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Controlled Switching System

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Changes for the Better

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Controlled Switching System

Cover Story

This special issue covers state-of-the-art the latest technologies of controlled switching systems which are commonly applied to reduce switching surges. (1) Capacitor switching application, where the controlled switching system (CSS) is installed in the mechanical cabinet. (2) and (4) Reactor switching applications, where the CSSs are installed in a local control cabinet. (3) Controlled switching system that controls switching according to the residual flux in the transformer. (5) Transformer switching application, where the CSS is installed in the local control cabinet.

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Overview

Author: *Klaus Fröhlich**

Although transmission and distribution systems of electric energy can claimed to be mature and extremely reliable, research and development efforts aimed at further improvement have never ceased, even in the difficult days of liberalization and cutting of funds for new investments in the utilities. The search for new solutions has been focussed towards reduction of maintenance costs by introduction of new procedures and employment of intelligence for the equipment provided by modern information technology tools.

Controlled switching of HVAC circuit-breakers, which is already widely applied for applications such as switching of capacitive and small inductive currents, is one of these solutions that can provide several technical and economical benefits. Avoidance of high inrush currents and serious temporary switching overvoltages as well as the reduction of the stress on an adjacent equipment or the maintenance burden on a frequently switched circuit-breakers are one of the most important advantages. The overall benefits were summarised in detail in a series of documents issued by CIGRE WG A3.07.

Japan has extensively developed controlled switching for a long time, thus having a long tradition in the subject. A new application to transformer energization considering the residual flux in the transformer core was realized and successfully demonstrated in a practical field. Controlled switching of power transformers can be a cost effective solution to mitigate the problem of high inrush currents, the latter may lead protective relay mal-operation and power quality reduction. The rapid advances in the use of digital equipment will soon open new possibility for series compensated line, load & fault switching and circuit-breaker up-rating.

The special issue covers the basics of controlled switching and introduces the more common applications for capacitor and reactor switching and more recent developments for a state-of-the-art technology transformer switching. Testing requirements and the benefits of controlled switching will also be summarized based on the survey of CIGRE WG A3.07.

I gratefully acknowledge the contributors, who evolve in promoting research, design and testing of controlled switching systems at Mitsubishi Electric Corporation, presented an updated technical view of controlled switching systems. No doubt, these following series of technical papers will give guidance to the users on how to study, specify and test the controlled switching system and assist them to assess the effectiveness of the system in Japan.

**Prof. Dr., Chairman of CIGRE Technical Committee, Swiss Federal Institute of Technology, High Voltage Laboratory, Switzerland*

Current Status and Future Trend of Controlled Switching System

Author: *Hiroki Ito**

1. Introduction

Life-cycle cost reduction of transmission and distribution systems is becoming increasingly important to adapt to global changes resulting from factors such as electricity market liberalization, electricity industry deregulation, environmental protection issues, as well as various emerging technologies developed using information technology advances.

Technical requirements for power equipment have also been changing. For instance, the development of high-voltage and large-capacity equipment has advanced to ensure stable power supply in the context of growing electricity demand. However, the most important requirement in this period of severe competition brought about by liberalization and deregulation is to develop more reliable and cost-effective equipment.

As emerging technologies such as controlled switching, remote monitoring diagnostic techniques and digital controls became practical, CIGRE (International Council on Large Electric Systems) have conducted extensive investigations on field experience of these technologies as well as international surveys on the reliability and maintenance practices of high voltage equipment. In the 1990s, market demands for extending the life while reducing life-cycle cost drove research and development towards further compactness, reliability and reduced operating energy. These efforts led to the 550kV one-break gas circuit breaker (GCB) and the 1100kV two-break GCB.

Controlled switching has become an economical substitute for a closing resistor and is commonly used to reduce switching surges. The number of installations using controlled switching has increased rapidly due to satisfactory service performance since the late 1990s. Currently, it is often specified for shunt capacitor and shunt reactor banks because it can provide several economic benefits such as elimination of closing resistors and extension of a maintenance interval for nozzle and contact. It also provides various technical benefits such as improved power quality and suppression of transients in transmission and distribution systems. Recently, an advanced controller considering the residual flux in a transformer core has been installed and has demonstrated good performance in the field. This controller can significantly suppress overvoltage induced by inrush currents in case of transformer energization and allows more flexible operations in accordance with load change of electricity.

IEC62271-302 TR, including the testing requirements and procedures for controlled switching of GCBs, will soon be issued and will clarify the required characteristics for both newly installed and existing GCBs resulting in a further increase of applications.

An IEC62271-302 Technical Report titled ‘High Voltage Alternating Current Circuit-breakers with Intentionally Non-simultaneous Pole Operation’ will be issued shortly in 2007, which includes the testing requirements and procedures for controlled switching and clarifies the required characteristics for both newly installed and existing GCB resulting in further increase of applications.

2. Installation Records of Controlled Switching in Service

According to the CIGRE survey (Figure 1), approximately 2,400 controlled switching systems (CSS) were supplied and installed around the world in 2001, and more than 4,000 units are now estimated to be in service. Before 1995, the number of installations was limited because of technological immaturity, but the number has increased rapidly since the late 1990s when effective compensation algorithms became available using advanced sensors and reliable digital relay technologies. Currently, about 70% of the installations worldwide are applied to capacitor banks, but in Japan controlled reactor opening is the most common application. No CSSs are used to shut capacitors in Japan

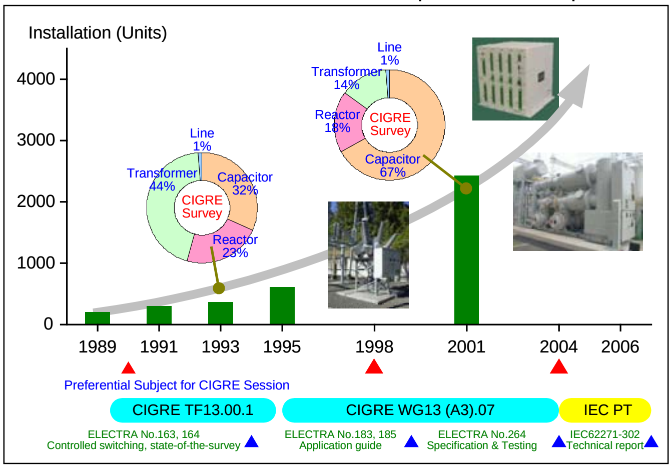

Fig. 1 CIGRE survey on installation records of controlled switching in worldwide service

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Japan because an installation of fixed inductors can suppress the magnitude of inrush currents, which are originally intended to reduce the 5th harmonics of the power frequency.

CIGRE has investigated technical trends of CSS in detail. First it installed TF 13.00.1 and published a general view of the features and feasibility of CSS(1) in 1995. TF was transferred to new Working Group 13.07 and an application guide to CSS(2) was published based on an international survey of field experience in 1999 and proposed testing requirements and procedures(3) in 2001. The guide emphasizes the importance of compensating for the variations of operating time because a CSS requires accurate operation consistency during the lifetime of a circuit breaker. Variations of 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 operating times on these conditions. The operating time should also be compensated to account for the deviations of the operating time caused by aging due to repeated operations and the first operation after a long idle time. Recent research has revealed that the closing time for some hydraulic operating mechanisms was significantly delayed after idle times of only a few hours(3)(4). Accordingly, idle time compensation is essential for even a CSS that is operated daily.

In accordance with the need for flexible operation and control of switching equipment in a transmission and distribution system, advanced controllers capable of controlled transformer energization considering the residual flux in the transformer core(5) and for controlled re-closing of uncompensated lines(6) have been demonstrated to be effective in suppressing switching transients in the field. Further development efforts will increase the number of installations of CSS for these applications.

3. Principles of Controlled Switching

CSS is composed of an independent-pole-operated circuit breaker, controller and sensors that measure system voltage, current through the breaker, ambient temperature and operating pressure of the drives (if required).

The term CSS refers to the technique of controlling the timing of the pre-strike (for close operations) or contact separation (for open operations) for each pole of a circuit breaker with respect to the phase angle of the system voltage or the current in order to minimize stresses on the components of the power system.

The schematic timing sequence for energization at a pre-determined phase angle is shown in Figure 2. The randomly issued closing command is delayed by an appropriate amount of time by the controller based on a calculated closing time for the next operation and a known pre-arcing time so that current is initiated at the target phase angle. The optimum instant for making differs according to the switching application as well as the breaker performance. Figure 3 summarizes major switching problems and their solution by CSS for various applications.

4. Applications

4.1 Capacitive and inductive switching

Energization of shunt capacitor banks causes high amplitude inrush currents and an associated overvoltage in the local substation and a remote overvoltage at the receiving end of transmission lines connected to the substation. A modern GCB generally provides a very low probability of restrike for capacitive current interruption. Nevertheless, the probability of restrike can be further reduced by means of CSS, which ensures long arcing times which are especially effective for GCBs with several fault current interruptions.

Controlled closing of shunt capacitor banks is used to minimize stress on the power system and its components. It also provides economic benefits such as elimination of a pre-insertion resistor or a fixed inductor and extension of the number of allowable operations before the nozzle and contacts of the GCB need to be replaced.

All circuit breakers exhibit a high probability of

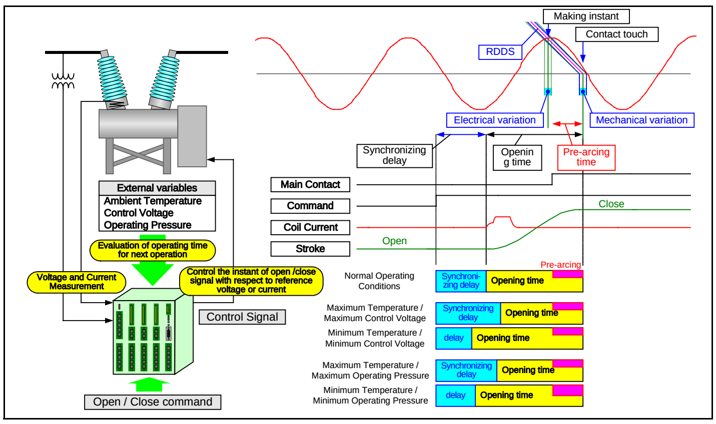

Fig. 2 Schematic closing sequence and compensation of operating time varied with external conditions

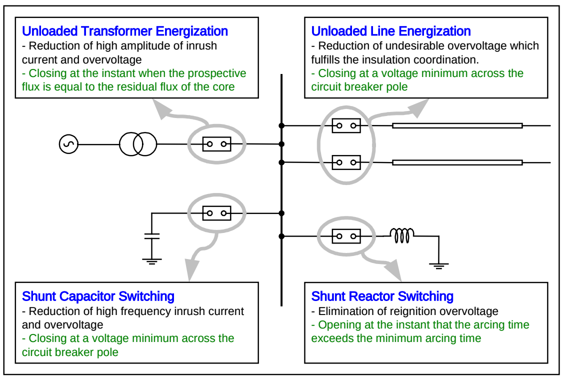

Fig. 3 Switching problems and solutions

reignition during de-energization of shunt reactors for arcing times of less than a minimum arcing time. Controlled opening can avoid reignition overvoltages by separating the contact when the arcing time will be longer than the minimum arcing time while considering the relative importance of chopping overvoltage, which increases with an increase in arcing time. Since reignition overvoltages are normally more severe than chopping overvoltages, it is a common practice in CSS applications to increase the arcing time.

Small inductive current interruption phenomena can be classified into three categories as shown in Figure 4. These depend on the contact gap at the instant of current interruption: (a) Reignition-free as a result of interruption success because the dielectric withstand between the contacts always surpasses the transient recovery voltage after the interruption, (b) Reignition as a result of dielectric breakdown, and (c) Thermal reignition as a result of thermal interruption failure. Thermal reignition, however, does not cause any significant transients and can be successfully interrupted at the next current zero. Accordingly, the periods of reignition-free window (a) and thermal reignition window (c) can be chosen as the opening target.

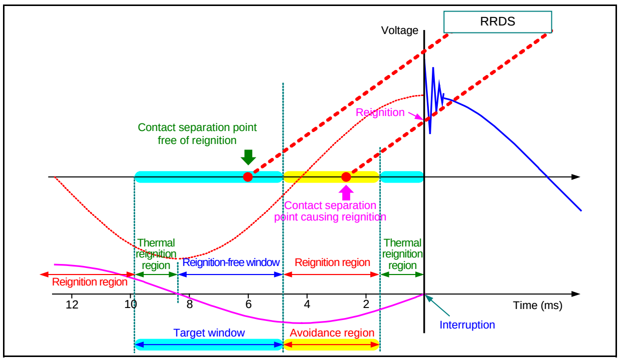

Fig. 4 Controlled reactor opening for preventing reignition free

Controlled opening of shunt reactor banks can eliminate the reignition overvoltage, which has the potential to induce damage to the GCB such as nozzle puncture. It also provides economic benefits such as reduced possibility of damage to the reactor and extension of the number of operations before the nozzle and contact need to be replaced by more than a factor of two relative to that required for a GCB without CSS.

4.2 Unloaded transformer energization

Transformer energization can create high-amplitude magnetizing inrush currents of up to several thousand Amperes and a temporary overvoltage depending on the energizing instant. These transients degrade the power quality and may cause false operation of protection relays. High inrush currents also impose severe electrical as well as mechanical stresses on the transformer windings and may reduce the life expectancy of a transformer exposed to frequent energization in the over-loaded condition.

Energization of a transformer with no residual flux in a core at peak voltage will cause no transients. However, the flux changes depending on the de-energization instant, and a random energization may generate greater saturation of the magnetizing currents. Therefore, the optimum targets should be adjusted taking into account the residual flux. The inrush current can be eliminated by energization only when the prospective normal core flux is identical to the residual flux. (See Figure 5.)

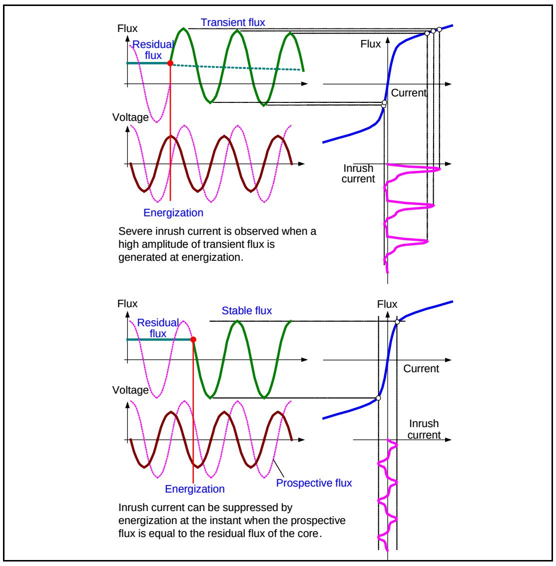

Fig. 5 Magnetizing flux in a core of a transformer and corresponding magnetizing current

The innovative residual flux measurement was developed and its accuracy proven in the field by integrating the voltage waveform after de-energization of the transformer as well as any CB operations in case of fault clearing connected to the system. It was incorporated into a commercial controller, which has already demonstrated good performance in several field applications.

4.3 Uncompensated and compensated line switching

Energization and auto-reclose of long transmission lines can cause undesirable overvoltages in the transmission network, so special overvoltage mitigation measures are employed to meet the insulation coordination considerations. The most common practice has been to use metal-oxide surge arresters which are often combined with closing resistors to improve reliability, but this approach is expensive.

CSS can potentially reduce the re-closing transients and further improve the reliability of restrike-free performance. It can also provide economic benefits such as elimination of closing resistors and reduction of the insulation level for surge arresters and transmission towers. For line applications, a circuit breaker with a higher normalized RDDS (Rate of Decay of Dielectric Strength) is generally preferable although the operating scenario and targeting strategies should be studied thoroughly. Idle time compensation is essential for drives whose operating times have this dependence. The strategies for different line configurations are described below.

a) In the case of an uncompensated line with an inductive potential transformer, the controller can suppress the transients effectively (less than 1P.U.) by controlled closing at voltage-zero on the source-side because the trapped DC charge is rapidly discharged (typically less than 100ms). (See Figure 6.)

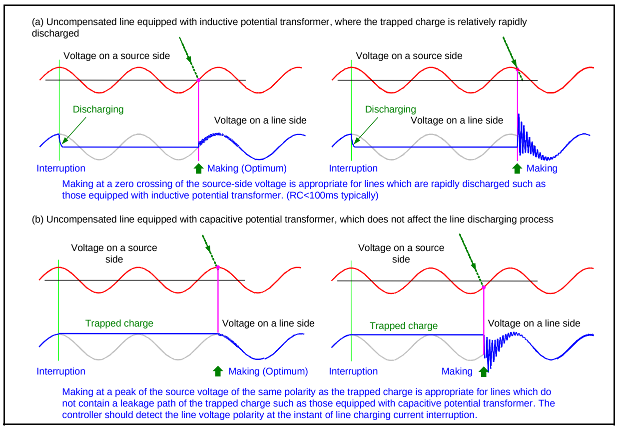

Fig. 6 Optimum making targets for unloading line controlled switching

b) In the case of an uncompensated line with a capacitive potential transformer, no leakage path exists for the trapped charge. The optimum target is the voltage peak on the source-side of the same polarity as the trapped charge.

c) In the case of a compensated line, the degree of compensation has a significant effect on the line-side voltage. The voltage across the breaker shows a prominent beat especially for a high degree of compensation because the line oscillation frequency typically falls in the range of 30–50 Hz. The optimum instant is the voltage minimum across the breaker, preferably during a period of minimum voltage beat[6] as shown in Figure 7.

5. Conclusions

The rapid increase of CSS applications is ascribed to several factors, such as successful field experiences of the systems with an effective compensation algorithm, the CIGRE proposal for type testing recommendations, and versatile operations and controls of transmission systems due to global changes in the electrical industry. Since CSS can provide significant technical and economic benefits, including enhancement of power quality and operational flexibility, it could be incorporated into circuit breaker control systems as a standard specification in the near future.

As information technologies progress, it may become possible to use CSS for fault current interruption, uprating of modern and aged circuit breakers, and compensated line auto-reclose with minimum surge-arresters. Furthermore, various monitoring results of GCBs recorded in the controller can be used for remote diagnostics and condition-based maintenance in order to improve equipment reliability and optimize maintenance practices.

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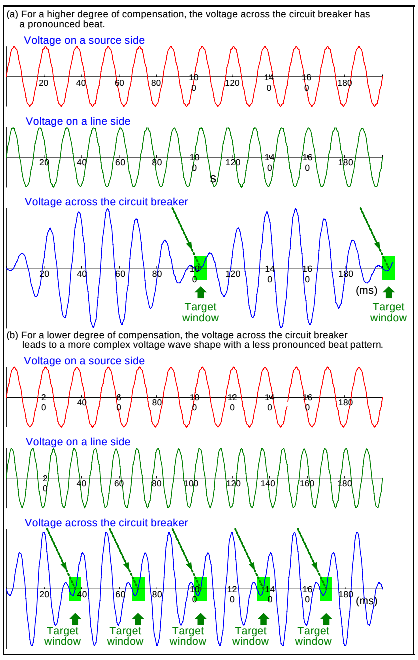

Fig. 7 Optimum making target for compensated line

Factory and Field Tests of Controlled Switching in Accordance with IEC62271-302 Standard

Authors: *Sadayuki Kinoshita** and *Hiroki Ito**

1. Introduction

In controlled switching, where a circuit-breaker is switched in the optimum phase to minimize switching surge, it is important to predict precisely the variations in the operating time of the circuit-breaker with respect to the ambient temperature, control voltage, operating pressure, and number of times of operation.

CIGRE has investigated the operating conditions of phase control of actual systems and proposed type test items and testing procedures required for controlled switching systems (CSSs).(1) Based on the proposal, a test standard IEC62271-302 has been prepared, and a new standard document will be published in the near future.

This paper discusses the type test items and testing procedures specified in the International Standard IEC62271-302 and also introduces the operating characteristics of circuit-breakers tested in accordance with the standard and the testing of combined CSSs.

2. Type Tests

Table 1 shows the type test items and test contents required for the circuit-breakers used in the CSSs specified in IEC62271-302. For this standard, the following test items are added to the tests conforming to the conventional International Standard for High-Voltage Alternating-Current Circuit-Breaker IEC62271-100:

- Mechanical characteristics test to evaluate the operating time with respect to specific operating conditions of circuit-breakers
- Electrical characteristics test to evaluate the variations in dielectric strength at the moment when the circuit-breaker is opened and when it is closed
- Controlled switching test to open and close a CSS, which consists of a circuit-breaker, a controlled switching unit, and a sensor, in a particular phase.

2.1 Mechanical characteristics test

The operating time of a circuit-breaker changes not only in accordance with such operating conditions as ambient temperature, control voltage, and operating pressure but also with total number of times of operation and idle time (time interval between the last operation and the next operation). This is why the standard specifies a test to evaluate the dependency of the variations on the operating conditions and the total number of times of operation.

The operating mechanism of a circuit-breaker is such that the plunger is excited according to the switching command to disengage the ratch mechanism and release the hydraulic pressure or spring energy for

Table 1 Type tests for circuit-breakers tested with dedicated controller

Type Tests item		Test procedure
Mechanical tests	Measurement of mechanical scatter	100 opening and 100 closing operations at rated control voltage, rated gas density, rated drive pressure
	Impact of temperature	10 opening and 10 closing operations at each ambient temperature (between -10°C and 40°C in not more then 15°C steps
	Impact of control voltage	10 opening and 10 closing operations at each voltage level (minimum, nominal, maximum, additional level)
	Impact of stored energy level	10 opening and 10 closing operations at each stored energy level (between its maximun and minimum value in not less then 5 equal steps)
	Impact of idle time	5 operating cycles (close and open) at each idle period (1, 2, 4, 8, 16, 32, 64, 168 hour)
Electrical tests	Determination of RDDS Determination of RRDS	Tests shall be performed with the circuit-breaker in new condition and also following pre-conditioning of three opening operations with arcing time as for T60 (same current as test duty T60) Delay the close impulse by 15 electrical degrees and perform a further 4 making operations Test voltage = 1.5 x rated voltage/$\sqrt{3}$ Test current for RDDS = <400A, Test current for RRDS = 315A
Controlled switching tests	Controlled closing type test	20 closing operations at voltage zero (with the circuit-breaker in new condition and pre-conditioned circuit-breaker) Test voltage = 1.5 x rated voltage/$\sqrt{3}$, Test current $\geq$10A
	Capacitive current switching test	Controlled opening with setting intended to minimise re-strike probability Controlled closing at voltage peak
	Test duty T100a	Controlled closing at voltage zero

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driving the main contact in the interrupting chamber of the circuit-breaker. The operating characteristics of the plunger which releases the ratch mechanism depend on the control voltage, which changes the coil current, and the ambient temperature, which influences the coil resistance. In addition, the switching characteristics of a circuit-breaker, which consists of many mechanical sliding parts, depend on the ambient temperature which changes the lubrication on the sliding surface or the coefficient of friction and the total number of operations and operating time in the past. Furthermore, in the case of hydraulic operation or pneumatic operation, the hydraulic pressure or pneumatic pressure also influences the operating characteristics.

Adaptive compensation, which compensates the average operating time through comparison between the actual operating time for about the 10 most recent operations and the predicted time, has been proved effective for evaluating the variations in the operating characteristics due to wear or the like of the sliding parts as a result of repeated switching of the circuit-breaker.(2)

On the other hand, the operating characteristics that depend on the idle time of the circuit-breaker change with the time-varying lubrication characteristics of the sliding surface and the air bubbles generated in the hydraulic circuit of the hydraulic-operating mechanism. The air bubbles generated in the low-pressure hydraulic circuit in the open condition are compressed when the oil is subjected to the transition to a high-pressure condition at the beginning of a closing stroke, thus causing a delay in the propagation of pressure to the piston. With the operating mechanisms subject to an operational delay depending on the idle time, the delay becomes conspicuous several hours after the beginning of the idle time, and it has been observed that the delay usually tends to saturate at about a maximum of 3 ms before reaching 100 hours.(2)

In controlled switching, the next operating time is compensated by predicting variations in the operating time with respect to the idle time on the basis of the respective condition values measured immediately before the switching operation or the previous operation, with the variations in the operating time under each operating state (state quantity) obtained from the mechanical characteristics tests memorized in the program of the controlled switching unit as the function of one or two state quantities.

2.2 Electrical characteristics test

The withstand voltage between the contacts of a circuit-breaker decreases with a decrease of the contact gap during the closing stroke. The making instant is when the voltage across the circuit-breaker exceeds the dielectric withstand between the gaps and its deviation results from a mechanical variation of the closing time and the pre-strike behavior characterized by Rate of Decay of Dielectric Strength (RDDS). On the other hand, the withstand voltage between the contacts increases with an increase of the contact gap during the opening stroke. The circuit breaker can interrupt an inductive current successfully and avoid re-ignition when the dielectric withstand between the gaps after interruption always exceeds a transient recovery voltage across the circuit-breaker. The characteristic of Rate of Recovery of Dielectric Strength (RRDS) is defined by an interruption test of a small inductive current.

The gradual wear of contact and nozzle may affect these RDDS and RRDS characteristics and therefore the RDDS measurement is required to evaluate it with the circuit-breaker in new condition as well as in wear condition following a pre-conditioning of the circuit breaker (after three interruptions with arcing times as for T60 similarly for a capacitive current switching for C2 class circuit-breaker).

2.3 Controlled switching test with circuit-breaker, sensor, and controlled switching unit combined

To verify the soundness of CSSs that combine a circuit-breaker (GCB), a sensor, and a controlled switching unit, a test in which a GCB is closed or controlled to break at a specified voltage or phase angle is required. For the target closing phase angle of controlled closing, the closing voltage is confirmed by executing controlled closing phase operation up to 20 times at zero-voltage and at a voltage wave crest point.

3. Results of Typical Type Tests

3.1 Mechanical characteristics test

(1) Dependence of operating time on operating conditions

Figure 1 shows the results of evaluating closing time measured on a 145 kV spring-operated GCB by changing the control voltage and ambient temperature. Two types of closing time were measured. One type of the time (“ratch release time”) refers to the time from coil current initiation to ratch release moment and the other type of the time (“contact operating time”) refers to the time from the ratch release moment to contact touch moment by means of the operating mechanism. The measurements showed that the ratch release time depends on the control voltage and ambient temperature and that the contact operating time mainly depends on the ambient temperature. The small dependency of the control voltage on the contact operating time is attributed to the fact that the operation of the plunger does not influence the operation of the main contact of the circuit-breaker after the ratch is released. When the dependency of the variations in connection with this

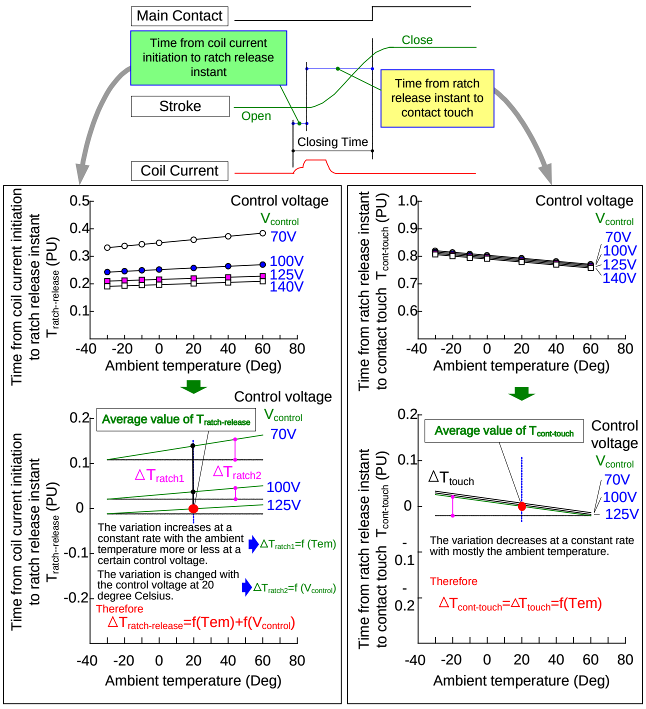

Fig.1 Closing time dependence on the external valuables and possibility of expressing independent functions with a single variable

ratch release time on ambient temperature appears to be almost the same with different control voltage levels, the variation in closing time can be approached as the sum of independent functions of ambient temperature and control voltage.

In the case of hydraulic-operated GCBs, the ratch release time depends on the control voltage and ambient temperature, while the contact operating time depends on the operating pressure and ambient temperature. Likewise, when the dependency of the variations in connection with this ratch release time on ambient temperature appears to be almost the same with different control voltage levels and the dependency of the variation in connection with the contact operating time on ambient temperature appears to be the same with different operation pressure levels, the variation in closing time can be approached as the sum of independent functions of ambient temperature, control voltage, and operating pressure.

(2) Dependency of total number of times of operation on operating time

Figure 2 shows the results of measuring the dependency of the closing time of 300 kV hydraulic-operated GCB and 145 kV spring-operated GCB on idling time.[2] With the hydraulic-operated GCB, the air bubbles generated in the low-pressure hydraulic circuit resulted in an operation delay several hours after the beginning of the idle time, and the variation saturated at about 2 ms after 100 hours of idle time. High-accuracy controlled closing is possible with GCBs, which have definite reproducibility of idle-time dependency, by compensating the variation in closing time on the basis of the idle-time dependency.

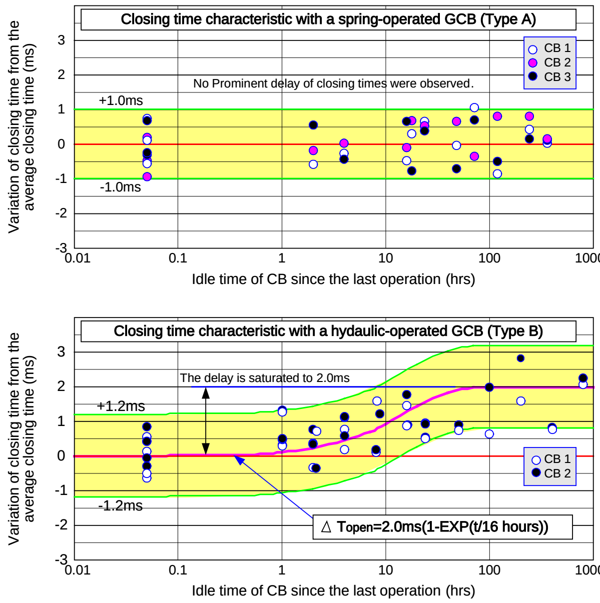

Fig.2 Idle time dependence of the circuit breakers with spring operating mechanisms and a conventional hydraulic operating mechanism

On the other hand, with the spring-operated GCB, the variation in closing time depending on the idle time is comparatively limited. Especially, this spring-operated mechanism uses a lubricating chemical coating instead of grease for the lubrication of major sliding parts, which results in outstanding characteristics with almost no operational delay before reaching 1,000 hours of idle time.

Figure 3 shows the results of evaluating the variation in the average closing time obtained by converting the closing time values measured during multiple operating tests to the normal operating conditions. The average closing time varies as the number of operations increases. However, since the variation remains within a certain range of scatter, the accuracy of predicting the operating time can be enhanced by compensating the closing time on the basis of the total number of times of operation in the past.[3]

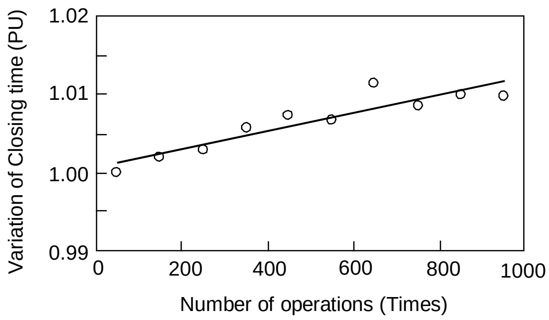

Fig.3 Typical drifts of the closing times measured without adaptive control of controller

3.2 Electrical characteristics test

Figure 4 shows a typical measurement of pre-strike characteristics plotted with a cycle of power frequency. The measurements consist of three series of tests with an EHV GCB in new condition and also following pre-conditioning of three and six opening operations (current interruptions) with the medium arcing time as for T60. The RDDS was obtained by the measurement of the pre-strike voltage and the pre-arcing times for different closing instants (electrical phase angles from 0 to 360 degrees) at the rated voltage.

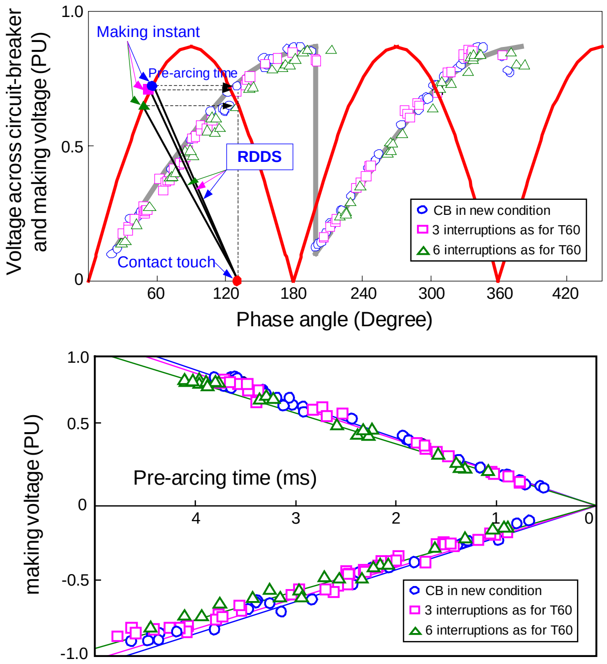

Fig.4 RDDS measurement with EHV GCB

According to the measurement results, the RDDS characteristic after the current equivalent to 60% of the rated breaking current is interrupted six times changes by up to 10% compared to the level of a new circuit-breaker. However, the characteristic after the current equivalent to 60% of the rated breaking current specified in the standard is interrupted three times shows a decrease of about 2%.

3.3 Controlled closing Test

Figure 5 shows the distribution of the closing instants for voltage zero target using 145 kV circuit breaker. The optimum close target for voltage zero are determined using the measured RDDS and the mechanical scatter. The distribution of making voltages was evaluated from the data measured by controller. The results of closing instants show a normal distribution around the target closing instant of 13 electrical degrees for 145 kV with a small standard deviation less than 0.3 ms. The maximum making voltage is 0.35-0.38 PU. The scatter of making voltage can be explained within the voltage deviations corresponding to mechanical scatter within ±1 ms around the target instant.

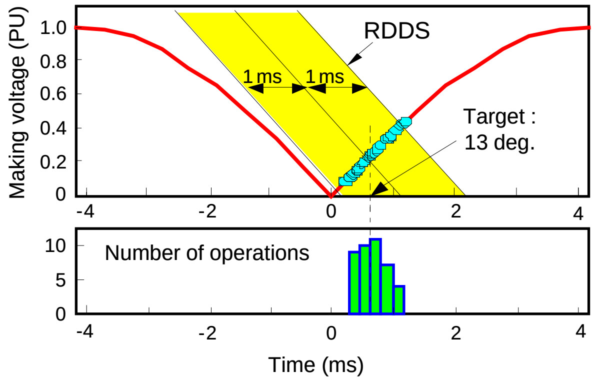

Fig.5 Distribution of making voltages and closing instants

4. Conclusions

Tests on the mechanical characteristics and electrical characteristics of circuit-breakers, which are very important for determining the optimum switching target of controlled switching, were evaluated in accordance with the type test procedures in compliance with IEC62271-302. As a result, the authors have confirmed that the controlled switching systems evaluated in accordance with the standard requirements can perform controlled switching at desired phase angles by the operation compensation function based on the operating characteristic data.

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Control Algorithm of Controlled Switching System

Authors: *Hiroyuki Tsutada** and *Takashi Hirai**

The effect of controlling high-magnitude voltage and current transients in controlled switching systems largely depends on the prediction accuracy of the operating time. This paper explains the operating principle of Mitsubishi's controlled switching systems and details the method for predicting the operating time based on environmental conditions, previous operating times and idle time. It also describes the results of validating the effectiveness of the method.

1. Operating Principle of Controlled Switching System

The operating principle of controlled switching systems is described using Fig. 1 "Block Diagram" and Fig. 2 "Timing Chart", both of which represent an example of controlled closing.

In controlled closing, the timing of mechanical contact touch (closing) for establishing electrical connection (making) between the contacts of the circuit breaker is controlled in a particular phase of system voltage. The function consists of the following steps:

(1) The target closing phase is determined taking into consideration the electrical characteristics and scattering in mechanical operation of the circuit breaker and the load-side conditions.

(2) The next closing time (time between input instant of the controlled closing command and the instant of closing) is predicted based on environmental conditions and previous operating times.

(3) The delay time is calculated and set in the timer. The delay time refers to the difference in time between the target closing phase minus the predicted

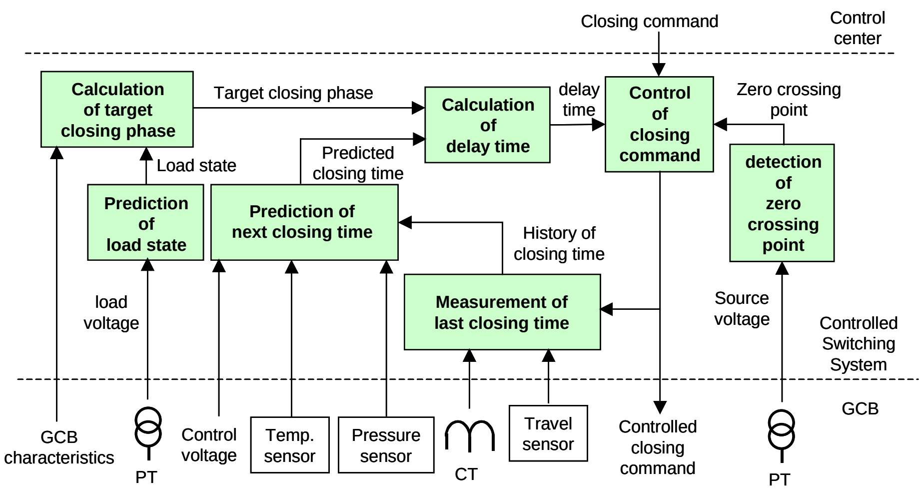

Fig. 1 Block diagram of controlled switching system (controlled closing)

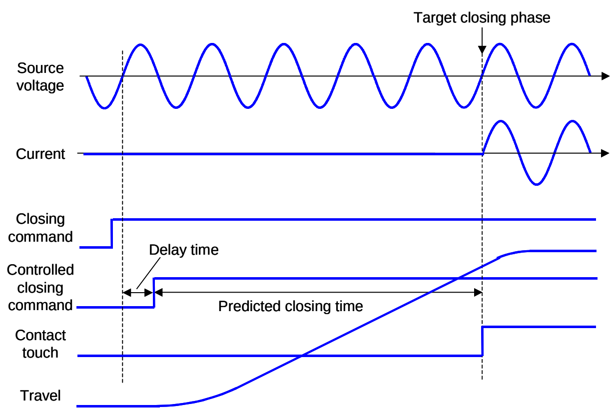

Fig. 2 Timing chart of controlled closing

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closing time and the latest zero-crossing point.

(4) With the closing command input, the zero-crossing point is detected to start the timer. After the elapse of the delay time, the controlled closing command is output to start the closing operation of the circuit breaker.

(5) After the elapse of the closing time, the circuit breaker is closed. The actual closing time is measured from the main circuit current or travel sensor, which is then reflected in the prediction of the next closing time.

2. Prediction Methods of Operating Time

2.1 Outline of prediction method

Since control is performed by the method described above, the circuit breaker is operated at a different timing than the optimum switching target when the real operating time deviates from the predicted operating time. To improve control accuracy, it is essential to predict the next operating time precisely.

The central value of the circuit breaker operating time changes with such factors as the control voltage, ambient temperature, operating pressure, contact wear from accumulated operations, long-term aging, idle time, intrinsic properties, etc. [1] [2] The predicted operating time is obtained by Eq. (1) below, with the average operating time T_{std} under normal environmental conditions compensated as shown in (a) through (c).

(a) Compensation time based on environmental conditions: ΔT_{env}

(b) Compensation time based on previous operating times: ΔT_{const}

(c) Compensation time based on idle time: ΔT_{idle}

$$\text{Predicted operating time} = T_{std} + \Delta T_{env} + \Delta T_{const} + \Delta T_{idle} \quad (1)$$

Each compensation time mentioned above is described in detail below.

2.2 Compensation based on environmental conditions

Figure 3 shows an example where the difference between the average closing time measured under each condition for the control voltage and ambient temperature and T_{std} are plotted in a two-dimensional rendering. The shape of the control voltage vs. operating time curve may differ within a high- or low-temperature range as shown in the figure, depending on the type of circuit breaker. From a practical viewpoint, it does not appear to be a problem to consider the dependency of the operating time on the control voltage and ambient temperature is independent when the variation width of the environmental conditions is small; however, it appears necessary to involve a two-variable function when the variation is expected to become comparatively large. So, compensation time functions in the form of a two-dimensional map as shown in Fig. 3 are prepared in advance for both opening and closing. This map can be used for common variation characteristics applicable to the same types of circuit breakers.

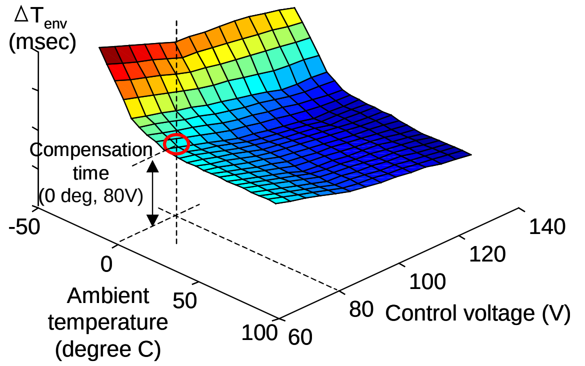

Fig. 3 Environmental compensation time map

During practical use, the compensation time ΔT_{env} is calculated by monitoring the control voltage and ambient temperature sequentially by means of the sensor installed in the circuit breaker and interpolating the two-dimensional map. In the case of a hydraulic- or pneumatic-operated circuit breaker, the operating pressure is further monitored and compensation is applied using the two-dimensional map of operating pressure and ambient temperature.

2.3 Compensation based on previous operating times

For the compensation based on previous operating times, it is necessary to know the precise operating times during actual use. Accordingly, the operating time is calculated based on the main circuit current for closing and travel sensor signal from the contact of the circuit breaker for opening. The operating time T_{meas} of each operation is measured, and then the compensation time ΔT_{const} is calculated by Eq. (2) below based on the previous 10 operating times for opening and closing, respectively.

$$\Delta T_{const} = \Sigma w(n)\{T_{meas}(n) - (T_{std} + \Delta T_{env}(n) + \Delta T_{idle}(n))\} \quad (2)$$

where n is an integer of 0 through 9 and w(n) is the weighting coefficient. The weighting coefficient is specified so that the data of an immediate operation is heaviest and the sum is 1.

2.4 Compensation based on idle time

The central value of the next operating time may fluctuate with the idle time, which is the time interval between the last operation and next operation, depending on the type of circuit breaker. So, the variation in average operating time based on idle time is measured in advance and the relationship between idle time and compensation time is rendered in the form of a map. This map can be used for common variation characteristics applicable to the same types of circuit breakers.

During practical use, the compensation time ΔT_{idle} is updated sequentially by checking the map in accordance with the elapsed time from the last operation of the circuit breaker.

3. Test Results (2)

3.1 Controller test

To confirm the function of a controlled switching system, a test was conducted using a GCB simulator. Control error was checked by inputting operating commands at random moments with the optimum target instant fixed. The control error under the condition that no noise is contained in the voltage or current signal, was approximately ±10 μsec.

3.2 No-load operation test

Next, a no-load operation test using a 145-kV/40-kA spring-operated gas circuit breaker was conducted to evaluate the control accuracy of the system in combination with a circuit breaker with respect to the variation in environmental conditions. AC 125 V as the standard control voltage was applied to the main circuit. Figures 4 and 5 show the control error when the ambient temperature was changed between −30°C and +60°C, with the control voltage maintained at a fixed level. The average error is plotted on the left side of the figures. The upper and lower bars indicate the standard deviation of the errors. The right side in the figure indicates the error distribution in the entire measurement.

The target instant was set at an electrical angle of zero degrees. The results show that control errors have a normal distribution around zero regardless of the variation in ambient temperature; proper controlled switching without steady-state error appears to have been made. The same result was obtained in the test with the control voltage changed.

Since the standard deviation of errors under the respective operating conditions almost agrees with the scatter of operating time, most of the factors behind the generation of control error under the same environmental conditions may be attributed to the mechanical operating scatter of the circuit breaker itself. Since the standard deviation, σ, for combination with this circuit breaker is 0.5 msec or less to meet the permissible operating scatter of ±1.5 msec for 3σ, which is a guideline of CIGRE (1), it can be concluded that the performance is sufficient for controlled switching.

Figure 6 shows the predicted errors (closing) when operated a number of times under the condition that the control voltage is maintained at a fixed level and the temperature is maintained at room temperature (DC 125 V, 10–30°C). The errors before and after applying compensation based on previous operating times are compared in the figure. Since the central value of closing time changes with long-term aging, the steady-state error increases with an increase in the number of operations when no compensation is applied. This means that control is performed without steady-state error by applying compensation based on previous operating times. The same trend was confirmed with controlled opening.

We intend to conduct further studies on expanded application ranges, improvement of control accuracy, and faster control algorithms.

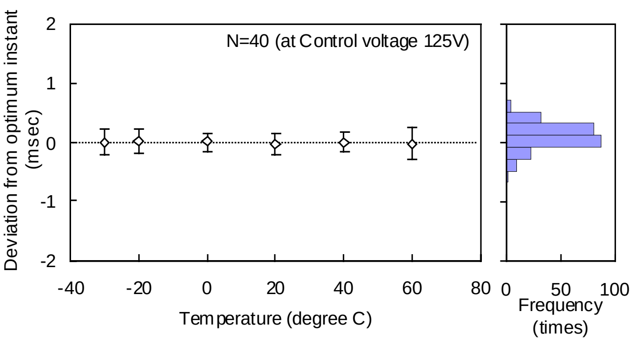

Fig. 4 Variation of controlled opening instants for different temperatures

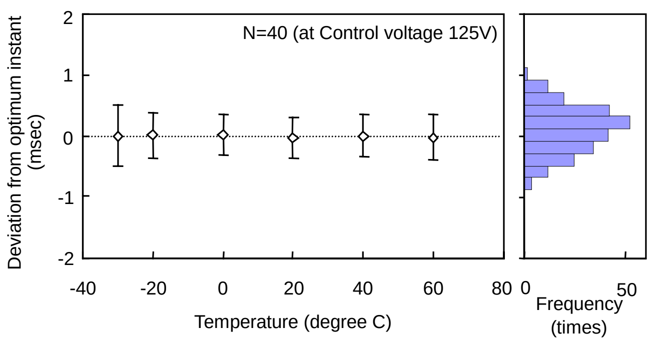

Fig. 5 Variation of controlled closing instants for different temperatures

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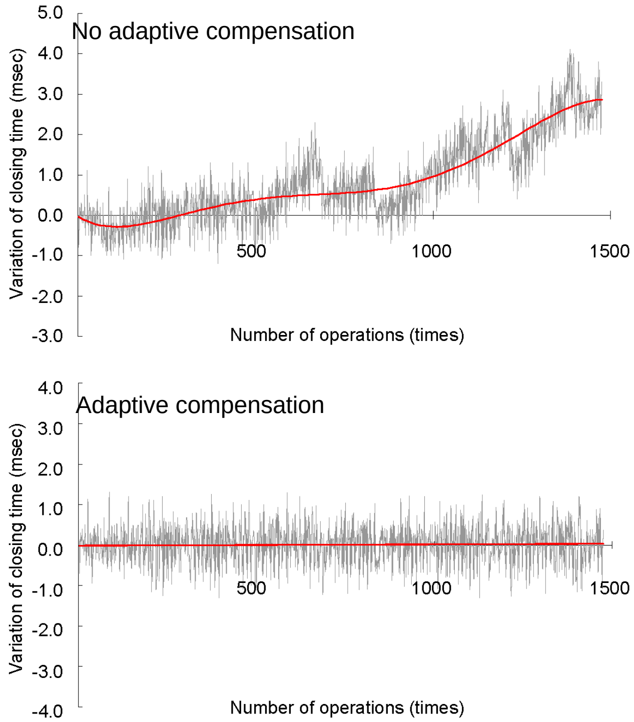

Fig. 6 Effect of adaptive compensation

Field Experience with Controlled Switching System Applied in Reactor and Capacitor Switching

Authors: *Haruhiko Kohyama**, *Tomohito Mori** and *Nobuhiro Torii**

1. Introduction

This paper presents a method to easily determine close or open targets based on electrical characteristics such as rate of decay of dielectric strength (RDDS) and mechanical characteristics such as scattering of operating time of circuit breakers. The validity of the method is verified based on the results of energization and de-energization of an actual circuit breaker system. This paper also introduces the excellent operating performance of a controlled switching system, including its compensation function for breaker operating characteristics, based on the records of actual long-term breaker operation as it was applied to capacitor banks and shunt reactors.

2. Setting of Energization Target [1]

The target point for energization can be directly determined from an energization test at a system voltage, with the breaker closing phase as a parameter, when the making voltage reaches its highest or lowest level. However, execution of multiple energization tests at real voltages may not be possible in certain cases, for example, the additional application of controlled switching function to an existing circuit breaker.

On the other hand, if the mechanical scatter and RDDS of the circuit breaker are known, the target point can be calculated as a function of these parameters. Figure 1 shows a conceptual representation of the relationship between the target point, mechanical scatter, and RDDS of the circuit breaker. For example, the target point for which the making voltage is set at the lowest level is given as a point that minimizes the largest making voltage in the distribution. Figure 2 shows the relationship between the mechanical scatter and target point in a case where RDDS is a parameter and the target is to minimize the making voltage. It is indicated that the target point approaches the zero voltage instant as RDDS increases and mechanical scatter decreases.

3. Application to Switching of VAR Compensation Equipment

When energizing phase-modifying equipment such as capacitor banks or shunt reactors with iron cores, a large inrush current is generated and causes problems such as increased wear of circuit breaker contacts and disturbance in system voltage. On the other hand, when de-energizing shunt reactors, re-ignition is generated, usually within short arcing times, and causes problems such as high re-ignition overvoltage and increased wear of circuit breaker contacts, etc. Even though re-strike free is required to prevent voltage escalation in de-energization of capacitor banks, it is a heavy task for circuit breakers that are required to perform numerous number of switching. As an effective and economical solution for such problems, the controlled switching system has become widely recognized and is increasingly employed.[2]

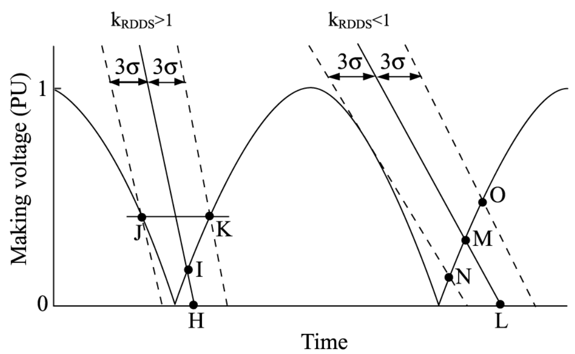

Fig. 1 Conceptual representation of target point for energization (Target: minimizing making voltage)

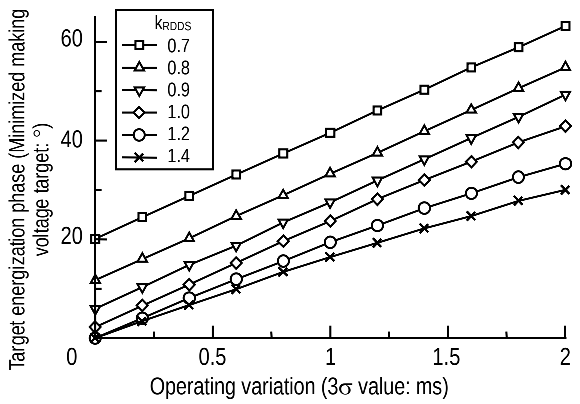

Fig. 2 Relationship between RDDS and target point for energization

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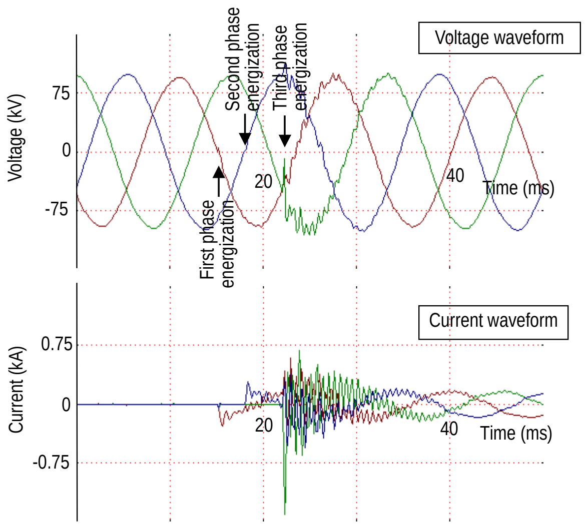
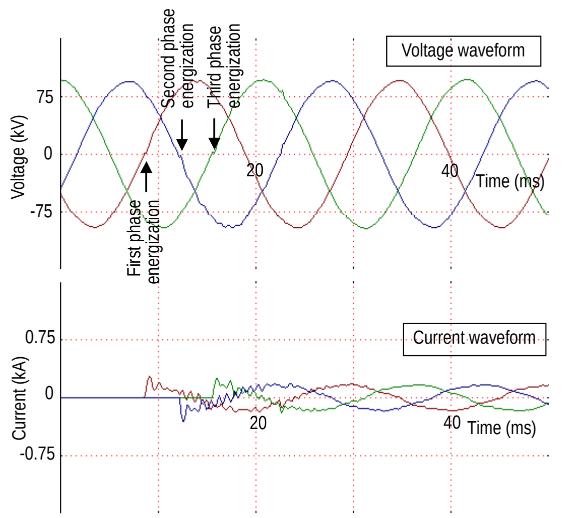
3.1 Example of application to switching capacitor banks

Figure 3 shows the results of the commissioning test conducted on-site where a controlled switching system was applied to 121 kV capacitor banks. In the first energization as shown in (a), energization of the third phase was delayed due to a tolerance of RDDS, resulting in the generation of an inrush current of about 7 PU. However, with the adaptive control effect of the controlled switching system, each phase was energized at zero voltage in the case of the tenth energization as shown in (b).



(a) First operation



(b) Tenth operation

Fig. 3 Voltage and current waveforms during capacitor bank energization

In the case of the controlled switching system used here, the tolerance of electrical characteristics of the circuit breaker mentioned above can be compensated by adaptive control[3] based on the operating history, since the energization time, which is the controlled result, is directly measured from the initiation of the main circuit current.

Figure 4 shows the distribution of making voltages in the actual operation over a period of about six months and the distribution of closing phases. The upper half of the figure shows the distribution of making voltages, and the lower half shows the distribution of mechanical closing instants. Distribution of closing instants is extremely limited; distribution centers on "16°", which is the close target. The maximum value of making voltage stands at about 0.35 PU, which is slightly lower than the estimated value of 0.4 PU based on mechanical scatter and RDDS. This is probably due to the actual mechanical scatter, which was lower than the results of the verification test at the factory.

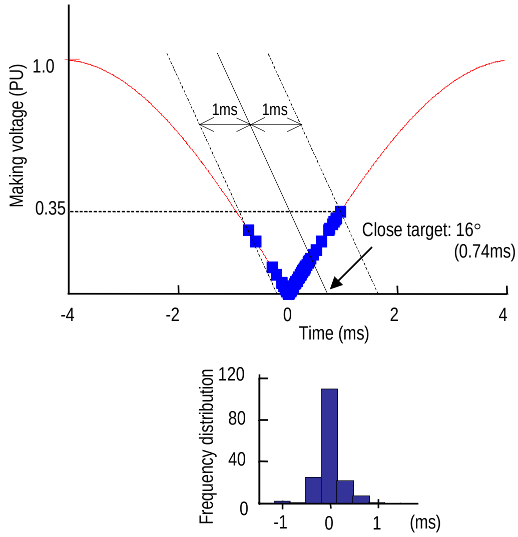


Fig. 4 Distribution of making voltages and closing instants

3.2 Application to switching of shunt reactors[4]

Figure 5 shows the voltage and current waveforms of controlled closing in the energization of a shunt reactor. We had confirmed that a maximum 3.0 PU of inrush current was generated in the energization of the shunt reactor without controlled closing. This figure, however, indicates that almost no inrush current resulted from controlled closing.

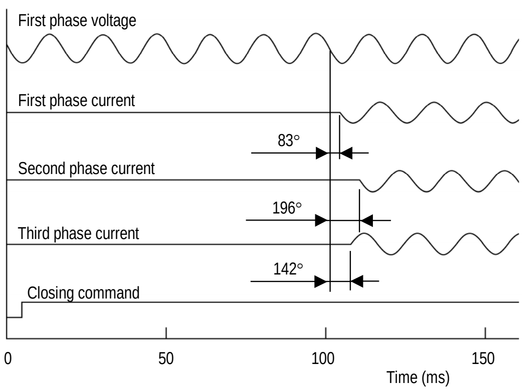


Fig. 5 Voltage and current waveforms of controlled closing in energization of shunt reactor (Controlled switching)

Figure 6 shows the voltage and current waveforms in de-energization of the load current of a shunt reactor. The current of each phase is de-energized from the first phase, third phase, to second phase in accordance with the phase rotation, and no high-frequency re-ignition current that indicates the generation of re-ignition is detected in the current waveforms. It is obvious that the GCB successfully completed de-energization without re-ignition.

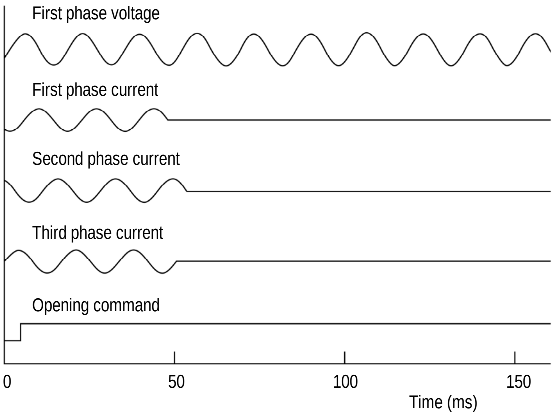


Fig. 6 Voltage and current waveforms in de-energization of shunt reactor (Controlled switching)

Figure 7 shows the distribution of making voltages in the actual operation over a period of about one year and the distribution of mechanical closing instants. The upper half of the figure shows the distribution of making voltages, and the lower half shows the distribution of closing instants.

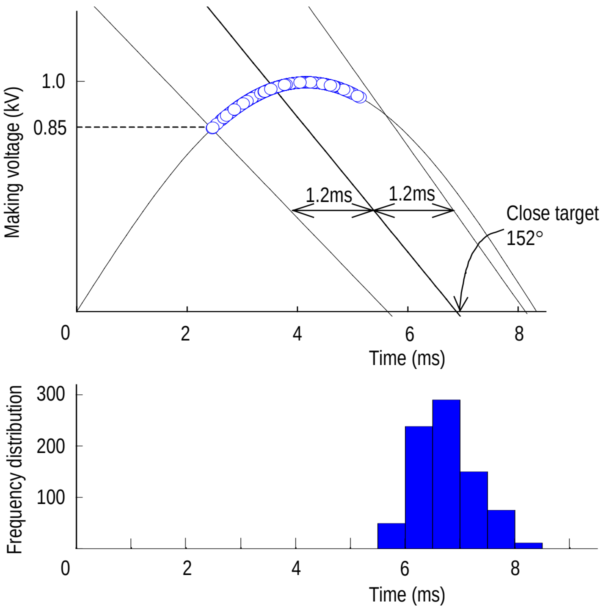


Fig. 7 Distribution of making voltages and closing instants

The mechanical closing instants distribution centers on "152°" after the voltage zero, in other words at about 7 ms, which is specified as the close target. All the control error were within ±1.2 ms, a sufficiently small distribution range that almost agrees with the value obtained in the verification test conducted at the factory.

The controlled switching system used for this purpose is provided with an alarm function set to start when the current continues in excess of 1/4 cycle of the estimated current de-energization time, which the function considers as generation of re-ignition. However, there was no alarm generated during the actual operation period; the controlled opening is also confirmed as functioning normally.

3.3 Evaluation of operating error in controlled switching

The validity of the operating characteristics verified at the factory was examined by evaluating the measurements of switching (opening/closing) time and the accuracy of controlled switching under the respective operating conditions of actual field operation over a period of about one year.

Figure 8 shows the ambient temperature in each closing operation. The ambient temperature varied from 4 to 33°C, for a width of about 30 K, and the maximum temperature gap between two adjacent closing times was 8 K. The variations in hydraulic oil pressure remain within a narrow range, from 31.5 to 32.5 MPa, which is the normal operating pressure range of the pump, and the control voltage remained at almost a fixed level due to stable power supply from the substation.

Figures 9 and 10 respectively show the variations in closing and opening time and the control errors during closing and opening operation. Both closing and opening time varied in accordance with the changes in operating conditions. However, the errors against the respective target were within ±1.2 ms in closing and within ±0.2 ms in opening, which verifies the relativity of operating conditions that were verified in the factory test and used in controlled switching and also the accuracy of the prediction for the closing and opening time based on the operating conditions.

Next, we examined the idle time characteristics in an actual application field. Figure 11 shows the relationship between the measurements of idle time and delay in closing time. Each point indicates the delay in closing time for the three phases in an actual application field, while the solid line indicates the idle time characteristics obtained in the factory test. The shortest and longest idle time during an actual operation period of about one year was 0.05 and 92 hours, respectively, and the delay in closing time is distributed within the range of ±1.2 PU centering on the value verified in the factory test.

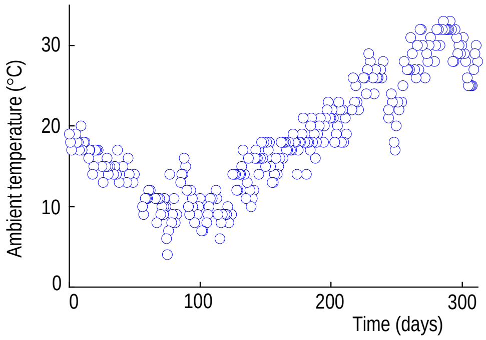


Fig. 8 Ambient temperatures during operation of circuit breaker

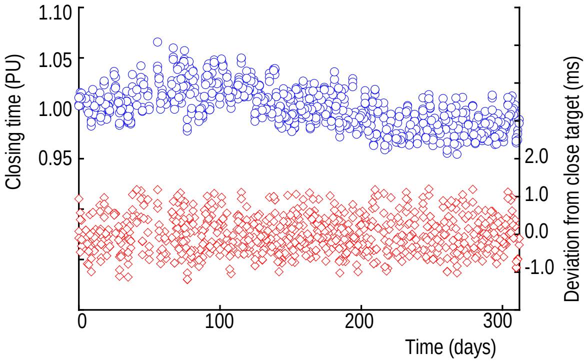


Fig. 9 Variation in closing time and deviation in closing target

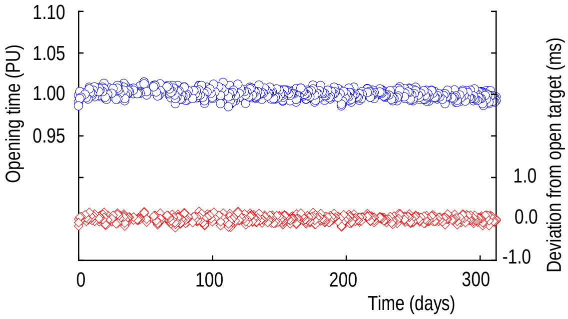


Fig. 10 Variation in opening time and deviation in opening target

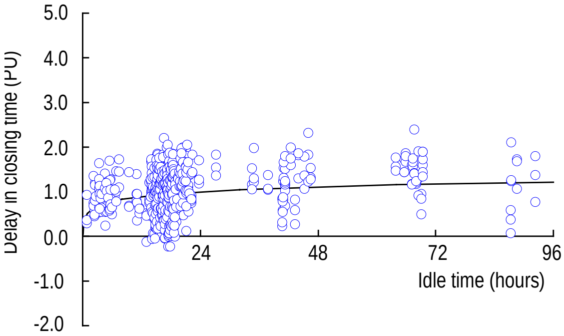


Fig. 11 Relationship between closing time and idle time in actual operation

4. Conclusion

This paper presented a method for setting the close and open targets in a controlled switching system based on the dielectric strength characteristics of circuit breakers and the mechanical operating variations obtained from no-load operation tests. In addition, it was confirmed, based on electromechanical switching operation in an actual system, that the application of controlled switching for capacitor banks and shunt reactors based on the close and open targets obtained from the method is effective for suppressing inrush current and preventing re-ignition.

Furthermore, it was confirmed, in connection with the variations in closing or opening time in response to the operating conditions, that the operating characteristics could be stably compensated over a long period by using the characteristics obtained from the factory test.

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Field Experience of Controlled Switching System Used for Transformer Switching

Authors: *Kenji Kamei** and *Haruhiko Kohyama**

1. Introduction

During unloaded transformer energization, the saturation characteristic of the iron cores is known to cause an inrush current that is several times as large as the rated current. The drop in system voltage accompanying this current is likely to adversely affect the operation of customers' devices or result in unnecessary tripping of protective relays in the local electric power station.

Recently, loaded equipment such as power electronics and electronic equipment that is sensitive to system voltage drops has rapidly increased. Therefore, it is important to suppress voltage drops caused by the inrush current in order to maintain and improve system stability and quality.

Conventionally, energization at fixed targets has been done without measuring the residual flux of iron cores. Usually, when an unloaded transformer is de-energized, a residual flux of several-dozen percent of the static flux remains. Whereas energization at fixed targets without measuring the residual flux enables the inrush current to be reduced by only about 60 percent of that when controlled energization is not applied, controlled energization taking into account the residual flux enables the inrush current to be suppressed to about 10 to 15 percent.

We were the first manufacturer worldwide to develop and apply in the field a controlled switching system that takes into account the residual flux. We verified that it considerably suppresses the inrush current that used to reach several thousand amperes and the voltage drop that exceeded 10% when controlled energization was not applied.

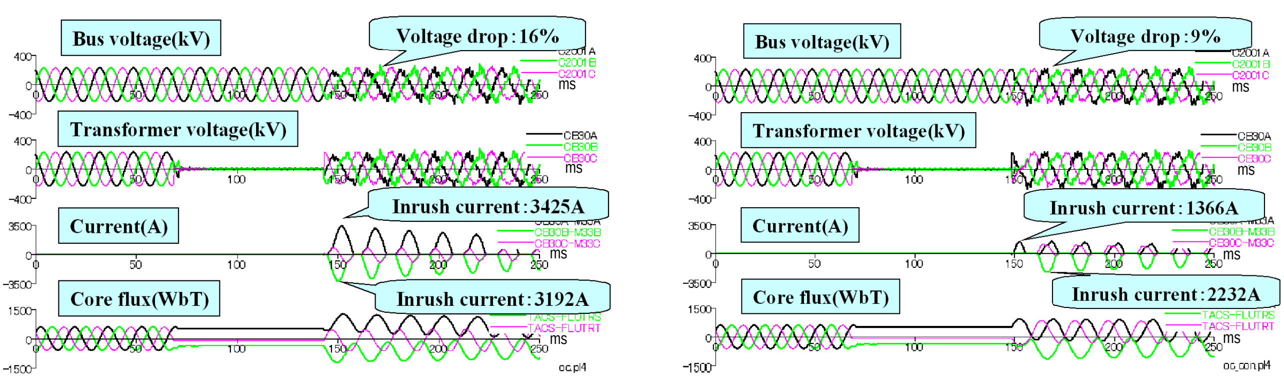
This paper discusses the method for using controlled switching to suppress the inrush current in unloaded transformers, an example of applying controlled switching to a power system, and remaining issues to be solved in order to increase the scope of application.

2. Generation of Inrush Current in Unloaded Transformer and Suppression Method

2.1 Generation of inrush current

In the case of shunt reactors or iron-core equipment such as unloaded transformers, the circuit breaker can be energized at the phase angle of voltage at which saturation of iron cores does not occur. Shunt reactors generally have an iron core with air-gap, and so the residual flux is extremely small. Therefore, if the circuit breaker is energized at the time when a static flux becomes zero, that is, at the voltage peak, no transient flux phenomenon occurs, the iron core does not become saturated, and no inrush current flows. The transformer can also be energized at the voltage peak in the same way as the shunt reactors if no residual flux is present.

Figure 1 shows EMTP analysis of transformer energization phenomena caused by three-phase simultaneous energization and conventional controlled energization without measuring residual flux. In this example, three-phase simultaneous energization causes an inrush current exceeding 3,000 A to flow, and hence a 16% transient voltage drop occurs. It is also clear that



(a) Simultaneous energization

(b) Conventional controlled energization

Fig. 1 Voltage disturbance at transformer energization (EMTP analysis)

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conventional controlled energization can reduce the inrush current by only about 60% of that at three-phase simultaneous energization.

Thus, effective suppression of the inrush current and voltage drop requires controlled energization taking into account the residual flux[1].

2.2 Controlled energization method taking into account the residual flux

The optimal closing target taking into account the residual flux is the time when the residual flux and the static flux match. If the circuit breaker is energized at this optimal closing target, no transient flux phenomenon occurs, and no inrush current flows.

In the actual circuit breaker, as scatters in the ratio of decay of dielectric strength (RDDS) and the closing time of the circuit breaker are present during energization, controlled energization taking into account those scatters is done.

Figure 2 shows the method for deciding the closing target while taking into account the residual flux: –40% (–0.4PU), RDDS (K_{RRDS}) normalized at the inclination at which the voltage is zero: 0.7±10% and closing time scatter: ±1 microsecond. In this figure, the intersection point R where the static flux and the residual flux match is the optimal closing target. However, if the electrical and mechanical scatters of the circuit breaker are taken into account, the inrush current can be more effectively suppressed by setting as a closing target the point where the possible difference between static flux and residual flux becomes smallest in the distribution range of the assumed closing target[2]. Figure 3 shows the result of calculating the closing flux error at each closing target under the conditions shown in Figure 2. This example indicates that the point P where the closing flux error becomes smallest can be set as a closing target.

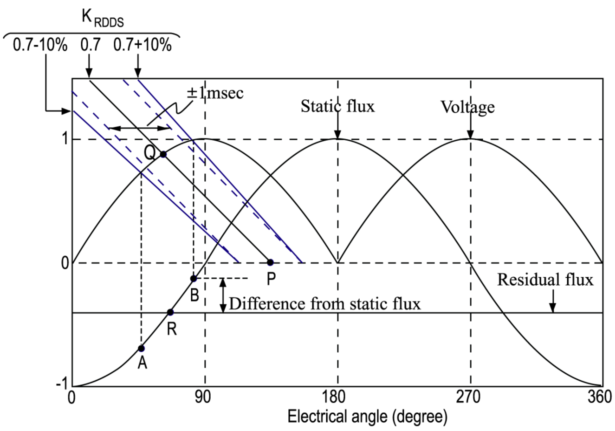

Fig. 2 Decided method of the optimal target for transformer energization taking into account residual flux

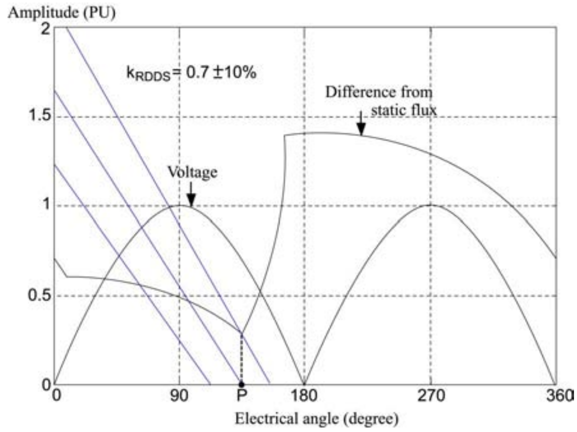

Fig. 3 Optimal target for the first phase dependence on a residual flux

2.3 Three-phase transformer energization sequence

In the case of a three-phase transformer, each phase circuit breaker can be energized at the optimal closing target for the flux at each phase. However, after energization of the first phase, because the remaining two phase fluxes change depending on the three-phase iron core configuration and connection state, the optimal closing targets of the remaining two phases cannot be decided by residual fluxes alone[3].

Figure 4 shows the controlled energization sequence taking into account the residual flux for a three-phase transformer having three-phase iron cores or delta connection.

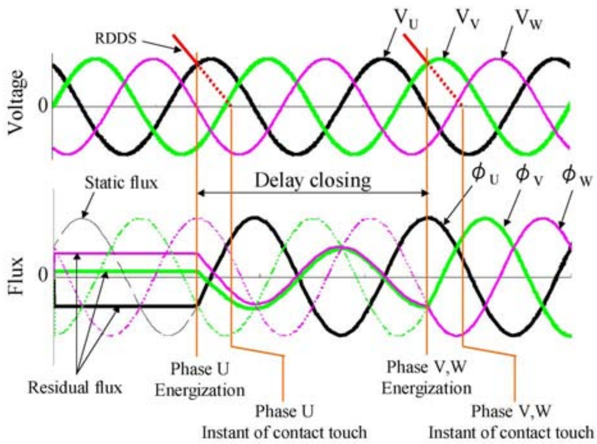

Fig. 4 Delayed energization sequence taking into account of the residual flux

In this figure,

(1) The phase at which the residual flux is maximum (phase U in the figure) is first energized at the phase angle of the voltage where the residual flux and the static flux match.

- When phase U is energized, the remaining two phase (phases V and W) fluxes converge to the same value while oscillating with the polarity opposite to and with an amplitude that is about half of three-phase iron cores or delta connection.

those at phase U under the influence of three-phase iron cores or delta connection.

(2) Phases V and W are energized at the peak of phase U flux after the time when the phase V and W fluxes become about the same.

- The peak of phase U flux is the phase at which phase V and W fluxes match the static flux.

Energizing the circuit breaker in the above sequence suppresses the inrush current.

2.4 Example of applying CSS taking into account the residual flux to a power system

Figure 5 shows the configuration diagram of CSS applied to an extra high voltage power system transformer to control energization taking into account the residual flux(4). In this configuration, the transformer terminal voltage is measured with the inductive voltage transformer (VT) when the circuit breaker is opened and the voltage waveform is integrated to obtain the residual flux. In this example, residual flux of approximately 40% is generated. As shown in Figure 6 (b), the phase (V) where the residual flux is maximum is first energized at the time when the static flux and the residual flux match and the remaining two phases (U and W) are energized at near the peak of phase V flux about 1.5 cycles after energization of phase V. It is clear that such energization control can reduce the transient flux phenomenon at phases and considerably suppresses the inrush current that reaches several thousand amperes and the voltage drop ratio that exceeds 10%, generated if controlled energization shown in Figure 6 (a) is not applied.

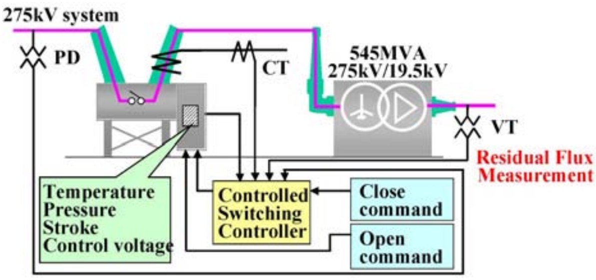

Fig. 5 Configuration of CSS for transformer

The system has been operated in the field for a half year to confirm EMC, climatic, and aging performance for practical reliability. Voltage and current waves, circuit breaker operating conditions, and residual flux at each operation were recorded in the switching controller and sent to the factory for analysis. Figure 7 shows voltage disturbance calculated from inrush currents. The circuit breaker was operated with an idle time of up to 278 hours, and inrush current were controlled within the operation target of 2% for voltage drop.

3. Problem with Application of CSS to Circuit Breaker Equipped with Grading Capacitor

To enhance the de-energization performance and improve the sharing of voltage among units in the multi-break circuit breaker, the circuit breaker may be equipped with a grading capacitor (Cp). When such circuit breaker is used to de-energize the unloaded transformer, the power-frequency AC voltage determined by the divided voltage at the impedance between Cp and transformer is generated on the transformer terminal even if the circuit breaker is opened. The amplitude of this voltage is estimated to be about several percent of the rated voltage of the transformer. However, this voltage magnetizes the iron cores, and a small hysteresis loss will always occur (a small hysteresis loop is referred to as a micro-hysteresis loop). If a system disturbance such as a line-to-ground fault occurs in the power side of the circuit breaker while the circuit breaker is opened, the power side voltage transiently drops, and a large voltage is generated on the transformer terminal depending on the frequency of the transient voltage.

Figure 8 shows the flux waveform obtained by integrating the transformer terminal voltage and the transformer terminal voltage during transformer de-energization obtained by an experiment using a small-capacity transformer (6.6 kV – 50 kVA). It is clear that the flux waveform pulses under the influence of Cp after transformer de-energization. It is also clear that a voltage drop simulating a system disturbance between A and B in the figure reduces the residual flux.

In Figure 8, a voltage continued to be applied for several hours after point B and controlled energization was then done based on the residual flux near point C, but almost no inrush current flowed. This indicates that the residual flux at point C also remained unchanged after several hours. This result shows that the micro-hysteresis loop does not affect attenuation of the residual flux and that a transient voltage drop changes the residual flux in the range of the experiment.

As previously discussed, the application of CSS to a circuit breaker equipped with a grading capacitor requires a function that can measure the change in the residual flux caused by the transient voltage during a system disturbance.

4. Conclusion

We developed a controlled switching system for transformers taking into account the residual flux and verified in the field that it can sufficiently suppress the inrush current and the voltage drop accompanying the inrush current. We also discussed the problem with applying CSS to circuit breakers equipped with grading capacitors.

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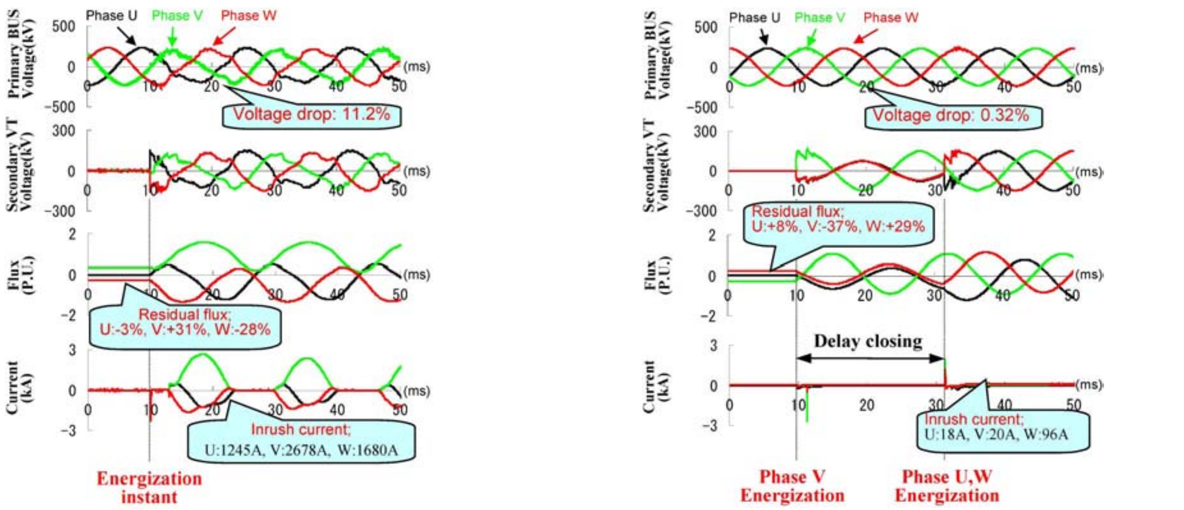

(a) 3 phases simultaneous energization (b) Controlled energization taking into account the residual flux

Fig. 6 Voltage, current and flux measurement

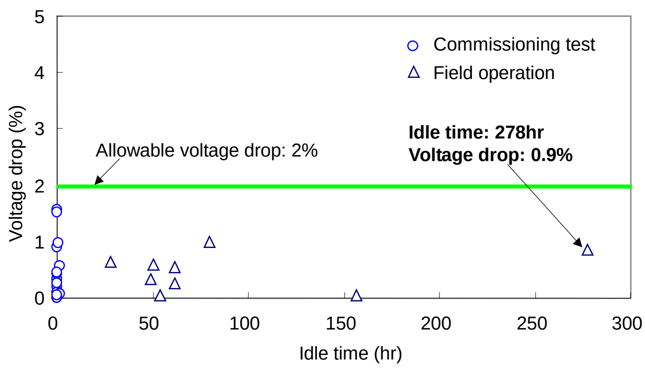

Fig. 7 Voltage disturbance by controlled energization of transformer by CSS taking into account a residual flux

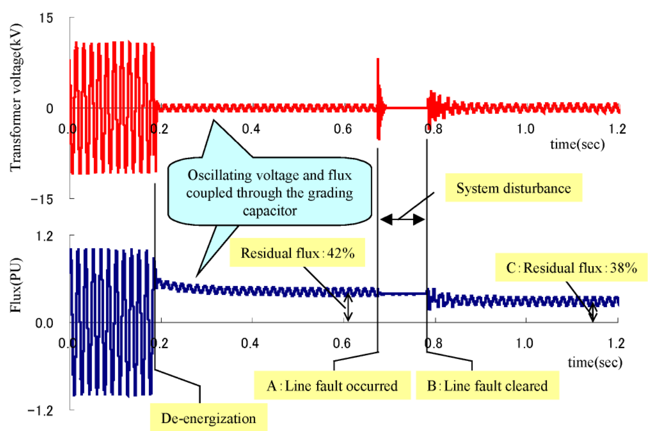

Fig. 8 Transformer voltage, flux measurement at single phase de-energization by the circuit-breaker with grading capacitor

Sensors Used for Controlled Switching System

Author: *Akihide Shiratsuki** and *Ryuichi Nishiura**

1. Introduction

To expand the scope of application of the controlled switching system, we developed a travel sensor for noncontact detection of electrode travel and a voltage/current sensor capable of completely nongrounded measurement as easy-to-use and low-cost sensors for the controlled switching system.

2. Travel Sensor

In the controlled switching system, parameters are corrected based on the actual value of operating time measured by the travel sensor to predict the next operating time, with the travel sensor as the key technology. In the conventional controlled switching system, the rotation sensor (encoder) is used to detect contact travel during the switching time. However, installing the system on existing equipment requires extensive modification of the synchronized driving system and it is difficult to apply the system. As the system will be applied to a wider range of applications, including existing equipment and many additional models, an easy-to-retrofit travel sensor based on a new system was requested.

As the method for detecting electrode travel, we propose a system in which the reflector is attached to the shaft connected to the electrodes and the position of the reflector moving with the shaft is detected optically, with no contact.

Figure 1 shows the principle of the proposed travel sensor. As the reflector to be attached to the shaft, a retroreflector that reflects light in the same direction as the incident direction of light is applied. The head of the travel sensor consists of a line image sensor that is a one-dimensional picture element, an imaging lens that forms an image of the light reflected from the reflector on the line image sensor, and a light-emitting diode (LED) as the light source. In addition, there is a coaxial optical system that uses a half mirror to ensure that the visual field of the line image sensor and the plane exposed to LED light are in the same plane. When the reflector moves with movement of the shaft, the position of the reflector image formed on the line image sensor also changes. Since the electrical signal output from the line image sensor becomes the brightness signal that peaks at the position of this formed image, the reflector motion, that is, the electrode motion, can be detected from the peak position of the picture element. Only the configuration of the sensor as previously discussed, with the reflector attached to the shaft and the sensor head installed so as to allow the reflector to enter the visual field of measurement, enables noncontact detection of electrode travel.

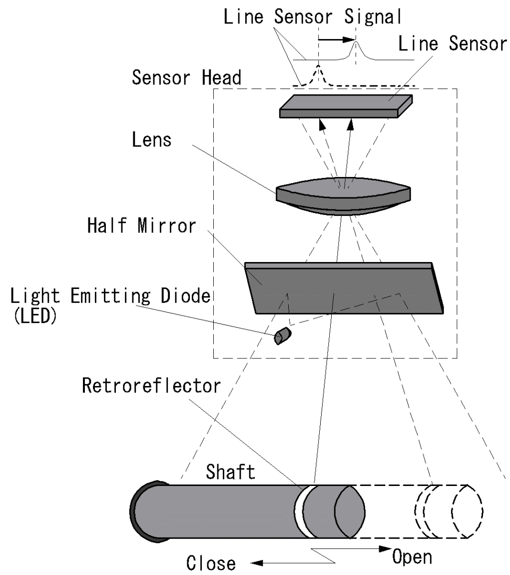

Fig. 1 Principle of travel sensor

The line image sensor used in the travel sensor has a resolution of 2,500 pixels or more, which can attain the target specification. The LED light source is configured to emit pulsed light (pulse width: 6.6 µs) at the blanking time of the line image sensor and ensure that no detection error is caused by image blur even during movement of the shaft.

With a manufactured prototype attached to an actual breaker, the changes in position of the shaft during breaking and making procedures were measured. At the same time, a conventional encoder was used for measurement. Figure 2 shows the results of measuring the travel sensor output and encoder output during 100 making tests.

As shown in Fig. 2, highly repeatable measurement results were obtained for 100 measurements. In the domain from 30 to 60 ms after starting measurement, a difference occurred between the encoder output value and travel sensor output value. While the encoder measures the rotational motion based on the movement of the shaft, the travel sensor directly meas-

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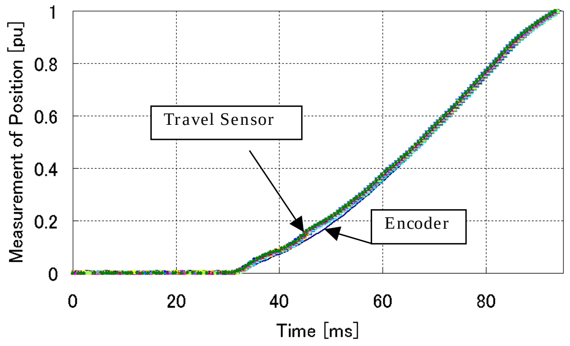


Fig. 2 Output of the travel sensor and encoder

ures the motion of the shaft. Therefore, the travel sensor is assumed to have detected wobbling due to play in the driving mechanism that cannot be detected by the encoder. In other words, the travel sensor faithfully detects the motion of the shaft.

At the position of 75 ms after starting measurement, the difference values between the travel sensor and encoder outputs were obtained to calculate their variations. The resulting value was a standard deviation (σ) of 0.14 mm. Considering that this value also includes encoder output variation, it means that high repeatability can be obtained, proving that the travel sensor has sufficient performance as an electrode travel sensor.

3. Voltage/Current Sensor

We developed a voltage/current sensor that measures voltage waveform on the load side and monitors current waveform in the controlled switching system for transformers and power lines. Since the controlled switching system standardizes and uses voltage waveforms as control parameters, a voltage sensor is regarded as functioning sufficiently if it can obtain the relative output signal.

The conventional device requires an isolator for ensuring isolation to ground, which is a main cause of the high cost. With the first aim of reducing cost, the sensor was designed to eliminate the need for the isolator and enable completely nongrounded measurement. This sensor roughly consists of a voltage measurement section, current measurement section, and radio data transmission section. Figure 3 shows an image of the sensor, and Table 2 lists the measurement specifications.

In the above voltage sensor, the current measurement section uses a conventional air-core coil current sensor. Details of the newly developed voltage measurement section and radio data transmission section are discussed below.

The method by which the voltage sensor is grounded to measure the overhead wire voltage to the ground requires an expensive member such as an isolator due to the problem of withstand voltage. Therefore, as shown in Fig. 4, a capacitor voltage dividing system employing a capacitor using air as the dielectric was designed.

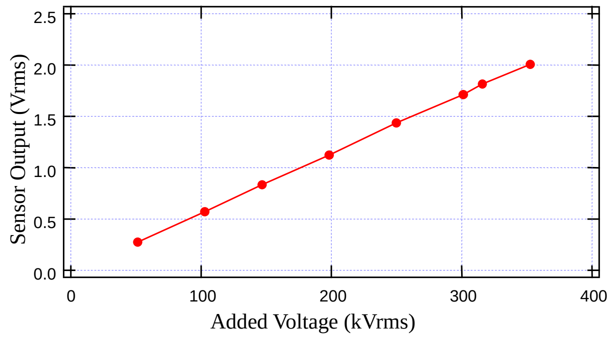


Fig. 4 Result of high voltage measurement

In this system, an electrode (intermediate electrode) paired off with the ground is provided to form the capacitor. With the voltage divided by this open-air capacitor and measurement capacitor, the potential at both ends of the measurement capacitor is the differential measured to measure the voltage. The ground of the sensor circuit is connected to the high-voltage overhead wire to place the sensor and high-voltage overhead wire at the same potential, which eliminates

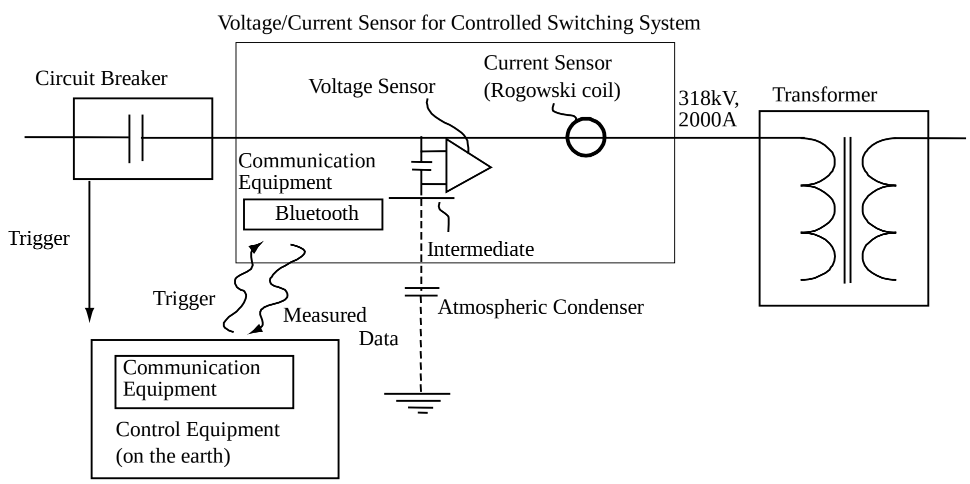


Fig. 3 Schematic diagram of voltage/current sensor

the need to take into account the withstand voltage.

In order to verify the principle, a prototype was manufactured and a high-voltage verification test was performed. As shown in Fig. 4, the verification test results confirmed that this sensor can measure voltage of up to 350 kVrms for high-voltage overhead wires with linearity of ±1.6%FS and proved that it is useful as a voltage sensor for the controlled switching system.

Since the purpose is to measure the voltage of high-voltage overhead wires (318 kVrms), the wire portion must be deleted due to the problem of withstand voltage. Thus wireless communication is employed for data transfer. If wireless communication is used for data transfer, there is a concern that electromagnetic noise such as corona discharge in the high-voltage overhead wire would adversely affect data transfer. Therefore, digital communication is indispensable, but real-time measurement is difficult since retrying data transfer causes delay due to the effect of electromagnetic noise. To solve this problem, we developed a digital wireless communication device that can use Bluetooth having a synchronous communication mode to ensure time synchronization between the control unit (ground) and the sensor.

Specifically, as shown in Fig. 5, in the Bluetooth synchronous communication mode, transmission and reception modes (slots) are alternately switched for communication, the timing of which is polled to establish synchronization. This device detects the slot switch timing and corrects the timing table update cycle to ensure that the timing table is updated at the same timing between the control unit and the sensor. This enables correction of the measurement time for processing on the control unit side.

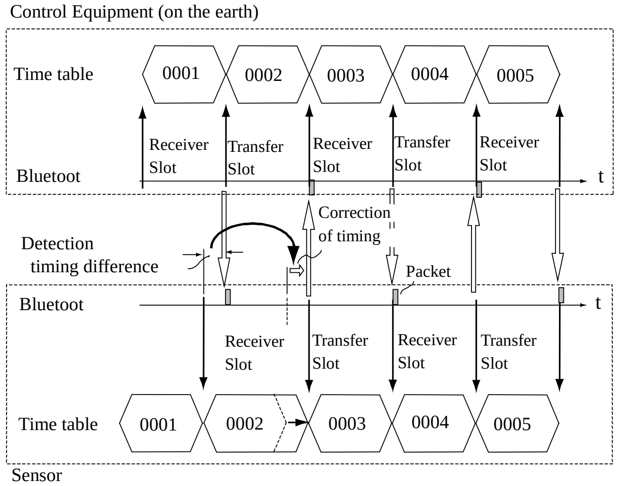


Fig. 5 Correction measurement time

In order to verify the principle of this time synchronization system, a prototype was manufactured and a verification test was performed. The verification test used a logic analyzer to measure the timing tables for two synchronous communication devices and the update time was monitored. In the verification test results, the values of the two timing tables matched within a time difference of 6 microseconds.

This verifies that the system can ensure time synchronization of 6 microseconds or less, and digital wireless data transmission based on this system maintains the time compatibility between the control unit and sensor.

These newly developed sensors are expected to expand the scope of application of the controlled switching system.

Controlled Switching System To Solve Transients Problem in the Field

Author: *Haruhiko Kohyama**

1. Controlled Switching System

The controlled switching system of gas circuit breakers (GCB) is an economical and effective solution to eliminate harmful transients in networks and to reduce the cost of maintaining equipment.

Table 1 summarizes the advantages of the controlled switching system for each type of switching purpose.

Table 1 Advantages of controlled switching system

Load type	Transients	Merit
Transformer energization	Inrush current	• Elimination of closing resistor • Improvement of power quality • Prevention of mal-operation of secondary system
Shunt reactor energization	Inrush current	• Elimination of closing resistor • Improvement of power quality • Prevention of mal-operation of secondary system
Capacitor bank energization	Inrush current	• Reduction of GCB contact wearing
	Over-voltage	• Reduction of insulation level
Line energization	Over-voltage	• Elimination of closing resistor • Reduction of insulation level
Shunt reactor de-energization	Over-voltage	• Reduction of insulation level • Reduction of GCB contact wearing
Line/capacitor bank de-energization	Over-voltage	• Improvement of re-ignition free reliability

2. Mitsubishi's Controlled Switching System

The controlled switching system using Mitsubishi's synchronous switching controller (SSC) has high accuracy and reliability backed by a solid track record in the field around the world. The main ratings of the SSC are summarized in Table 2.

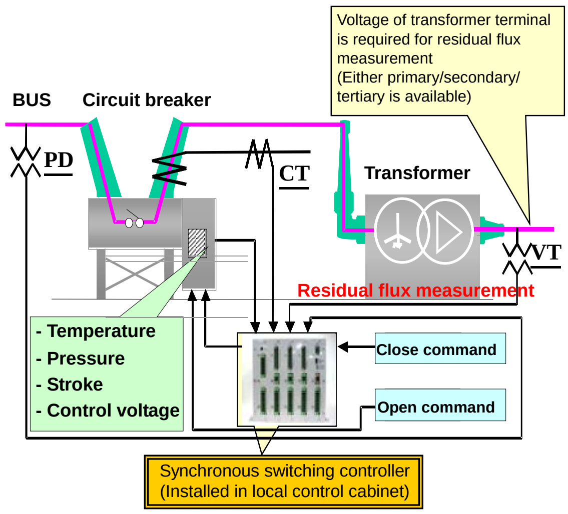
Table 2 Main ratings of Mitsubishi SSC

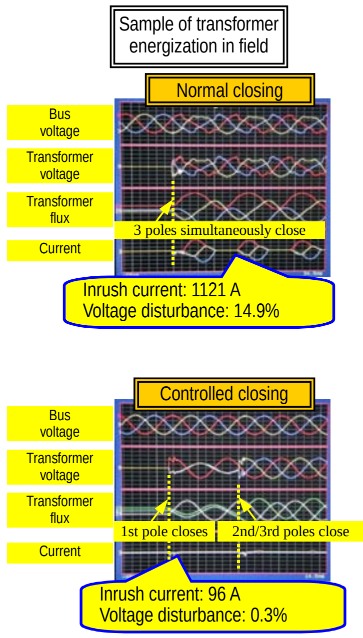
Item	Rating
Control voltage	DC 100/125 V
Frequency	50/60 Hz
Consumption	35 W or less
Control output	3 close and 3 open signals
Reference voltage	57/100/110 V
Reference current	1/5 A
Ambient temperature	-30 to +60°C (<95% RH)
Dimensions	W: 220 × H: 260 × D: 260 (mm)

(1) Compensation of GCB operation
The operating time variation of GCB can be compensated to maintain accurate control according to operating conditions, past operation results, idle time, ambient temperature, control voltage and operating pressure.

(2) Measurement and recording of GCB operation
The SSC can store the operation times and conditions of the past 200 operations, thus allowing GCB conditions to be monitored.

(3) High reliability
The SSC is designed using advanced technology supported by experience in relay and monitoring systems, and has excellent reliability and robustness.





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