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RELIABILITY OF SEMICONDUCTOR CONTROL DEVICES FOR SYNCHRONOUS AIR-BLAST CIRCUIT BREAKER FOR ONE CYCLE INTERRUPTION (Part 1)
RELIABILITY FOR IMPULSIVE SURGE

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I. INTRODUCTION

The synchronous air-blast circuit breaker for one cycle interruption (hereinafter referred to as ABBS) is a high speed circuit breaker, whose moving contact is driven 1.5 ms before zero current and current interruption is completed at this following zero current point 1.5 ms. In conventional magnetic control equipment, a considerably long period of time was required for the operation of the controlling device. Hence, these devices were not satisfactory for control of high speed operating equipment. For this reason, the ABBS, (previously described in detail in the Fuji Electric Review Vol. 11 No. 4, 1965), employs a semiconductor control device to effectively minimize operating time. Design considerations in this device differ radically from those of conventional breakers. These differences are described in the following.

Generally, semiconductors have a much lower overload capacity than magnetic equipment which operates in slow motion and may be extensively damaged if proper circuit design considerations are not applied with respect to instantaneous input load. Hence, in designing ABBS, full consideration was given to providing an appropriate safety factor and various tests were performed toward improving reliability. Based upon these considerations, Fuji Electric has developed a reliable high speed semiconductor control device for ABBS.

Although there has been a trend toward increased use of semiconductors in power equipment, there has never been realization in the use of semiconductors for ultrahigh-voltage equipment. The following essential (prerequisite) conditions must be satisfied in applying semiconductors to such equipment.

1) Wide temperature range (−20°C to +70°C)
2) Long service life with highly reliable circuit operation, without the need for frequent inspection.
3) Complete reliability with respect to surges caused by lightning or switching.
4) High level insulation.

External view and primary circuit connections are shown in *Figs. 1* and *2*.

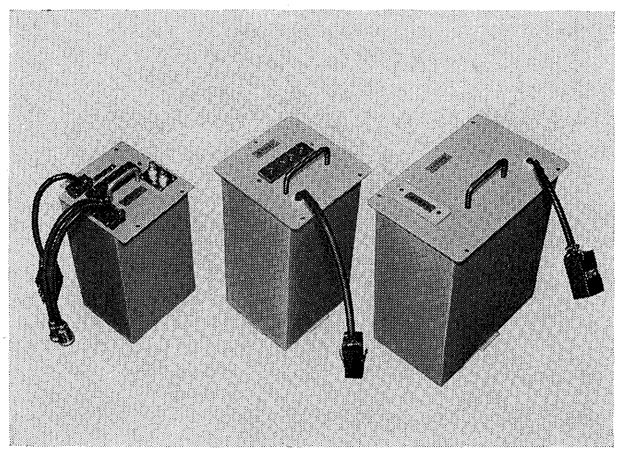

Fig. 1 Photopulse acceptor, photopulse generator and synchronous pulse generator

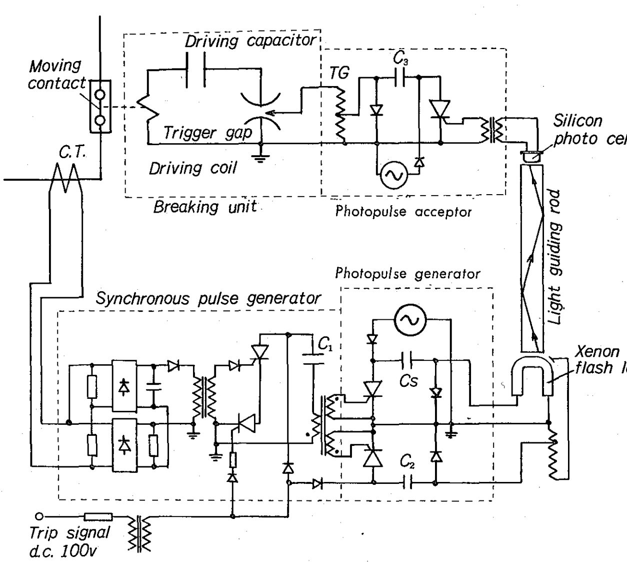

Fig. 2 Construction of semiconductor control device

With the synchronous pulse generator connected to the current transformer, detection occurs approximately 1.5 ms. before the zero point of line current "*I*", which flows through the breaker. When line current is small, a pulse is generated approximately 7 ms. after the trip signal, independently of the phase of the line current. Synchronous pulse generator output is imposed upon the photopulse generator thyristor to convert the charge of capacior C_s to a photopulse by applying it to a xenon flash lamp. However, under actual operation, these circuits which are dormant must be activated by trip signals. To accomplish this, source capacitor " C_1 " must be constantly charged and the power source " C_2 " of the photopulse generator must be actuated by a trip signal. Time required is approximately 1 ms. The photopulse generated by the xenon flash lamp as a result of the trip signal is effectively transmitted through an acryl resin light guiding rod due to complete boundary reflection. This photopulse is then reconverted to an electric pulse by the silicon photocell, a photo accepting element, to turn on directly the thyristor in the photo acceptor. When the thyristor becomes "on", the charge on C_3 is discnarged to T_g through the thyristor, inducing a high voltage at the T_g output terminal which operates the trigger gap for discharge of the driving capacitor. As a result the moving contact is quickly driven to complete interruption. (Refer to separate sheet for further information on interruption.)

II. CAUSES OF SEMICONDUCTOR DISTURBANCES

1. Disturbance Caused by Lightning

Overvoltage due to lightning depends upon the strength of the lightning and the surge impedance of the transmission line. However, it can be generally represented by a standard wave of $1\times 40\ \mu$s and an impulse voltage of 1050 kv in a 300 kv line when arrester action is considered. Thus, careful attention must be given to induced voltage, electrostatically induced from the high voltage, and withstand voltage.

2. Disturbance due to Surge Caused by Switching

The control device is more liable to be affected by switching surge under special circuit conditions than by lightning, since the rate of rise of surge is sharp and high. For example, consider breaker disconnection from the line by a line switch (L.S.) in a substation where a potential divider (P.D.) and line switch (L.S.) are placed near the breaker as shown in *Fig. 3*. *Fig. 4* illustrates the operating principle. However, a few cycles are required in practical interruption since it coincides with the dielectric strength curve between LS contacts.

Assuming that $C_0 \gg C_1$ and the charge in C_0 discharges through C_1, maximum 275 kV line voltage can be expressed as follows:

$$Em = 2\sqrt{2}E = 2\sqrt{2}\times 275/\sqrt{3} = 450\ \text{kV}$$

In considering only the variation part of voltage and current:

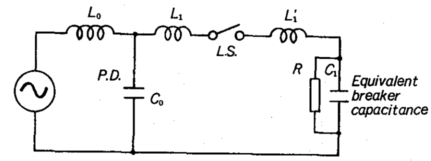

Fig. 3 Equivalent circuit for switching surge

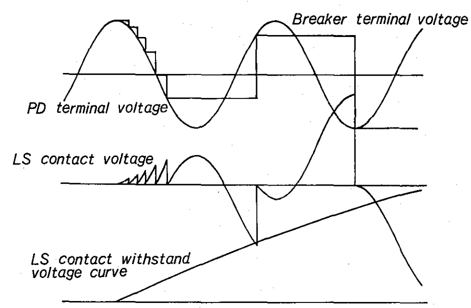

Fig. 4 Oscillogram of interruption by L.S.

$$i = \frac{Em}{\sqrt{L/C-(R/2)^2}}\varepsilon^{-\alpha t}\sin\beta t$$

$$v = 1 - \left[\frac{\varepsilon^{-\alpha t}}{\sqrt{1-C/L(R/2)^2}}\sin(\beta t + \theta)\right]\cdot Em$$

Where: $\alpha = R/2L$

$\beta = \sqrt{1/LC-(R/2L)^2}$

$\theta = \tan^{-1}\beta/\alpha$

Where $C_0 = 8000$ pF, $C_1 = 300$ pF and $L = 30\ \mu$H, the natural resonance frequency will be as high as 1.6 Mc/s and the rate of change in voltage build-up will reach 4500 kv/μs. It has generally been assumed that phase-to-ground voltage was about 1.5 *Em* (675 kv) of the peak value, due to oscillation. However, it has been found, and substantiated through tests, that no difficulties are encountered with test voltages 1.8 times (1210 kv) the prescribed value.

Current at the opening of L.S. is:

$$I \doteqdot Em/\sqrt{L/C} = 1.43\ \text{ka}$$

Rate of change in current is:

$$di/dt = \beta I = 14.2\ \text{ka}/\mu\text{s}.$$

Thus, current equivalent to the rate of change in current due to lightning is applied during a period of several cycles with interruption.

Since only a part of the lightning charge in the transmission line may flow to ground through the breaker capacitance or may merely pass through the line, a severe switching surge is more dangerous for the semiconductor control device than lightning.

3. Disturbance from Other Causes

Lightning current from the transmission line can also affect the synchronous pulse generator through the current transformer. In addition, the peak value of the making current must also be considered.

Also, surging may affect the control wire due to unbalance in ground potential caused by ground, arrester discharge or lightning current. Some potential differences are reported to be as high as several thousand volts. This can be effectively prevented by electrical shielding between control wires with a shielded isolation transformer.

III. BASIC DISTURBANCE PREVENTIVE METHODS

1. Common Preventive Methods

Power silicon elements are widely used as circuit elements because of their high withstand voltage and current which permit this device to be used under a wide temperature range. Moreover, these elements are used with one-fourth of rated voltage and normally at least two elements are connected in series. Hence, the failure in one element does not necessitate immediate repair ; constant checking is not required and extended service life is obtained.

Since the semiconductor control device is extremely weak for high values of *dv/dt*, it is installed in a highly conductive case to prevent adverse effects therefrom. Shielded or copper or steel tube covered cable is used for external wiring to provide complete shielding. Moreover, the control device is of unit construction with a one-point ground and is carefully connected for assured reliability against external disturbance.

2. Protective Methods for Individual Units

The breaker is used under more severe *dv/dt, di/dt* conditions. Thus, surging from external control wires may have an adverse effect. To provide proper protection, low-pass filters composed of MP capacitors are provided for each input terminal with shielded isolation transformers provided on each input terminal connected to external circuits. Through this shielding and small capacitors connected to the secondary wiring of the transformer, the conversion ratio of the primary winding-to-ground voltage is limited to less than 1% at the secondary winding.

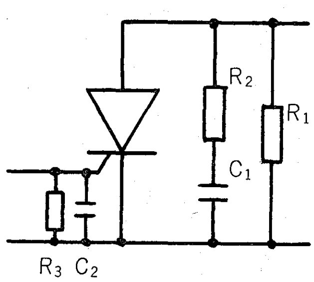

Fig. 5 Standard circuit for thyristor

Through the use of the low-pass filters and shielded transformers, surge voltage and current are effectively reduced, as can be clearly seen with respect to distributed voltage, which is discussed later.

With respect to the thyristor in the unit, it is designed with considerations for protection of the gate circuit and a decrease in forward breakover voltage. *Fig. 5* shows the basic composition. A zener diode is series connected to the gate circuit for confirmation of gate signals.

3. Interlock by Trip Signals

Various methods are provided to protect the semiconductor control device. Moreover, the semiconductor control circuit is designed to prevent failure or improper operation due to frequently incurred thyristor failure.

1) Synchronous pulse generator

As shown in *Fig. 2*, the control system employing thyristors is normally open. However, when trouble occurs in the transmission line, voltage potential in the defective portion instantly changes into a travelling wave, reaches the stations, and is then stabilized into commercial frequency fault voltage and current. Travelling waves with surge of greater *dv/dt* and *di/dt* are more likely to cause damage and affect operation. If abnormal operation is observed, it would most probably be during this period. At the moment trouble occurs, the protective relay does not operate nor is a trip signal generated. Consequently, the synchronous pulse generator is taken out of operation at the moment surge current and voltage are applied. Therefore, even if the thyristor is not properly triggered, there is no output and proper conditions are restored as the surge disappears. Trouble is then detected, a trip signal is generated, and normal operation is immediately restored.

2) Photopulse generator

The trigger power circuit of the photopulse generator is normally open and functions in a manner similar to that of the synchronous pulse generator. The main contact circuit is always activated and thus, even if a thyristor is not triggered, the xenon flash lamp does not operate since the trigger electrode does not operate. Since the thyristor is designed to be below holding current, it is restored to normal as surge disappears, and then operates as the trip signal is generated.

4. Protective Methods for Entire Control Circuit

Photopulse generator, photopulse acceptor, synchronous pulse generator, etc., are combined in units to facilitate inspection, maintenance, and replacement as well as providing effective electrostatic shielding and one-point grounding. ABBS has two independent operating systems to provide positive operation when one fails. The grounding wires

Table 1 **Effect of Fundamental Protection**

			Principal Effect of Protection		
			Permanent destruction	Improper operation	No control
A	Usage of power silicon elements		○		
A	Large voltage/current margin		○	○	
A	Electrostatic shield		○	○	
A	Single point ground			○	
B	Low-pass filter		○	○	
B	Transformer with shield		○	○	
B	Improvement of thyristor gate circuit			○	
B	Thyristor parallel capacitor			○	
C	Interlock by trip comand			○	
D	Unit construction			○	○
D	Dual construction				○
E	Wiring consideration	Good ground		○	
E	Wiring consideration	Shield wire		○	
E	Wiring consideration	Suitable wire		○	

of the circuit have sufficient diameter and minimum length, and effectively dispose of instantaneous surge current. See *Table 1* for fundamental protection.

IV. ANALYSIS OF INTERNAL DISTRIBUTED VOLTAGE IN ABBS

Fig. 6 is the impedance diagram showing surge effects in ABBS and the current transformer for one of the 300 kv single-phase dual poles. Although it is extremely difficult to substitute circuits of unknown return current with lumped constants, equivalent surge is calculated in *Fig. 6*, as based on the following broad assumptions:

a) Inductance of iron structures 2 μH/m
b) Circuit with return line grounded 2.5 μH/m
c) Circuit with two-way conductance 1.5 μH/m

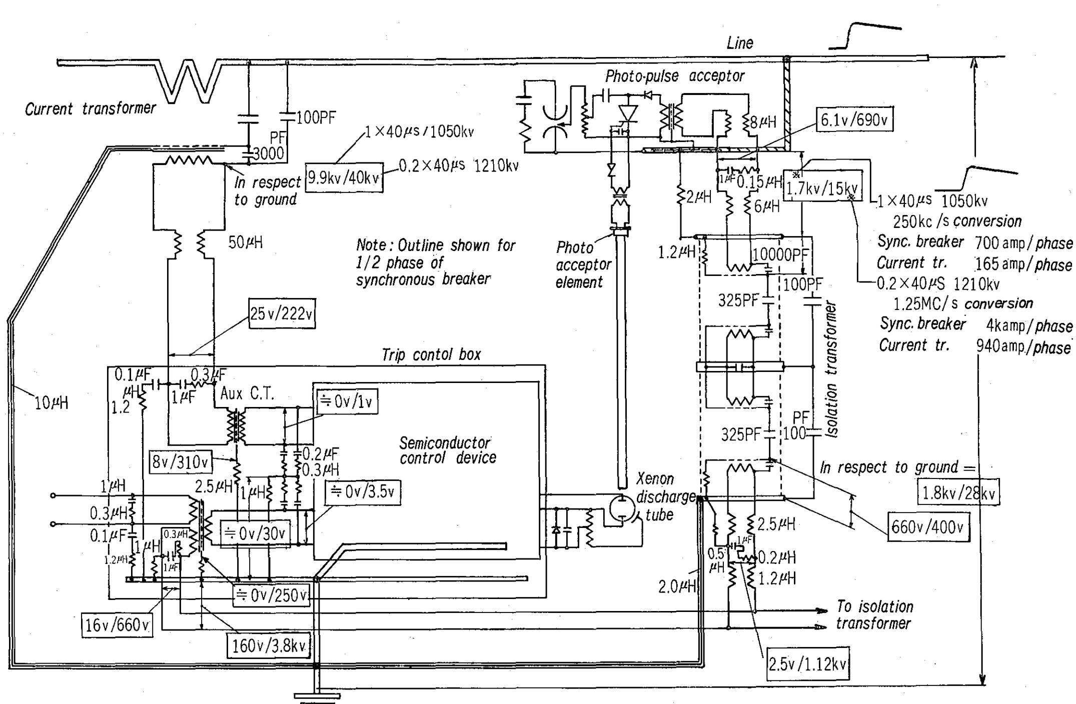

Fig. 6 Impedance map of ABBS

For internal distributed voltage, the slope of impulse voltage was converted into frequency, and the equivalent impedance for inductance and capacitance was calculated at that frequency. For instance, 1 μH and 1 μF under 250 kc/s and 1.25 Mc/s were calculated as:

	250 kc/s	1.25 Mc/s
1 μH	1.56 ohm	7.85 ohm
1 μF	0.642 ohm	0.128 ohm

The equivalent circuit in *Fig. 6* was developed by calculating internal distributed voltage under the constant flow of impulsive voltage current. Thus, if 2 ka of 1.25 Mc/s flows into 1 μH, terminal voltage will be 15.7 kv. *Fig. 6* shows results of the most critical calculations and indicates effects of the method applied outside the device, disregarding attenuation within the semiconductor.

Insulation test for standard impulsive wave

If 1 × 40 μS, 1050 kv are selected for example;
250 kc, 700 amp/phase, 350 amp/pole
Current transformer: 165 amp/phase

Insulation test for chopped impulsive wave

If 0.2 × 40 μs, 1210 kv are chosen for example:
1.25 Mc/s, 4 ka/phase, 2 ka/phase
Current transformer: 940 amp/phase

The values in *Fig. 6* are distributed voltages to the above current. The voltage at the input terminal of the semiconductor control is sufficiently suppressed (max. 3.5 v).

V. RESULTS OF VERIFICATION TESTS

Throughout the verification tests, with equipment operated and no interlock control by trip signals, no erroneous operation nor damage to the equipment was observed and superior surge characteristics were clearly displayed.

1. Commercial frequency test

Making current test (peak value)	131 ka
Ac insulation test	460 kv
Short circuit tests (tens of repetitions)	

2. Impulse insulation test

Standard wave	1 × 40 μS	1050 kv
Impulse wave	0.2 × 40 μS	1210 kv
Impressed voltage frequency		1.2 Mc/s (estimated)
Passing ground current		4.4 ka (estimated)
Rate of change in current buildup		20 ka/μS (estimated)
Passage test of impulse current		
Passing current		9.7 ka (estimated)
Current frequency		0.32 Mc/s (estimated)
Rate of change in current buildup		20 ka/μS (estimated)

3. Control circuit impulse insulation test

Voltage impress test was applied to the control power and trip control circuits and secondary current of C.T. under operating conditions as follows:

1 × 40 μs	7 kv	positive and negative
0.2 × 40 μs	7 kv	positive and negative

VI. CONCLUSION

It was determined that many problems remain to be solved and protective methods must be provided against environmental conditions such as EHV, large current, high *dv/dt* and *di/dt*, etc., before semiconductors can be effectively used in the control circuits of such equipment.

However, after intensive effort in the development of proper designs and repetition of stringent tests, we have finally overcome the difficulties and have succeeded in developing a highly stable reliable control device which is superior to conventional magnetic control devices. We hope that this new device will be used extensively in various systems and will contribute to the progress of overall systems engineering as well as to expanded use of ABBS, with its high speed and reliability.