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RELIABILITY OF SEMICONDUCTOR CONTROL DEVICES FOR SYNCHRONOUS AIR-BLAST CIRCUIT BREAKER FOR ONE-CYCLE INTERRUPTION (Part 2) RELIABILITY OF CONTROL DEVICES IN RESPECT TO AGING AND SERVICE LIFE

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I. FOREWORD

This unit and the magnetic repulsion drive system for movable contacts greatly affect circuit breaker reliabitity. Items (for example, semiconductor elements, flash discharge lamps, and silicon photoelectric cells) not generally used in conventional circuit breakers are employed, giving ample reliability and trouble-free operation over extended periods. This article describes the manufacturing techniques, points pertaining to circuit design, and construction related to satisfying objective requirements. Sample calculation, based on Earles prediction method, of equipment reliability appears at the end of the article.

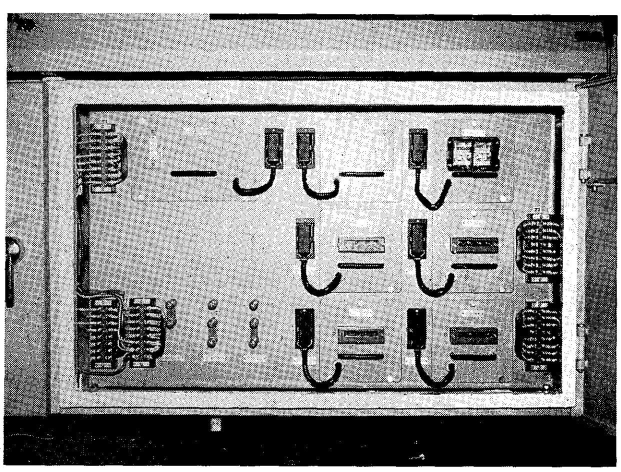

Fig. 1 Equipment exterior

II. FEATURES

Since this control equipment is employed outdoors as an electronic trip or electronic signal relay for circuit breakers, it must be able to withstand operating conditions more severe than those of other general electronic equipment. These operating conditions are:

(1) Wide temperature variation

This equipment must withstand temperature variations of ±50°C, from direct sunlight in summer to snow in winter.

(2) Humidity

Although this equipment is housed in a case, consideration must be given to the possibility of moisture forming inside the case due to temperature variation. Once water enters the case, it cannot be easily removed.

(3) Corrosive gases

Since circuit breakers are frequently installed in locations where industrial plants, which consume large amounts of electric power, are concentrated, consideration must be given to existing gases to protect the equipment against corrosion.

(4) Dust and salt contamination

Since it is difficult, as well as undersirable in respect to the removal of moisture from the case, to seal the control equipment in a case, measures must be taken to give effective protection from dust and salt contamination.

(5) Maintenance

Inspection of the synchronous pulse and photopulse generators located in the section which is at ground potential is simple. However, maintenance of the photopulse acceptor located in the high-voltage section is impossible and this acceptor must therefore have reliability which precludes unscheduled maintenance periods. As shown in *Fig. 2* the standard interval between maintenance periods for this circuit breakers is three years: The circuit breaker must be able to operate reliably during this interval.

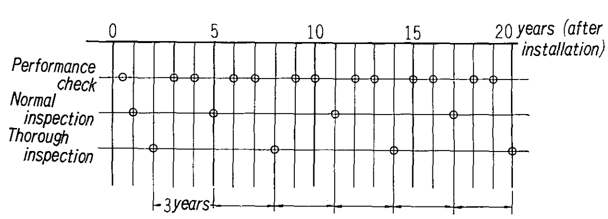

Fig. 2 Maintenance and inspection intervals

III. DESIGN CONSIDERATIONS

The following items were taken into consideration in the design of the semiconductor control equipment for long term use under severe operating conditions.

1. Use of High Quality Components

This first consideration was use of the highest quality components available. The major components and usage are follows:

(1) Thyristors

Approximately thirty thyristors are used for one phase of a 300 kv circuit breaker. Eight of these thyristors are employed in the photopulse acceptor in the high-voltage section of the circuit breaker. Fuji thyristors are specially aged and are selected for general use by means of the d_v/d_t test. Thyristors to be employed in the photopulse acceptor are selected, gate sensitivity, and other items.

These thyristors are employed either in a normally non-conducting state, preservative condition for an applied voltage of 0 v (synchronous pulse generator), or in a state in which d-c voltage is always applied (photopulse generator, photopulse acceptor). In this application, the capacitor charge is discharged instantaneously by switching action of those thysistors when tripping.

(2) Diodes

All the diodes used in this equipment are Fuji silicon types. Germanium diodes are not used because of their thermal characteristics. Only those silicon rectifiers having maximum inverse voltage characteristics are selected from among the many manufactured. The reference diodes (Zeners) are selected according to dynamic resistance and voltage characteristics.

(3) Capacitors

High temperature paper capacitors are used when the required capacitance is less than 0.1 μF and MP (foil) capacitors or oil paper capacitors when the required capacitance is large. All of these capacitors have an ample voltage margin.

(4) Resistors

The use of small, fixed, metal-film resistors is standard. These are the most reliable resistors available. Ceramic resistors are employed in the high-power sections and sealed wirewound resistors are employed where low resistances are required.

(5) Connectors

Large, strong connectors are used and, as shown in *Fig. 3*, the leads and pins of the plug are soldered and sealed with resin to prevent breaking of the moisture and dustproof leads by repeated bending.

(6) Transformers

Power, pulse, and other transformers are of vacuum molded epoxy resin types. These transformers have excellent airtight characteristics, good durability, and can even be used in water. This contributes greatly to increased reliability of small power transformers which have voltage applied at all times. These transformer coils are shown in *Fig. 4*.

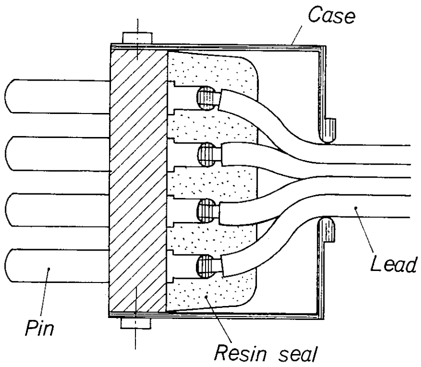

Fig. 3 Resin sealed lead wires and connector pins

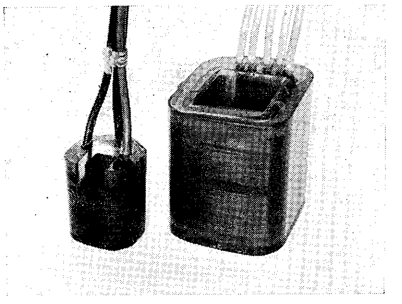

Fig. 4 Molded transformer coils

(7) Photoelectric cells

A special silicon solar cell having a grid type electrode and internal resistance one-tenth that of conventional cells is used as the light sensitive element in the high-voltage section. This increases output power during illumination several fold. The cell is constructed of a silicon wafer inserted into an acryl resin case and sealed. The cell is forced against the end of the light guiding rod by means of a spring.

(8) Flash discharge lamps

These contain xenon gas and are installed in a sturdy metal housing. Since the lamps have considerable random trigger sensitivity, only specially selected lamps are used.

Since light transmission efficiency (covered later) of the light guiding rod is excellent, the required input is approximately one-fifteenth of maximum input and therefore a high light level is not required.

2. Highly Reliable Construction

In order to attain high overall reliability of the equipment without degrading the reliability of individual components, it is necessary to select appropriate construction from the standpoint of circuitry and mechanical strength.

This equipment is constructed as follows:

(1) Simplification

The main operation of this electronic equipment is simple monostable switching. Although the number of components is not necessarily small because of the redundancy system (described later) employed, simplicity in construction is still attained. Simplicity of this equipment far surpasses that of electronic equipment, such as radio communications equipment and computers.

For example, the basic photopulse acceptor circuit of *Fig. 5* has been developed into the practical circuit of *Fig. 7* by adding a safety factor and a redundancy system to individual elements of the basic system.

After assembly, there are only three adjustment points in the time adjustment section of the synchronous pulse generator and no adjustment points in the photopulse generator and photopuls acceptor.

Since signal transmission (pulse) to the high-voltage section by means of light is the most important operation, an acryl resin rod (described later) is employed. This provides extremely efficient light transmission which enables photo cell output greater than one watt, thereby facilitating direct trigger of the two thryistors in the photopuls accptor section. This, in turn, contributes greatly to improvement in reliability. One end of the light guiding rod is shown in *Fig. 6*

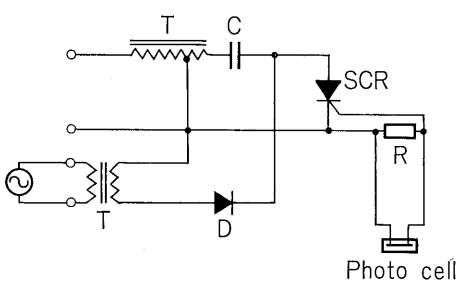

Fig. 5 **Basic photopulse acceptor circuit**

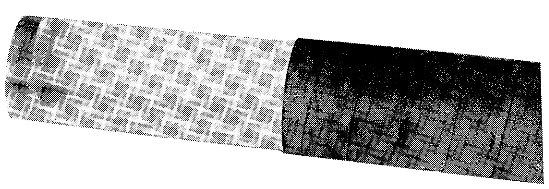

Fig. 6 **End of light guiding rod**

(2) Derating

One method of increasing the reliability of individual components is operation well below specified ratings. It is, however, a difficult problem to determin the exact extent of derating. Due to the nature of this equipment, almost the entire lifespan consists of idle time and the majority of components are those through which current flows and voltage is applied only during operation of the breaker. The examples shown in *Fig. 7* are *PC, Z,* R_3, C_3, T_2, and T_3. The period during which these components are subjected to electrical stress can be calculated for a total of ten thousand operations as $0.5\times10^{-3}\times10^{4}=5$sec. The total operating time, therefore, for each operation is only 0.5 ms and is too small to cause any problems. For this reason, perhaps the handling of these components, as far as reliability is concerned, should be the same as during storage.

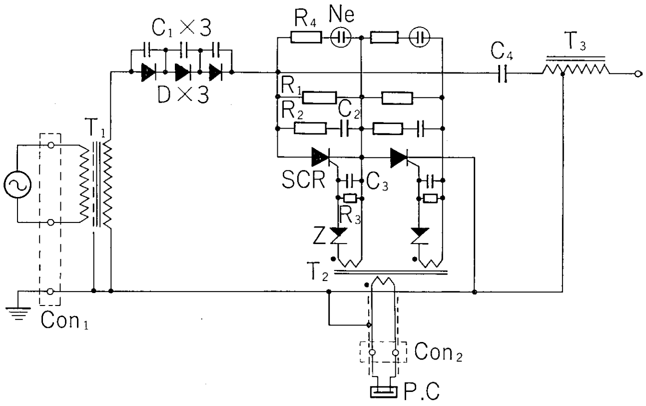

Fig. 7 **Photopulse acceptor circuit**

(3) Redundancy

The reliability of components which greatly influence the circuits or have comparatively poor reliability is greatly increased by the use of a redundant system. Therefore, the overall signal transmission system in this equipment is doubled and, at the same time, redundancy systems are employed for the thyristors, diodes, and other components. The reliability of the thyristors, diodes, etc., is thus comparable to or greater than that of other components. This is due to the fact that consideration has been given to the magnitude of influence on reliability of the equipment and protection against sudden surges.

(4) Other aspects

As described in Part I of this article, a special feature of this circuit breaker control equipment

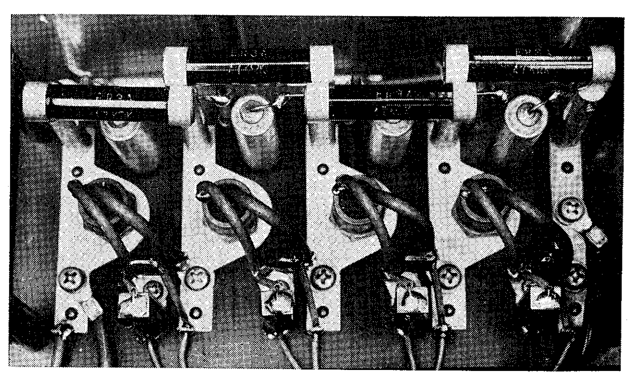

Fig. 8 **Interior of photopulse generator**

is activation of the photopulse generator section of the synchronous pulse generator by the trip signal to prevent erroneous operation. Reliability is also increased by the use of plug-in units and interchangeable components which greatly facilitate troubleshooting.

The location, installation, and mechanical strength of individual components are also important factors contributing to reliability of the equipment. Therefore, consideration is given to these points during design and manufacturing phases. *Fig. 8* shows the interior of the photoelectric generator.

IV. RELIABILITY PREDICTION

Design and manufacture of individual component parts of this equipment are based on the above description. It is extremely difficult to obtain a concrete quantitative value for the actual reliability of the equipment. However, a considerable quantity of data on electronic equipment and components has been collected recently and general reliability calculation has been based on this data. In this manner, the causes of equipment reliability drops have been ascertained, enabling techniques which give even greater reliability and revealing the extent of capability which service organizations must possess. Reliability of this equipment is determined by the Earles prediction method, now considered the most practical method.

This method involves calculation based on amassing failure rata data of electronic components in the United States, determining the failure rates of applied components in equipment for which the failure rate is to be determined, applying a stress factor which pertains to the particular surroundings, and applying a redundancy factor. The Earles method is represented mathematically by:

$$\lambda=\sum_{i=1}^{k}\lambda_0\cdot n_i\cdot K\cdot K_r$$

λ: Equipment failure rate
λ_0: Individual component failure rate
n_i: Quantity of individual components
K: Environmental stress factor

***Table 1* Failure rate calculation**

Symbol	Component	Applied Voltage		Degree of Influence			$\lambda_0\ (\times 10^{-6}/h)$	Value Employed			n_i	K	K_r	$\lambda_0\times n_i\times K\times K_r$
		Continuous	Momentary	Short-circuit	Open circuit	Overall		Lower limit	Average	Upper limit				
SCR	Thyristor	○		×	×	Great	0.02* (SCR + C₂: 0.045)				2	1.8	2 redundancy system 6.6×10^{-4}	1.07×10^{-10}
C_2	Capacitor	○		×	○	Great	0.025		○					
D	Silicon diode	○		×	×	Great	0.2 (D + C₁: 0.225)		○		3	1.8	3 redundancy system 7.96×10^{-12}	9.67×10^{-18}
C_1	Capacitor	○		×	○	Great	0.025		○					
Z	Zener diode		○	○	×	Small	0.08	○			2	1.8	1	0.288×10^{-6}
T_1	Power transformer	○		×	×	Medium	0.03	○			1		1	0.054
T_2	Pulse transformer		○	×	×	Small	0.03	○			1	1.8	1	0.054
T_3	Trigger transformer		○	×	×	Small	0.03	○			1	1.8	1	0.054
C_3	Capacitor		○	×	○	Small	0.01	○			2	1.8	1	0.036
C_4	Capacitor	○		×	×	Great	0.025		○		1	1.8	1	0.045
R_1	Resistor	○		\	○	None	—				2	1.8	1	—
R_2	Resistor		○	\	○	None	—				2	1.8	1	—
R_3	Resistor		○	\	○	None	—				2	1.8	1	—
R_4	Resistor	○		\	○	None	—				2	1.8	1	—
P.C	Silicon photoelectric cell		○	×	×	Great	0.05 (Assumed value)				1	1.8	1	0.09
Ne	Neon lamp		○	○	○	None	—				2	1.8	1	—
	Soldering point	\	\	\	×	Great	0.004		○		40	1.8	1	0.288
Con_2	Connector	○		×	×	Great	0.003/pin		○		3	1.8	1	0.016
Con_2	Connector		○	×	×	Great	0.003/pin		○		2	1.8	1	0.0108

* General value

$\lambda=\sum\lambda_0\cdot n_i\cdot K\cdot K_r=0.936\times10^{-6}$

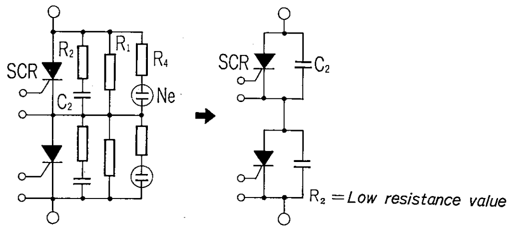

Fig. 9 **Equivalent circuit of reliability calculation**

K_r: Redundancy factor

The relationship between the failure rate λ and reliability is:

$$R=\varepsilon^{-\lambda t}$$

R: Reliability t: Term

The portion of this equipment requiring the highest reliability is the photopulse acceptor which is serviced only once every three years, since it is located in the high-voltage section of the equipment. Inspection of components (synchronous pulse generator, photopuls egenerator) located in the section at ground potential is possible without disturbing normal operation of the circuit breaker and, since activation is by means of the trip signals, the possibility of trouble or erroneous operation is minimized. Thiis article discusses reliability of the photopulse aceptor circut shown in *Fig. 7*. The table gives the effect on equipment reliability of λ_0, n_i, K, and K_r in the case of failure, applied voltage to individual components. Since failure of R_1, R_2, R_3, and R_4 is not directly related to equipment trouble the addition of λ_0 is unnecessary.

Thus, from the standpoint of reliability, the circuit of the thyristor portion can be replaced with the equivalent circuit of *Fig. 9*. The only necessary consideration is shorting of C_2. Environmental stress factor K is a value which shows to what extent the failure rate increases in a particular environment. In this case, stress factor K was made 1.8 times that of ground equipment. Redundancy factor K_r is a value which shows to what extent the failure rate is decreased by employing a redundant system. (as shown in *Fig. 7*.)

In the case of a double system,

$$K_r \doteqdot \frac{\lambda_{eq}}{2\lambda}$$

λ_{eq}: Equivalent failure rate of redundant system
λ: Failure rate of single system

$$\lambda_{eq} \doteqdot \lambda^2 t$$

t=term (h)

The term "t" is the total time during which the equipment will be operated without maintenance and inspection. For this equipment, "t" is taken as three years ($=2.64\times10^4$ h). The case of a triple system is similar to that of a double system:

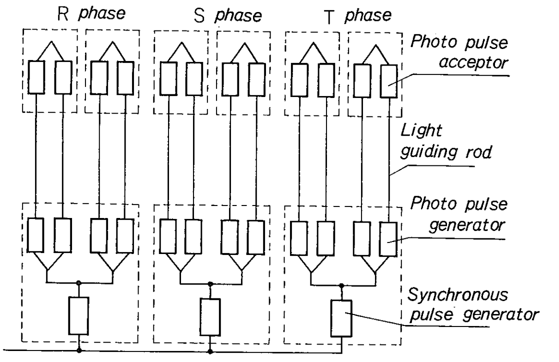

Fig. 10 **Overall connection of control equipment (in the case of a 300 kv ABBS)**

$$K_r \doteqdot \frac{\lambda_{eq}}{3\lambda} \qquad \lambda_{eq} \doteqdot \lambda^3 t^2$$

The failure rate λ_1 of the photopulse acceptor is obtained in the following manner:

$$\lambda^1 \sum \lambda_0 \cdot n_i \cdot K \cdot K_r = 0.936 \times ^{-6}/\text{hr}$$

The failure rates of the photopulse generator and synchronous generator are obtained in the same manner:

Photopulse generator: $\lambda_2=0.93\times10^{-6}$/hr
Synchronous generator: $\lambda_3=0.21\times10^{-6}$/hr

The λ_3 value of the synchronous pulse generator is obtained from a double system for the pulse generator, in addition to the synchronous pulse. Construction shown in *Fig. 10* is used in the case of 300 kv application when considering the entire circuit breaker. There are two insulating tubes per phase, and three phases. One insulating tube represents the path between a photopulse generator and photopulse acceptor, as shown in the figure. Failure of one tube is classified as trouble. A look at the failure rate reveals the following.

The failure rate $\lambda_{1,2}$ of a photopulse generator and photopulse acceptor system is,

$$\lambda_{1,2}=\lambda_1+\lambda_2$$

This forms a redundant system and the equivalent failure rate $\lambda_{eq\,1,2}$ becomes:

$$\lambda_{eq\,1,2}=\lambda_{1,2}^2\cdot t$$

Therefore, the failure rate λ_p for one phase becomes:

$$\lambda_p=2\times\lambda_{eq\,1,2}+\lambda_3=\lambda_{1,2}^2 t+\lambda_3=2(\lambda_1+\lambda_2)^2\cdot t+\lambda_3$$

The failure rate λ_{3p} for three phases becomes:

$$\lambda_{3p}=3\{2(\lambda_1+\lambda_2)^2\cdot t+\lambda_3\}$$
$$=[2\{(0.936+0.93)\times10^{-6}\}^2\cdot 2.64\times10^4+0.21\times10^{-6}]$$
$$=3(0.184+0.21)\times10^{-6}=1.18\times10^{-6}/\text{hr}$$

(after three years)

R (reliability) is obtained in the following manner:

$$R=\varepsilon^{-\lambda_{3p}t}\doteqdot 1-\lambda_{3p}t+\frac{(\lambda_{3p}t)^2}{2}$$

$$=1-0.0312+\frac{0.0312^2}{2}=0.97$$

This indicates that the probability of this equipment operating for three years is 0.97.

When considering the reliability of conventional circuit breakers, it is important to note that solenoid valves or coils are incorporated. For example, the failure rate of a solenoid coil (magnet) is calculated as 2.02×10^{-6}/h (lower limit) from the Earles table. When calculating the failure rate, it is necessary to include some assumptions or estimations. Although the control equipment for synchronous circuit breakers contains a large number of components, when compared to other general circuit breakers, reliability is estimated at a comparatively high value.

As shown in *Fig. 2*, operational inspection, including standard inspection and thorough inspection, is made annually and inspection of the synchronous generator and photopluse generator, which occupy considerable space in the equipment can be conducted during circuit breaker operation. The actual reliability then becomes greater than 0.97. Therefore, in actual practice, ample reliability is realized.

V. CONCLUSION

This article adds to "reliability for impulsive surge" presented previously, and covers "reliability in respect to aging and service life." A description of items pertaining to design procedures and engineering techniques required to elevate reliability has been included, along with design precedures and engineering techniques applied to various portions of the equipment for the objective of obtaining specified reliability. Reliability is discussed quantitatively, revealing that the probability of trouble not occurring during the three-year period between routine inspections is 0.97. This figure is better than that of equipment used in conventional circuit breakers, and thus this equipment exhibits a high degree of reliability.

Although placing electronic circuit breaker equipment into practical use was considered difflcult by many, Fuji Electric has accomplished another first. In the future, this system should contribute greatly to improved reliability as incorporation of this type of electronic equipment in systems engineering expands.

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