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DEVELOPMENT OF THE VACUUM-SWITCH LOAD TAP-CHANGER (VS-LTC)

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I. PREFACE

Conventional on-load tap-changers have adopted the tap changing method in which the arc is extinguished in oil. In recent years, however, longer service life and shorter operation interval are desired in addition to considerable improvement and simplification of maintenance for unmanning of a substation for labor saving.

It has been well known that adoption of a vacuum-switch having excellent breaking performance and long contact life as a current switching element in a diverter switch is very effective. Manufacturing technique of vacuum-switch has advanced so much in recent years that they are manufactured at sufficiently low costs but with satisfactorily high reliability. Adoption of a vacuum-switch as a current switching element in an on-load tap-changer will ensure the following effects:

(1) A very long contact life resulting in an appreciable lengthening of inspection and replacement cycles.

(2) Limitation of the arc generation accompanying the current switching to within a highly evacuated envelope (vacuum-switch), resulting in no contamination of neighboring media. In case of an oil-immersed on-load tap-changer, the insulation oil in the diverter switch chamber is always maintained at a good quality level. The insulation relaibility and the maintenance work efficiency is improved as represented by the elimination of the on-load oil purifier.

(3) Capability of switching at short intervals.

(4) Excellent breaking performance of the vacuum-switch to enable frequent overload switching. This type of an on-load tap-changer may be said to be ideal in satisfying the above-said requirements in performance and maintenance.

Because of these excellent features, the on-load tap-changer using vacuum-switch displays the highest efficiency when applied to the industrial transformer for an electric furnace or rectifier which requires a long service life, short switching intervals, and frequent overload switchings. The evaluation of the on-load tap-changer using vacuum-switch has been rising among customers.

As already known, the current limiting impedance of an on-load tap-changer may be classified as;

(1) continuous rating reactor, and
(2) short time rating resistor.

As apparent from dominating use of resistors in conventional oil-immersed on-load tap-changers, the resistor type is superior to the reactor type in the following points:

(1) Excellent breaking performance (Power factor at the current breaking is 1).

(2) Reduced on-load tap-changer size because of the use of a small-capacity short time rating resistor.

(3) Easy application to an extra-high voltage and large-capacity transformer.

In a vacuum-switch type on-load tap-changer, the resistor type is favorable in obtaining far-reaching effects, being applied to a wide varieties of transformers from the above-said industrial ones to extra-high voltage and large-capacity ones.

Fuji Electric has long been studying the effective method to apply vacuum-switch with excellent characteristics to an on-load tap-changer to cope with the requirement of the times, and has recently succeeded in developing a vacuum-switch type on-load tap-changer using the resistor switching system for introduction to the market. The new product called "VS-LTC" is adopted in an aluminum smeltering plant in the USA (6 units). Several more units have been in process for domestic market. Genral description of the new product is given in this report.

II. SPECIFICATION EXAMPLE

1. Applied Transformer

(1) Use: For rectifier
(2) Phase and frequency: 3-phase, 60 Hz
(3) Capacity: 28,600/2 x 14,300 kVA
(4) Voltage: 115,000/578 V
(5) Connection: See *Fig. 1*

2. On-Load Tap-Changer

(1) Type: VLN/B3 x 800/WF9/30
(2) Phase and frequency: 3-phase, 60 Hz
(3) Adjusting method: Neutral point adjustment
(4) Switching method: 3 vacuum-switches and I transition resistor per phase

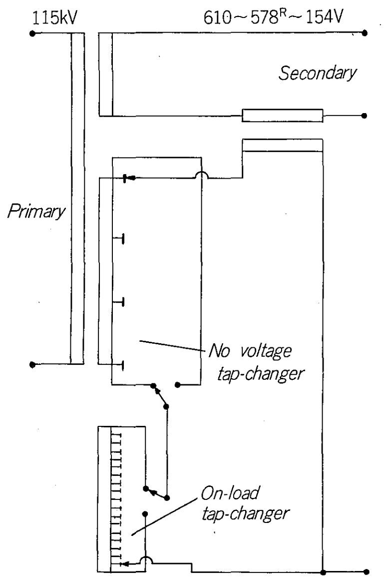


Fig. 1 Connection diagram of transformer

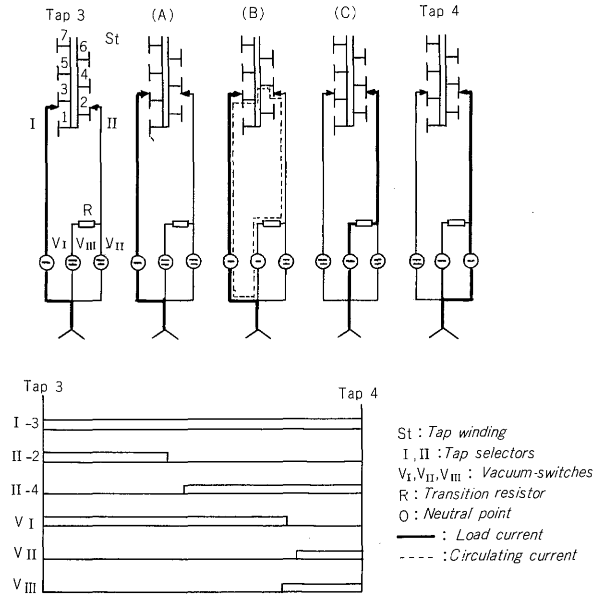


Fig. 3 Tap changing process of vacuum-switch load tap-changer (VS-LTC)

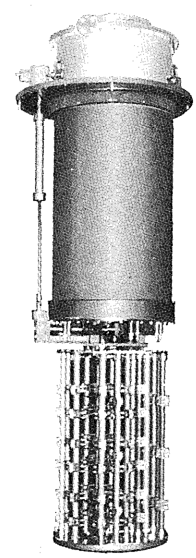
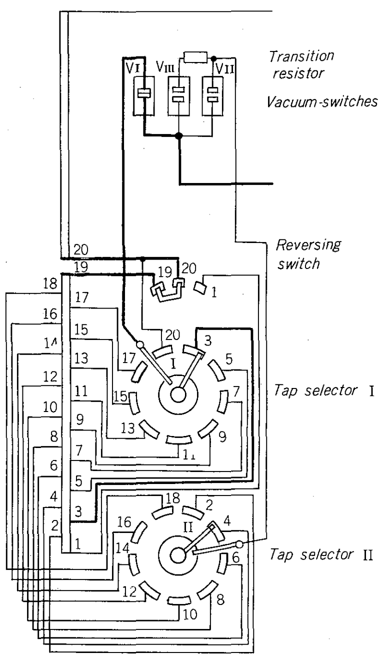


Fig. 4 Vacuum-switch load tap-changer (VS-LTC)



Tap selector connection

Tap No.	Tap selector I	Tap selector II	Reversing switch	
1	3			
2		4		
3	5			
4		6		
5	7			
6		8		
7	9			
8		10	20	20
9	11		|	|
10		12	19	19
11	13			
12		14		
13	15			
14		16		
15	17			
16		18		
17	20			
18		2		
19	3			
20		4		
21	5			
22		6		
23	7			
24		8		
25	9		20	20
26		10	|	|
27	11		1	1
28		12		
29	13			
30		14		
31	15			
32		16		
33	17			

Notes) (1) *Tap No. 1 is shown*
(2) *Bold lines are the current path*

Fig. 2 Connection diagram of vacuum-switch load tap-changer (VS-LTC)

(5) Insulation class: No. 30
(6) Maximum through current: 800 A
(7) Maximum step voltage: 2,500 V
(8) Number of taps: 33
(9) 1 step changing time: 5 seconds
(10) Connection: See *Fig. 2*
(11) Tap-changing process: See *Fig. 3*

III. STRUCTURE

1. Vacuum-switch Load Tap-changer (VS-LTC)

This tap-changer adopts the 3-vacuum-switches 1-resistor (per phase) system which is one of the resistor type on-load tap changing methods have many merits. The sequence and operation of this system are very simple, and this system facilitates structural simplification and size reduction of the equipment. As the result of extensive efforts to reduce the size and weight without damaging the quality and reliability by adding special design for a vacuum-switch type on-load tap-changer to our rich experience and basic technologies in manufacturing conventional on-load tap-changers, the new vacuum-switch load tap-changer has come out with a remarkably long service life while its weight and size have both been reduced by about 30% as

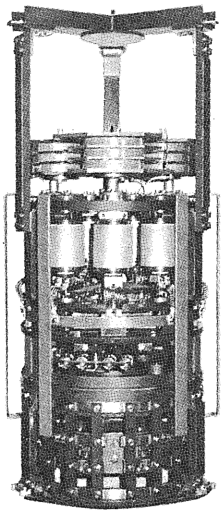


Fig. 5 Diverter switch of vacuum-switch load tap-changer (VS-LTC)

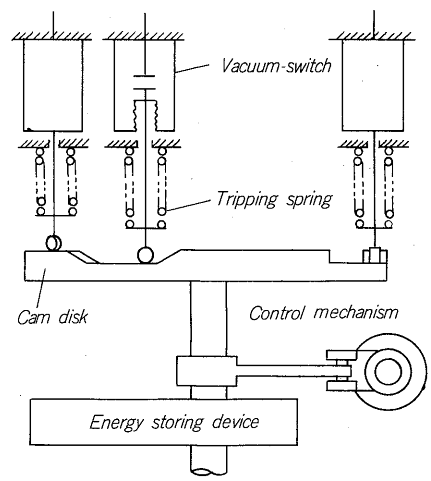


Fig. 6 Driving mechanism for vacuum-switch

compared with our conventional on-load tap-changer with the same rating.

Fig. 4 shows the appearance of the vacuum-switch load tap-changer. Since the vacuum-switch load tap-changer does not contaminate the insulation oil, it is generally unnecessary to separate the tap-changer from the oil in the transformer. To facilitate mounting to the transformer and maintenance by lifting the tap-changer from the transformer without discharging the oil from the transformer, the diverter switch portion is partitioned from the transformer oil by an insulating cylinder suspended in the transformer while the tap selector portion is placed in the same room with the transformer contents.

The diverter switch portion consists of vacuum-switches, transition resistors, energy storing mechanism, and vacuum-switch driving mechanism arranged in a com pact space and the total unit is plugged into the insulating cylinder. *Fig. 5* shows the appearance of the diverter switch portion. Nine vacuum-switches for three phases are arranged to form a circle, and all movable contacts use neutral potential. So a single cam disk can open or close all vacuum-switches. As a result, the structure is simplified and the size is minimized in addition to the ease of vacuum-switch inspection with the unit lifted from the transformer. The vacuum-switch driving mechanism has a gap which changes in proportion to the wear of the vacuum-switch contact to facilitate the contact wear status monitoring and vacuum-switch replacement time estimation.

Fuji's conventional time-proven high-reliability and long-life WF type tap selector and MD75-2 type motor-drive mechanism are adopted as the tap selector and motor-drive mechanism.

2. Vacuum-Switch Driving Mechanism

The most important task in developing the vacuum-switch load tap-changer was how to open and close three vacuum-switches per phase. It was decided to open and close three vacuum-switches by quick operation using the force stored in springs, and sequential opening and closing of three vacuum-switches were designed to be effected by a cam disk. For full utilization of the excellent breaking performance and long service life of vacuum-switches, the opening and closing speeds must be controlled at a proper level and the impact at the switching must be controlled to minimize.

As the solution to this problem the following measures are taken as shown in *Fig. 6*:

(1) Tripping springs are provided, and the spring force is utilized skilfully. By this method, the vacuum-switch opening speed is accelerated to ensure good breaking performance, and the vacuum-switch closing speed is decelerated to decrease the impact at the contact closing.

(2) A control mechanism interlocked to the cam disk is provided to control the opening and closing speeds of every vacuum-switch at the specified values.

Equations of motion of the cam disk shaft during vacuum-switch opening and closing operations are as follows:

Vacuum-switch opening period: $T_1 = T_2 + J \cdot \frac{d\omega}{dt} + T_3$

Vacuum-switch closing period: $T_1 = T_2 + J \cdot \frac{d\omega}{dt} - T_3$

Vacuum-switch stationary period (normal state):

$$T_1 = T_2 + J \cdot \frac{d\omega}{dt}$$

Where,

T_1: Torque by the energy storing spring

T_2: Reaction torque by the control mechanism

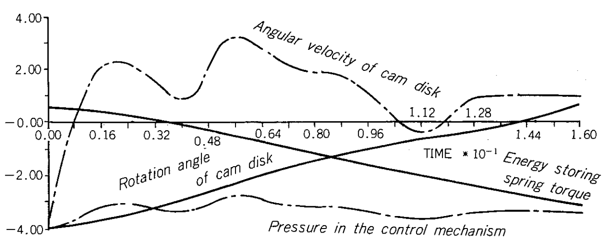


Fig. 7 Some results of calculation

J : Total moment of inertia converted with respect to the cam disk shaft

ω : Angular velocity of the dam disk

T_3 : Torque required for vacuum-switch driving

The optimum stored energy, tripping spring, and damper mechanism throttle size were decided by calculating the transient states expressed by these equations of motion using a computer. *Fig. 7* shows some results of such calculation.

Fig. 8 shows oscillograms indicating switching status of actual vacuum-switches. The vacuum-switch opening and closing speeds are almost linear over the entire travel length. The opening speed is fast and the closing speed is fast and the closing speed is slow. The closing speeds of initially closed V_{III} vacuum-switch and finally closed V_{II} vacuum-switch are almost the same. No chattering in the closing period is seen. These oscillograms show that the control mechanism shown in *Fig. 6* is operating as expected.

Thus an ideal driving mechanism for a vacuum-switch type on-load tap-changer having fast opening speed and slow closing speed in addition to the capbility of maintaining constant opening and closing speeds from the beginning until the end of the sequential switching process of three vacuum-switches has been developed (Patent pending).

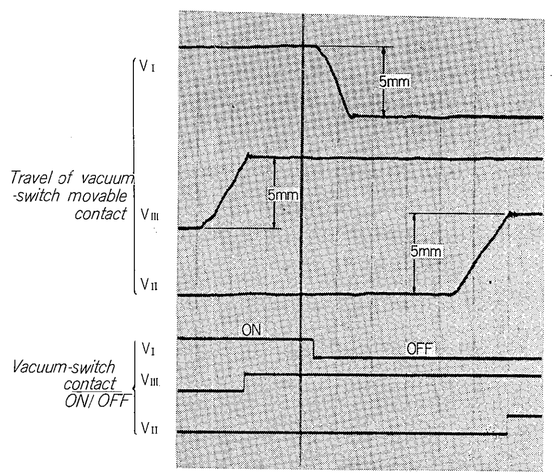


Fig. 8 DC oscillograms showing switching condition of vacuum-switch contacts.

IV. PROTECTION SYSTEM

The remarkable improvement of vacuum-switch reliability in recent years and adoption of simple mechanism consisting of three vacuum-switches and one transition resistor have made this newly developed vacuum-switch load tap-changer highly reliable. The reliability is further ensured through various tests, but the protection system shown in *Fig. 9* is provided considering the worst.

1) CT

detects an abnormal current in tap-changer circuit and cuts off the transformer from the circuit.

2) Pressure relay and pressure relief device

protect the diverter switch chamber from internal pressure rise and these are same as what are normally used in conventional tap-changer.

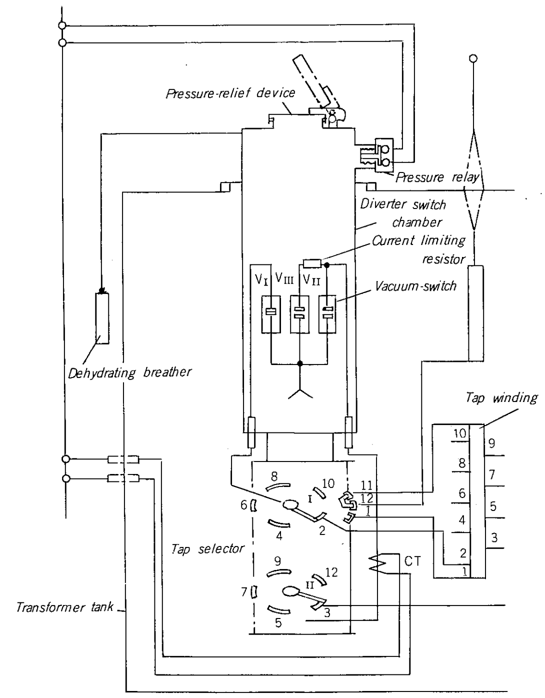


Fig. 9 Protection system for vacuum-switch load tap-changer (VS-LTC)

V. TESTS

Various test including quality and performance test specific to a vacuum-switch load tap-changer, electrical life test (1 million times), and mechanical life test (5 million times) conforming to JEC186 standard have been using the prototype and regular product. Main test results are described below.

1. Operation Characteristics Test

As a result of measurement of basic operation characteristics, such as the vacuum-switch opening and closing specific to a vacuum-switch load tap-changer, electrical life test (1 million times), and mechanical life test (5 million times) conforming to JEC186 standard have been using ing as expected.

2. Electrical Life Test

1-million-times electrical life test under the through current of 800 A, step voltage of 2,200 V, and circulating current coefficient of 0.5 was carried out. For each 50-100 thousand times, the switching time, wear of vacuum-switch contact, contact · resistance, and withstand voltage were measured. No degradation was observed, and the contact wear was sufficiently below the allowable limit of 1 m. (See *Fig. 10*). *Figs. 11* and *12* show the electrical life test circuit and oscillograms at 100% load tap changing, respectively.

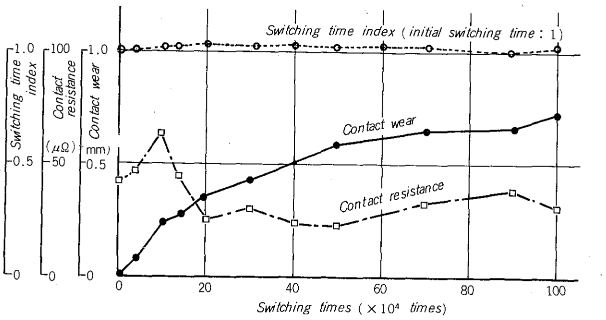
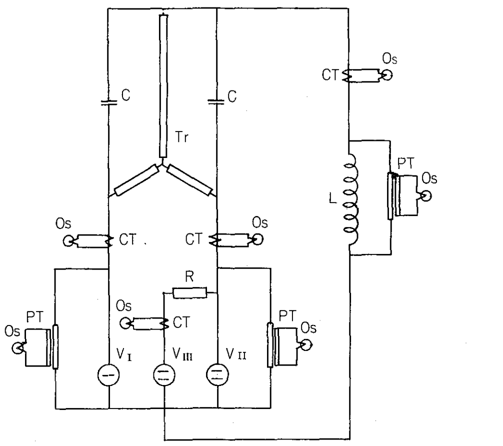


Fig. 10 Some results of electrical life test



T_r : Unbalanced transformer
C : Capacitor
L : Load reactor
R : Transition resistor
$V_I V_{II} V_{III}$: Vacuum switches
CT : Current transformer for measuring instrument
PT : Potential transformer
O_s : Oscillograph element

Fig. 11 Circuit of electrical life test

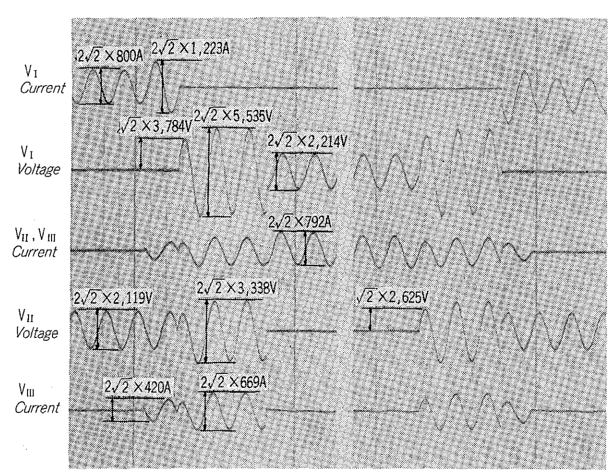


Fig. 12 Oscillograms at 100% load tap changing

3. Overcurrent On-Load Tap-Changing Test

After the end of the electrical life test, a continuous 40-time overcurrent tap changing test under 200% load current (1,600 A) specified in IEC214 was conducted. This test is far severe than the continuous 3 tap changings under 150% load current specified in JEC186. There was no ap-

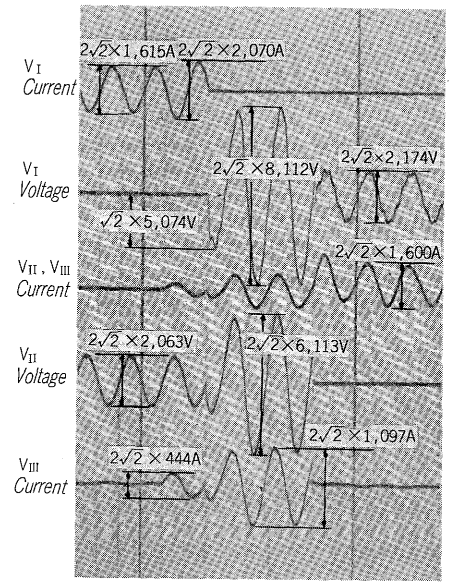


Fig. 13 Oscillograms at 200% load tap changing

preciable increase in the arcing time, and it was evidenced that the breaking performance was so good as to ensure the maximum arcing time of 0.7 cycle or blow. The excellent breaking quality of the vacuum switches was found to be fully utilized (See *Fig. 13*).

4. Mechanical Life Test

A 5-million-time mechanical life test was conducted with regard to the diverter switch portion and driving mechanism. No abnormalities like damages, abnormal wear, or loosening were observed. It was confirmed that the mechanical properties were excellent. Vacuum-switches were replaced with new ones per each 1 million operations after checking their characteristics were not abnormal.

5. Tap Changing Test Under Low Temperatures

Since the control mechanism adopted for vacuum-switch operation control utilizes the fluid resistance of the oil passing through the throttle in the mechanism, the viscosity of the oil passing through the throttle does not affect the performance as far as the theoretical equation is concerned. Tap changing test under low temperatures, where the

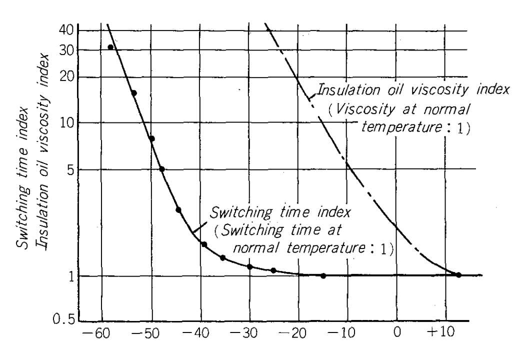


Fig. 14 Results of tap changing test under low temperatures

viscosity changes greatly, was conducted to prove that this assumtion is not wrong.

The vacuum-switch switching time values measured under various temperatures showed that the switching time was almost constant at about $-25°C$ and above. So it was proved that the oil viscosity does not affect the performance (See *Fig. 14*)

It was also found that the switching was effected without temporary stagnancy at $-60°C$. When considering the heat capacity of the transition resistor, $-30°C$ to $-40°C$ may be considered as the practical lower limit.

Tap changing test under high temperatures was also conducted for the temperature range up to $105°C$ (above the specified value in JEC 186). The switching time was also observed to be almost constant.

6. Surge Measurement

The surge generating during vacuum-switch operation mainly depends on the following factors:

(1) Transformer circuit conditions
(2) Vacuum-switch characteristics

However, the use of vacuum-switches in on-load tap-changer is superior to other method in the following points:

(1) Since the power factor of a resistor type on-load tap-changer during current breaking is always 1, the generated surge is sufficiently low.
(2) The insulation structure of the transformer including the on-load tap-changer is by far sturdier than that of a general motor circuit.

As the result of theoretical examination from various angles under these conditions, it was concluded that the surge generating during switching of the vacuum-switch load tap-changer was negligible.

To confirm this conclusion actually, several thousand times of surge measurements were carried out for each of rated-current rated-voltage switching in the equivalent circuit and the same in combination with an actual transformer. As the result, the observed surge was very small, and the maximum value was twice the step voltage. This value is smaller than the recovery voltage generated during normal tap changing operation. So it was confirmed that the surge is practically negligible.

VI. SUMMARY

The vacuum-switch load tap-changer developed and merchandized this time has the electrical life to endure 1 million operations and mechanical life of 5 million operations. Its quality is far superior to the specifications of JEC186. Since the oil contamination is not caused, the maintenance labor required for conventional on-load oil purifier becomes unnecessary, resulting in remakable improvement in maintenability. Further, adoption of the resistor method favorable in an on-load tap-changer overcoming many technical difficulties is very significant.

It is expected that vacuum-switch type on-load tap-changers will be widely adopted for use with electric furnaces and rectifiers requiring short-interval switchings because of the excellent characteristics attained. If further reliability improvement, organization into series products, and concentrated efforts for user-oriented improvements are made, the vacuum-switch type on-load tap-changers may become the mainstream of on-load tap-changers in the future. We are determined to continue the study based on our past achievements to meet such expectations.

Reference

(1) Ikeda and Kumagai, Vacuum-switch Load Tap-changer Development, Denki Gakkai Tokyo Regional Meeting 110, 1978.