly small idle time dependence after 100 hours of idle time do not increase for further idle time. Therefore the requirement of the idle time compensation can be judged from a measurement up to 100 hours.

3.7 Controller Functional Performance Test

Functional performance tests of the controller have not yet been standardized. Their purpose is to verify the timing scatter of controlled close and open commands issued by a controller, compensation functions, self-check functions, alarm functions, etc. The important compensation functions required for the controller are summarized below.

(a) Idle time compensation for the increase of closing time due to idle time
(b) Conditional compensation for the variation of operating time with ambient temperature, control voltage and mechanism pressure
(c) Adaptive compensation for the deviation of operating time due to long-term aging and wear

Controlled command scatter was evaluated using an ideal circuit breaker model that shows no deviations of operating time and no pre-strike. The reference voltage and current signal with 60Hz were input through the interfaces of the controller. Figure 9 shows the timing scatter for opening commands at the control voltage of 125V and temperatures from 10 to 30 ºC. The deviation of both open and close commands were about 10µsec during a number of consecutive operations [7].

Various compensation functions were also checked using artificial signals for operating conditions.

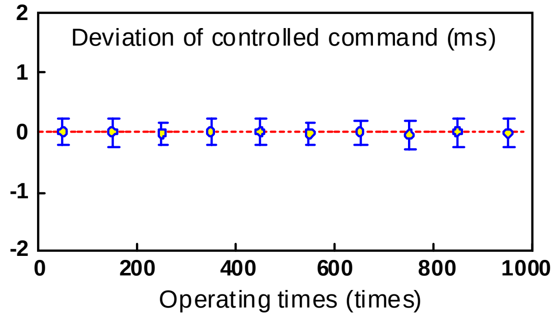


Fig.9 Deviation of the controlled switching commands issued by the controller during the consecutive operations

4. Integrated System Testing

A performance check of the complete CSS is essential when implementing a particular combination of circuit breaker, controller and sensors for the first time. Capacitive and inductive current switching tests at testing stations with the complete CSS serves as a convenient controller conformance test (mechanical, dielectric, EMC etc.) because random closing or possible reignition generates severe switching surges that may exceed the standard withstand values specified for relay systems.

The compensation function during the consecutive operations was checked for a complete CSS. The drifts of the operating times over a number of consecutive operations due to wearing of the parts can be compensated using the adaptive control. The effective compensation of the adaptive control during the lifetime of the circuit breaker was demonstrated.

4.1 Drifts of Operating Times caused by a number of Consecutive Operations

Gas circuit breakers are designed using several sliding parts such as contacts and sliding seals rubbing between metal surfaces during close and open operations. Accordingly, operating characteristics are affected by the change of friction or sticking force on the surfaces of these parts due to long-term aging and wear. As the change will progress slowly, adaptive control can effectively compensate for the drift of operating time over a number of consecutive operations.

The effect of adaptive control varies with the number of previously measured operating times and their weighting factors. These parameters are determined by detailed investigations of a series of mechanical endurance tests. The previous 10 operating data are used for the adaptive control and the weighting factors are given as $\omega_i = k^i/c$, where $c = \Sigma k^i$ and i is the integer from 1 to 10.

Figure 10 shows typical drifts of the measured closing time measured with and without adaptive control over 1500 operations of a 145kV spring operated gas circuit breaker. The deviation of the closing time is given by the difference between the predicted closing time and the result. Although the closing time becomes longer with the increase in the number of operations, the closing time can be effectively compensated with good accuracy by adaptive control. The width of deviation was decreased from +4.1/-1.2 ms to +1.2/-1.2 ms. The drift of the RDDS characteristic can also be compensated to the actual value with this adaptive control, when the controller is able to detect the making instant directly by measuring the main circuit current.

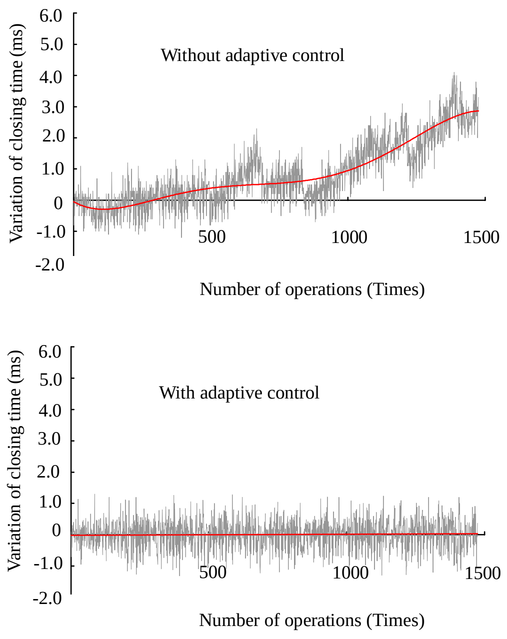


Fig.10 Typical drifts of the closing times measured with adaptive control of controller and without adaptive control

4.2 Controlled closing Test

Figure 11 shows the distribution of the closing instants for voltage zero target using 145kV and 362kV circuit breakers. The optimum close targets for voltage zero are determined using the measured RDDS and the mechanical scatter as shown in Figure 5. The distribution of making voltages was evaluated from the data measured by the controller. The results of closing instants show a normal distribution around the target

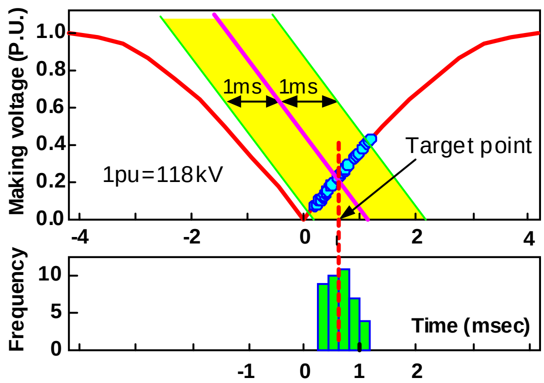


Fig.11 (a) Distribution of making voltages and closing instants using a 145kV GCB

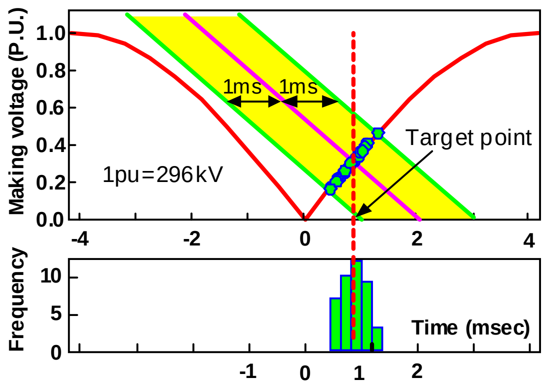


Fig.11 (b) Distribution of making voltages and closing instants using a 362kV GCB closing instant of 13 electrical degrees for 145kV and 20 electrical degrees for 362kV with a small standard deviation less than 0.3ms. The maximum making voltage is 0.35-0.38 P.U. The scatter of making voltage can be explained within the voltage deviations corresponding to mechanical scatter within ±1 ms around the target instant.

5. FIELD VERIFICATION

Controlled switching tests were conducted to check the performance of the complete CSS applied to a 121kV capacitor bank and a 204kV reactor bank in the field. A total of 10 controlled energizations and 10 controlled de-energizations of the CSS were carried out by means of the controller during the commissioning tests.

5.1 Controlled Capacitor Closing Tests

The characteristics of the circuit breaker were programmed into the software of the controller. In addition to the type and routine tests at the factory, commissioning tests at the site were performed to calibrate several parameters such as the average operating time, the travel, the control voltages taking into account the difference of the operating conditions between the factory and the field. These calibrations are performed automatically using the software installed in the controller.

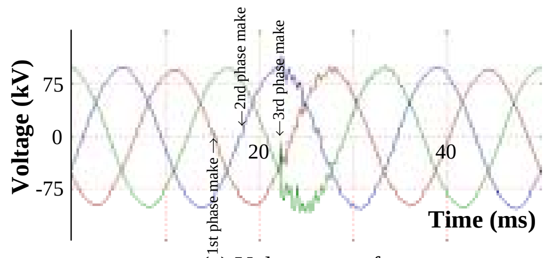
After calibration, controlled switching tests were performed at the system voltage of 121kV using the target closing instant of 16 electrical degrees determined by the method described in previous chapter plus a slight safety factor. Figure 12 (a) shows the voltage and current waveforms of the first making test, and Figure 12 (b) shows the waveforms of the tenth test. For the first making test, the making instant of the third phase shows a slight delay though it is within the permissible tolerance. This delay is probably caused by a difference of the actual RDDS due to design tolerance of the interrupter dimension or closing velocity scatter.

The controller applied to this circuit breaker can compensate for such difference by adaptive control. Figure 12 (b) shows more successful results of controlled closing to the voltage zero targets because the adaptive control can reduce the prediction error caused by the tolerance after learning from the previous nine operation results. A controller that measures the operating time mechanically (for example, use of auxiliary switches) cannot compensate for the error related to RDDS.

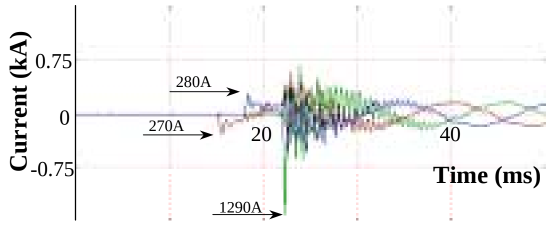
The CSS has continued, after the commissioning tests, to operate daily in the field. The controller measures and stores the operating conditions and the results of each operation. These data are also useful for circuit breaker maintenance because they provide detailed operating characteristics of the circuit breaker.

5.2 Controlled Capacitor Opening Tests

Since capacitance current switching, such as load current switching of a capacitor bank, is one of the most severe duties of a gas circuit breaker, IEC62271 defined two classes of circuit breakers depending on the restrike

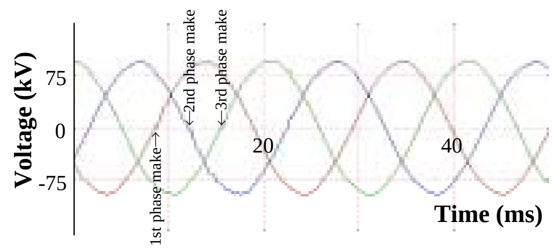


(a) Voltage waveform

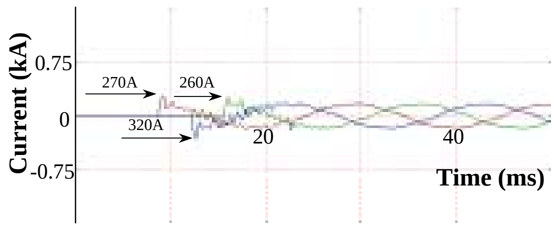


(b) Current waveform

Fig.12 (a) Waveforms of the 1st capacitor energization



(a) Voltage waveform



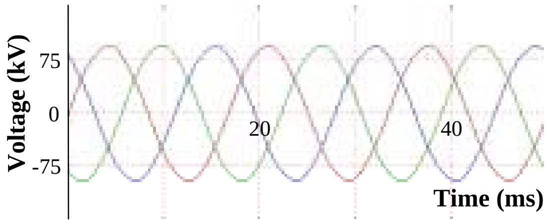
(b) Current waveform

Fig.12 (b) Waveforms of the 10th capacitor energization

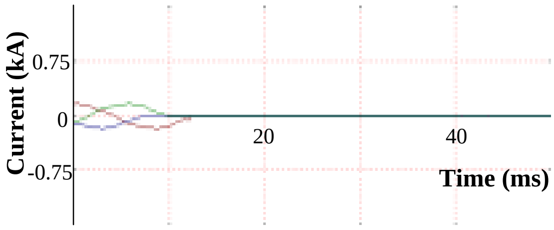
probability. Although a circuit breaker may be designed and verified with restrike-free performance (C2), the application of CSS can improve the restrike-free reliability of the circuit breaker. On controlled opening for capacitor bank switching, the circuit breaker is controlled to interrupt the current with adequate arcing time to achieve enough contact gap at the instant of current extinction. Figure 13 shows a typical measurement of voltage and current waveforms in the case of controlled opening of a capacitor bank. More than a few hundred operations have been successfully conducted in the field and no restrikes have been observed.

5.3 Controlled Reactor Switching Tests

Controlled reactor switching can reduce the inrush current or the transient stresses. The making target that



(a) Voltage waveform



(b) Current waveform

Fig. 13 Waveform of controlled capacitor de-energization

minimizes reactor inrush current is the voltage peak. The associated switching overvoltage in this case is generally low, but a steep voltage wave front may stress the reactor insulation. Though it is impossible to achieve reduction of both inrush current and transient stresses on the reactor energization with the same target, a compromise solution must be reached.

Figure 14 shows voltage and current oscillograms for a 204kV controlled shunt reactor de-energization and energization in the field. The maximum inrush current of 1270A attained by random closing can be suppressed to below 50A. The controller demonstrates successful opening with reignition-free performance at the instants around the maximum arcing time (a half-cycle before interruption) and closing at the instants around the voltage peak.

6. Conclusions

Factory evaluation tests as well as field verification tests for the components and the integrated system were conducted using different types of circuit breakers according to CIGRE recommendations.

Effective compensation for deviations of operating time associated with past operations has been demonstrated. The idle time dependence of the close operation with spring drives and a conventional hydraulic drive was compared. It can be seen that the requirement of idle time compensation can be judged from the measurement up to 100 hours. Innovative operating mechanisms do not show any delay of the operating times for idle time up to 1000 hours.

The measurement of RDDS can be obtained by random closing. Little difference of RDDS value was shown for the polarity of the voltage. From the results of type tests, a practical method of determining the optimum close targets was proposed. This method was verified by

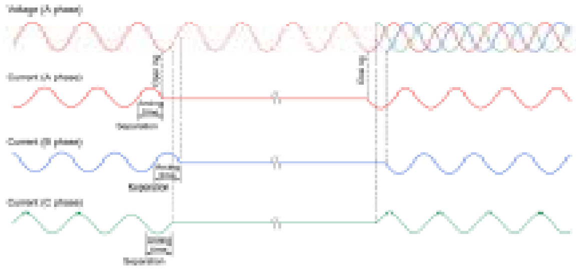


Fig.14 Voltage and current behavior of controlled shunt reactor de-energization and energization

making tests at the factory as well as controlled switching tests at the site. We conclude that the proposed method of determining the close targets is more effective for any switching application and requires less effort at the site.

Finally, field verification tests were conducted during the commissioning tests. Controlled shunt capacitor switching in the field showed more successful results of controlled closing to the voltage zero targets because the adaptive control can reduce the prediction error caused by the design tolerance after learning from the previous operation results. The CSS also demonstrates successful reactor opening without any reignition when the open target is set as the middle point between the minimum and the maximum arcing times.

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