RECENT DEVELOPMENT OF ON-LOAD TAP-CHANGING EQUIPMENT FOR FUJI POWER TRANSFORMERS

By

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I. OUTLINE OF PRESENT CIRCUMSTANCES

On-load tap-changing power transformers for power systems have been used in Japan from as early as 1925. Recently, remarkable developments have been achieved in quick succession and many high voltage large capacity equipments have been manufactured and put into operation.[1),2)] Table 1 shows the number of large capacity equipment manufactured by our company in recent years. Fig. 1 and 2 show the external appearances of our 90,000 kVA on-lord tap-changing power transformer. The following five points can be given as the distinctive features seen recently in power transformers of this type :

1) Direct tap-changing system (one iron core system)
2) High tension side neutral point tap system
3) Totally enclosed type (housing method of on-load tap-changer in the transformer tank)
4) Adoption of on-load tap-changer with current limiting resistor (so-called Jansen switch)
5) Higher voltage and larger capacity

Remarkable developments are being made steadily in this field and it will not be long before large capacity equipment of 200 MVA will come into actual use in our 275 kV-380 kV systems. The Siemens-Schuckert Company of West Germany which has concluded technical agreements with our company and other large companies of Europe have already manufactured large capacity on-load tap-changing power transformers which are widely used by RWE, RAG (West Germany) and other power systems. This fact indicates the trends (1)~(5) shown above.

One of the products requiring the highest technical level in this field is the 3 × 220,000 kVA single-phase single-winding on-load voltage and phase regulator used on 400 kV systems. These regulators have been manufactured by Siemens-Schuckert

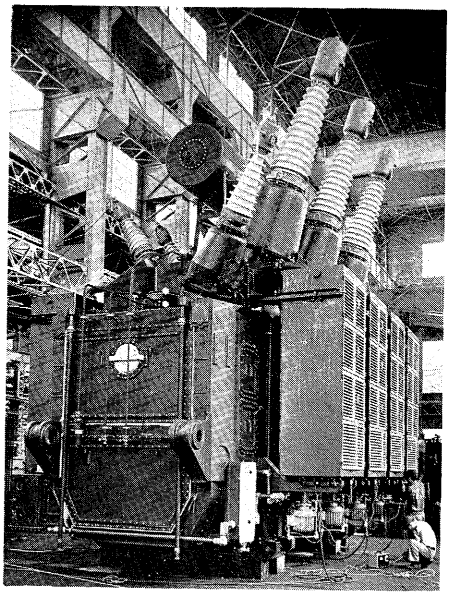

Fig. 1. 90 MVA R 154/77 kV on-load tap-changing transformer

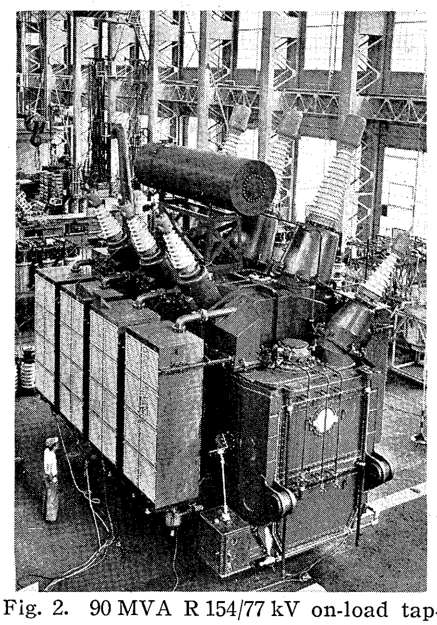

Fig. 2. 90 MVA R 154/77 kV on-load tap-changing transformer

Table 1. Typical Products

Type of core	No.	Output (MVA)	Rated Voltage (kV)	Tap Range (kV)	No. of taps	Phase	Fre-quency (c/s)	Name of Customer
Single core	1	90	151 /77	157 ~142	11	3	60	Chubu Electric Power Co. (Okazaki)
	2	90	154 /77	161.5 ~146.5	11	3	60	Chubu Electric Power Co. (Shin Shimizu)
	3	75	143.5/66	159.1 ~127.9	17	3	50	Tokyo Electric Power Co. (Kuramae)
	4	60/66/30	105/66/21–10.5	115 ~100	7	3	60	Chugoku Electric Power Co. (Iwakuni)
	5	60	147/73.5	158.75~135.25	11	3	60	Kansai Electric Power Co. (Shinhatiman)
	6	45/50/20	154/66/10.5	168.1 ~139.9	13	3	50	Tohoku Electric Power Co. (Hachinoe)
	7	40	70/11	76.4 ~70	6	3	60	Nippon Light Metal Co. (Kanbara)
	8	35	146/22	157 ~135	11	3	60	Toto Steel Mfg. Co. (Toyohashi)
	9	30	147/73.5	158.75~135.25	11	3	60	Kansai Electric Power Co. (Shin Hachiman)
	10	30	140/22	151.2 ~128.8	11	3	50	Kawasaki Steel Co. (Chiba)
	11	15	100/46/13.8	115.5 ~ 93.5	17	1	50	Eisenberg & Co. (India)
	12	10	77/6.9–3.45	80.5 ~ 70	7	3	60	Kansai Electric Power Co. (Noe and others)
	13	10	70/33(22)	77 ~ 66.5	8	1	60	Chubu Electric Power Co. (Toyoda and others)
Double core	101	150/ 150/(50)	275/66/15	275± (7.5%)	13	3	50	TokyoElectric Power Co. (Yokosuka)
	102	42	66/0.242	0.308~0.176	25	3	60	Shin Nippon Chisso Hiryo Co. (for Electric Furnace)
	103	27	63/0.186	0.234~0.138	25	3	60	Sumitomo Chemical Co. (for Electric Furnance)

N. B.: No. 101 consists of an ordinary main transformer and a single core type on-load tap-changing transformer. Each of No. 102 and No. 103 consists of a single core on-load tap-changing transformer and a series transformer.

Company, AEG and Brown Boveri Company. The equipment of the respective companies shows the distinctive characteristics of the respective companies in design and construction; however, the on-load tap-changers with current limiting resistors and using spring drive system (generally called Jansen switch) are used in all these regulators. Furthermore, it is noted these transformers have extremely complex functions which make it possible to use one transformer for all three voltages of 400 kV, 231 kV and 30 kV.

II. DISTINCTIVE FEATURES OF RECENT ON-LOAD TAP-CHANGER

1. History

The designation of on-load tap-changer instantly brings to mind the name "Jansen switch" which is evidence of its wide popularity. The Jansen on-load tap-changer was originated by Dr. Jansen in the 1920. At about the same time, Blume and others of the U.S. designed an on-load tap-changer using the current limiting reactor. Dr. Jansen obtained patent rights for the principal sections of his design which included the "quick motion mechanism using springs", "current limiting system by resistor" and "mechanism composed of four-leg links". The superiority of this system has been recognized by users and makers of all countries. During the 30 years following its invention, the "Jansen switch" has established itself as the leading type on-load tap-changer and is widely used in all parts of the world. Fuji on-load tap-changers are manufactured according to the same system. To date, we have completed several hundred units.

In recent years, considerable developments have been made by Schwaiger and others and new models of the on-load tap-changer have been designed. This new system is used in all products of Siemens and our company. They are designated S type and DS type in order to distinguish them from the former type (AS type).

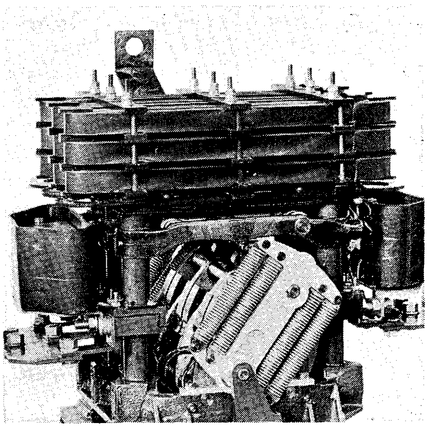

Fig. 3. S type Jansen Switch

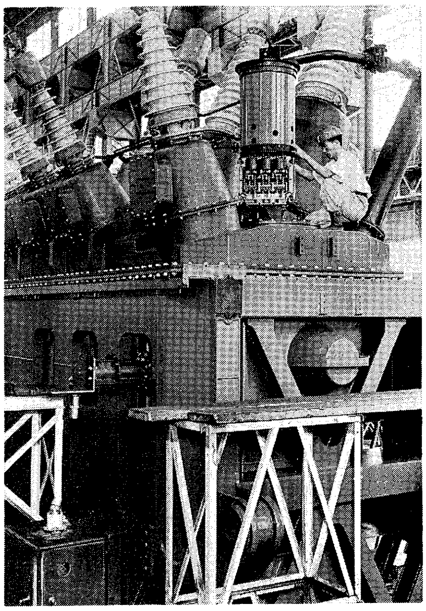

Fig. 4. D S type Jansen Switch

2. Distinctive features

The basic distinctive features of all three types, the S, DS and AS types are as follows:

1) Quick motion mechanism composed of spring and 4-leg link
2) Non-stop operation at intermediate positions
3) Cross current between taps is limited by resistor
4) Power factor of arc current at time of break-off = 1
5) Good arc suppression, minimum arcing time
6) Carbonizing of oil and wearing down of contacts are very small

The following is a brief explanation of the above features. In the instance of on-load tap-changing, the diverter switch lever is operated by the motor driven operating mechanism through the axle. It revolves and streches the spring joined to the lever. When the required energy is stored in the spring, the four-leg link reaches upper dead point. After this, the accumulated energy in the spring causes quick motion from upper dead point to the final position. This quick motion requires only 0.065 seconds to complete. Furthermore, since the upper dead point is utilized there is no stop at intermediate positions. The lead connection is so designed that tap 1 of the transformer is connected up to the time the link reaches the upper dead point and tap 2 is connected when it reaches the final position. In this way, there is no suspension of operation. Equipment possessing the " non-stop at intermediate positions " characteristic is defined as " Sprungschalter " in VDE 0532 (transformer specifications). An equipment which has characteristic that will probably stop at intermediate positions due to mechanical trouble or power cut-off is called "Laufschalter" in VDE. According to these specifications, the Jansen-Schalter is a "Sprungschalter". Likewise, Fuji on-load tap-changer is a Sprungschalter.

A power factor = 1 at time of current cut-off can be obtained by using a pure resistor for limiting cross current. This improves arc suppression and there is no abnormal excessive voltage as the restriking voltage. An ideal short interval cut-off of current is possible. This decreases the rate of erosion of the contacts and carbonizing of oil. Thus the Jansen-switch has many technical advantages. Since the interval of current flowing in resistor is about 0.02 second, little loss is generated and temperature rise of the resistor is pretty low.

The S type and DS type which were developed in recent years possess the following additional features:

7) Parallel division of arcing contacts and use of current balancer
8) Rolling system of contacts
9) Increase of life replacement of contacts not required

Owing to divide contacts into several pieces and to insert a balancer between the parallel circuits, the flow of current has been balanced. This system was devised by Schwaiger and others. This method decreases the erosion of metal of the contacts.

The moving contacter has a curved surface and it is devised so that this curved surface rolls along the surface of the stationary contact to make connection. By using an auxiliary spring to control the rolling, the energy at time of switch-in is decreased so that damage or welding of contacts is effectively prevented.

The foregoing improvements have increased the life and durability of the equipment so that the replacement of conntacts which was necessary in the former AS type are not required in the new S and DS types. Under ordinary conditions, this equipment is expected to give satisfactory service for a period of more than a score or even several score years.

III. COMPARISON OF SYSTEMS

Various systems and wiring are used in on-load voltage regulators and on-load tap-changing transformers and each has its distinctive features. Also, each maker is constantly striving toward improvement and the results are all protected through patent rights. There are many instances in which it is not reasonable to make comparisons of the various models with the object of selecting the most superior type. In this article, a general explanation shall be given. Therefore, this study may not be an accurate explanation of special types.

1. Reactor system and resistor system

In order to restrict the cross current, it is necessary to use a reactor or resistor in the on-load tap-changing transformer to prevent short-circuiting between taps.

The reactor system was developed in 1920 by Blume of General Electric Company and this system has been used in the U. S. since that time. An epochal invention in divertor switch was made in Europe in 1927. This is the so called Jansen switch. This invention led to the wide use of the resistor system. Both systems are manufactured in Japan but the resistor system came to be widely manufactured after the patent expired for the original Jansen switch. Our company has always adopted the resistor switeh and this system will be used in all future products.

2. Common tank type and separated tank type

Fig. 5 shows common tank type and Fig. 6 is separated tank type. Both the resistor system and reactor system can be designed and manufactured into the common and separated tank types. Actually, however, as can be seen from Fig. 6, in case of reactor system the reactor, tap selector and diverter switch are constructed into one separate unit, since the current limiting reactor takes up considerable

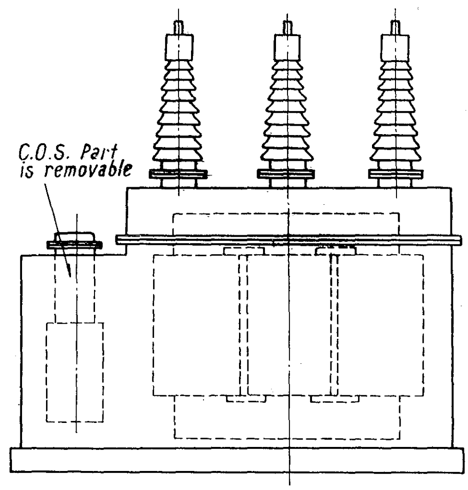

Fig. 5. On-load tap-changing equipment, common tank type

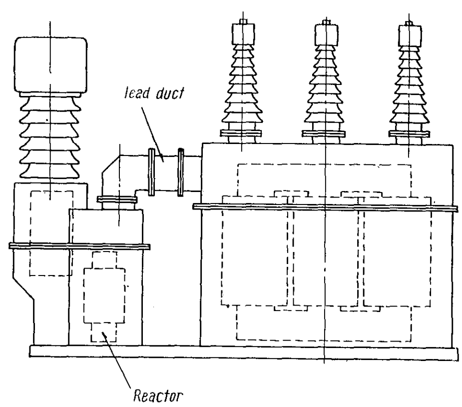

Fig. 6. On-load tap-changing equipment, separate tank type

space. Otherwise, it is difficult to transport the transformer together with the reactor etc. In this instance, the heat is radiated from the surface of the separated tank. Since the surface of the separated tank is generally large, no radiator is usually installed on the tank.

The common tank type has the advantage of assembly and transportation without disassembling the lead sections after it has been assembled in the factory. This results in higher reliability. In this case the transformer tank will become slightly larger but it is possible to manufacture a tank that can be transpoted in the assembled condition.

The advantages of the separated tank type are that the tank can be designed in a smaller size and mechanical trouble of the on-load tap-changer can be repaired by removing it at the lead duct section. However, it is important that the lead duct section is designed to be removed without damaging complate oil-tight and insulation. Also, consideration must be given to the problem of absorption of moisture at time of removing. Thus, it is doubtful whether the separated tank type is convenient. Our company gave close study to these points and adopted the common tank type for Jansen switch. It goes without saying that care has been given to the problem of carbonizing of oil by the switching action. It has been so designed that the diverter switch is completely separated from the main body of the transformer so taht there will be no mixing of the oil.

3. Totally-enclosed type and bushing type

Fig. 7 shows the totally-enclosed type. This is the type adopted in all recent products of our company The 220 MVA, 380 kV on-load tap-changing transformer referred to in Chapter I (manufactured in Germany) and our most recent large capacity on-load

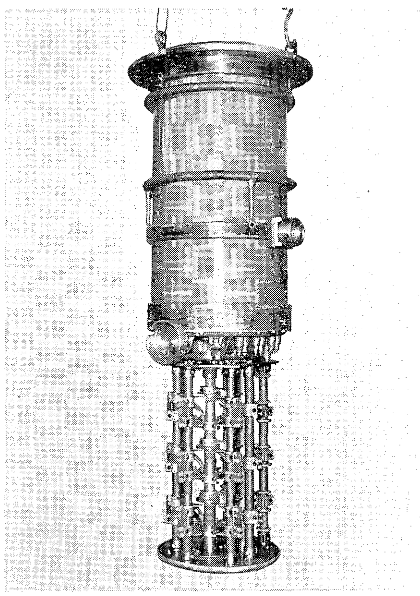

Fig. 7. Jansen switch, totally-enclosed type

tap-changing transformers as well as those for medium and small capacities are manufactured according to this type. The bushing type is a model that was manufactured up to several years ago. The diverter switch is placed in a case installed on top of the bushings. (See Fig. 8) In many instances, the transportation of the bushing type transformer was difficult due to the height of the bushing. Also, the problem of damage from sea-breeze and mechanical durability remains to be solved. Compared to this type, the totally enclosed type has no exposed high voltage sections. Also, no sections have to be disassembled for transportation. This accounts for its high degree of reliability. That is, no checking or adjustment is required after it has been assembled at the factory. The feature of the total enclosed type is that the exposed insulation section (bushing section of Fig. 8) has been immersed in oil which acts as the good insulating body. Thus, the large insulating section

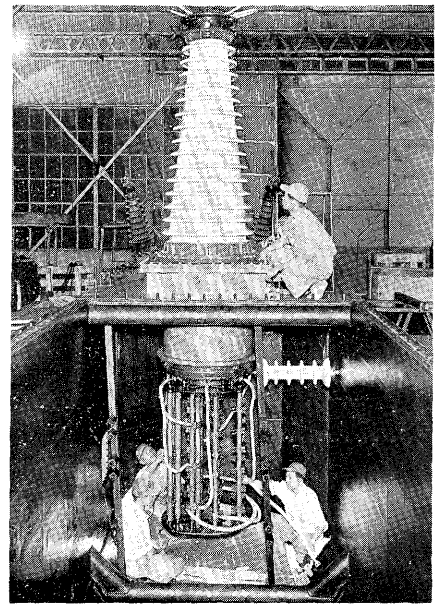

Fig. 8. Jansen switch, bushing type

which is exposed to the air dust and rain has been done away. The result is a compact highly reliable tap-changing transformer.

The upper cover section of the total-enclosed type on-load tap-changer has the same electric potential as the tank so it is possible to install various protective devices and oil pipe in this section. This also makes it possible to filter the oil required for the diverter switch. The oil filtering system at service condition of transformer was developed by our company. Details shall be given in Chapter V.

IV. HIGH-SPEED PHOTOGRAPHY OF TAP-CHANGING PROCESS

The principle of the operation of the Jansen type on-load tap-changer is the same as has been explained in Chapter II. Its external appearance and structure are shown in Figs. 3 and 4. Strict mechanical and electrical tests are required to ascertain whether " this equipment will operate satisfactorily as an good on-load tap-changing equipment." Numerous tests have been conducted to date and the following is a report of the tests conducted by our company.

This paragraph will give the explanation of the high-speed photography of the tap-changing process.

1. Photographing of switching operation and circuit

As can be seen by the mechanism of the diverter switch, the link mechanism is operated by the rapid release of energy accumulated in the spring. Therefore, it is impossible to obtain sharp pictures of the operation with cine cameras of normal speed (16 frames/second). The details of the mechanism can be obtained only by using a high-speed cine camera (several thousands frames/second) and projecting it to screen at normal speed (16 frames/second).

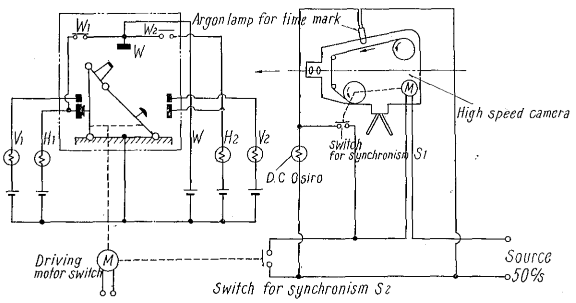

Fig. 9. Circuit at high-speed motion picture photography

The circuit shown in Fig. 9 was used for the high-speed photography of the operation of the diverter switch. We succeeded in obtaining photographs of the operations that were hitherto difficult to observe. Photographs were taken of the diverter switch operating in oil (cased in glass) and of one operating in the open air. Both photographs are used for the analysis of the fluid resistance of oil. Speed of photography was 1,000 ～ 3,000 frames/sec. For example, when pictures taken at speed of 1,600 frames/sec is projected at 16 frames/sec, the picture on the screen will appear at a speed 1/100 of real speed. Fig. 10 shows the typical examples of the pictures taken.

As can be seen from the circuit diagram, the time mark is made on the film by using an argon lamp and the situation of the contacts is recorded by a DC oscillograph (Fig. 11). A synchronizing signal was marked in both the DC oscillograph and film by using a synchronizer switch. By examining the film and DC oscillograph, a detailed analysis can be made of the speed of the link mechanism, movements of the conntacts, braking action at time of switch-on and expansion and contraction of the spring.

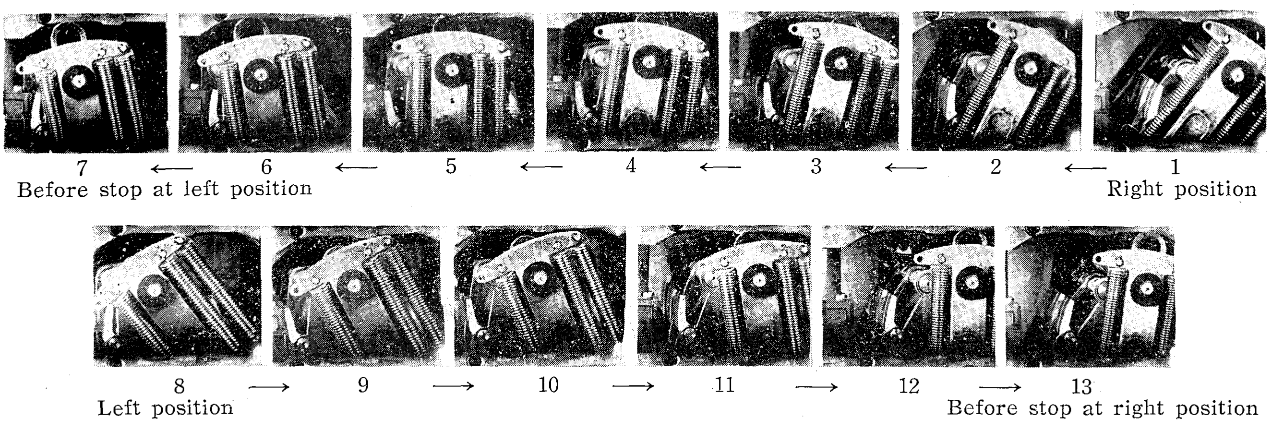

Fig. 10. Typical scenes from high speed movies of S type Jansen switch

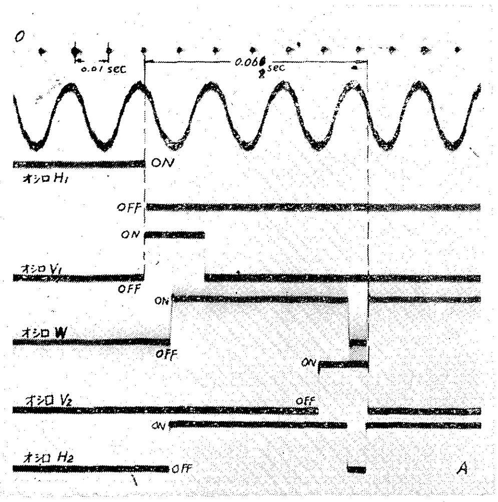

Fig. 11. DC oscillogram showing switching-off and switching-on of contacts

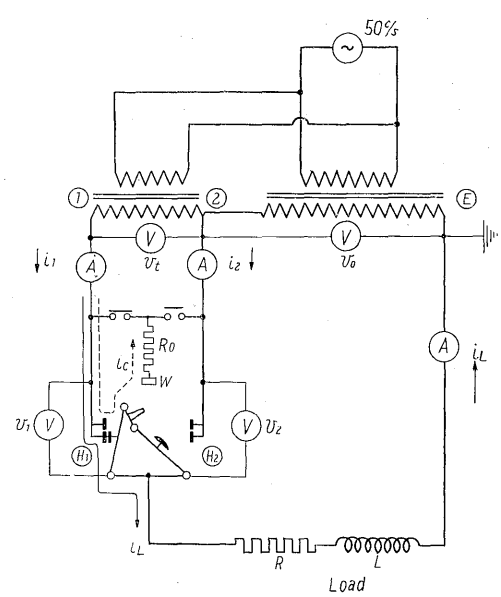

Fig. 12. Circuit of on-load tap-changing test

2. Circuit and method of photography when current is flowing

Since load current was to be switched on and off, the switch was placed in a glass case filled with oil and the switch was operated under rated current condition while immersed in oil. Voltage and current were recorded by an oscillograph and photographs were taken with an high-speed cine camera. The circuit is shown in Fig. 12. An electromagnetic oscillograph was used to record the transient voltage and current. The same method as that described in the foregoing paragraph was used to take high-speed motion pictures.

3. Results

By making a comparison of the test results and theoretical calculations, we were able to verify the fact that the equipment was operating at the expected speed, time and order. It can be said that the results of this test brought about a further improvement in the reliability of Fuji on-load tap-changer.

According to calculations and test results, the angular velocity of the link lever ranges from 0 to 1,000 deg/sec while linear velocity ranges from 0 to 180 cm/sec. Especially, the auxiliary springs work effectively to brake motion when contacts are switched on ; there is absolutely no bouncing on the surface of the stationary contacts. At the same time, there are no undesirable effects on the other sections of the mechanism ; distortion also were not noted. In short, the most satisfactory conditions of operation were observed. As can be seen from Figs. 3 the moving contacts are crescent shaped. When switched on, the surfaces roll along the surfaces of the arcing contacts. The auxiliary springs brake the movement and the contacts stop when they reach the main cantact surfaces. It is believed that the aforementioned satisfactory operating conditions are due to the rational design of the mechanism. If the mechanism were so designed that the contacts came into collision with each other at switching on, the shock resulted by this impact would be difficult to absorb.

Very little data had been available concerning the generation and suppression of arc. Since the recent test conducted by our company used the same circuit as that used in the on-load tap-changing transformer in service with rated current, many valuable data were obtained. Particularly interesting data and photographs were obtained concerning the generation of arc. Figs. 13 and 14 show the voltage and current oscillograms and high-speed motion pictures of arcing.

The time mark is recorded on the upper part of the film so the time between the generation and suppression of the arc can be easily discerned. This period was about 0.005 second (0.25 cycle) which was the interval based on theoretical calculation. In the resistor type, the interval was generally estimated to be not more than 0.01 second (0.5 cycle) since it was believed that the arc was suppressed when the current passed through 0 value for the first time. The results of the test verified the correctness of this estimate. (See Fig. 14)

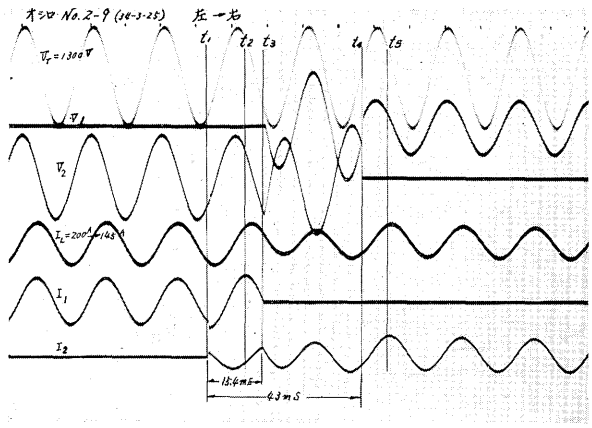

Fig. 13. Oscillograms at on-load tap-changing process

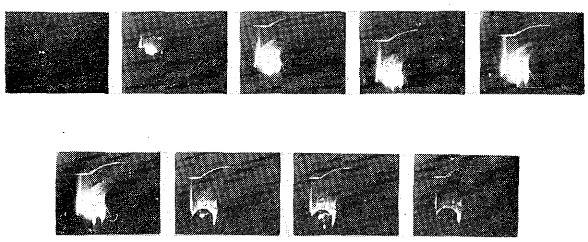

Fig. 14. Typical scenes from high-speed movie of S type Jansen switch at on-load tap-changing

V. OPERATION AND MAINTENANCE

1. Operation and maintenance of on-load tap-changing transformer

Normally, all equipments are operated by remote control from the switchboard ; however, the special switch which can be used for the direct control is in the box of motor driven operating mechanism. Tap-changing can be continued by operating the manual handle even in time of cut-off of the auxiliary power source. In this instance, the revolution of the handle has no relation with the speed of the diverter switch at all. This is because the diverter switch is operated by the energy stored in the spring.

Even when the mechanism revolves exceeding the tap range, there will be no trouble because the stopper will work and effectively restrict the revolution. Also, when tap range is exceeded in power operation, trouble is effectively prevented by the automatic operation of the limit switch, brake and clutch. In other words, all possibilities of mis-operation are effectively forestalled by the various effective protective apparatus. Therfore there is absoltely no cause for worry concerning mechanical trouble of mis-operation. However, it ts advisable for all operators to have a thorough knowledge of the mechanism.

The development of the relay system has resulted in the wide use of the automatic voltage controlling system. In this instance, when the suitable controlling system is not selected, hunting will generate and this will increase excessive burden on the on-load tap-changer. For this reason, it is essential to give careful consideration to the stability of the automatic voltage controlling system. The actual state of voltage changes of network systems must be studied in order to select the controlling system best suited to these conditions. This subject has not been explained here ; however, it is a problem that must be given close study. When several banks of on-load tap-changers are used for parallel operation, a relaying system that can be used for future increase in the number of equipment must be selected.

A study of the present conditions abroad shows that the on-load tap-changing transformer is used more widely in Europe than in the U.S. In other words, the on-load tap-changing transformers are used for almost all newly constructed substations which use large capacity equipment. In the U.S., less than one half of the large capacity transformers are of the on-load tap-changing type. In Japan, large capacity on-load tap-changing transformers are being used in many new installations and this will become the standard type in the very near future. Automatic control systems are used for the control of voltage while non-automatic systems are used for the phase regulating.

In Germany and England, field magnets of generators are partially controlled, then on-load tap-changers are equipped on step-up transformers for the purpose of regulating voltage. In Belgium, France, Holland, Japan, Norway, Sweden, Switzerland and the U.S., the on-load tap-changing transformers are not usually used for power plants.

Both the alternating current and direct current are used for auxiliary power source. In Germany and England, the alternating current is used for the operation of the motor only while the direct current is used for indication only. In Japan, alternating current is used in almost all instances. In the majority of the countries, the allowable voltage regulation of the relaying circuit is fixed at 15 per cent. The controlling system for parallel operation can be selected from among (1) simultaneous system, (2) master-follower system, (3) circulating current system and (4) reversed reactance system. (1) and (2) are widely used in Japan and European countries while (3) and (4) are used in the U.S.

2. Maintenance

The points of difference from usual transformers are the maintenance of the diverter switch oil, arcing contacts and motor driven operating mechanism.

No. 2 oil of JIS C 2320 is best for the diverter switch. It is best to follow this standard when sampling and inspecting oil. (JIS C 2320 No. 2 oil is especially prepared for use in transformers and is of similar quality as oil used in foreign countries.) Close attention must be given to absolute values of the breakdown voltage, acid value and tan δ and further, yearly changes in quantity of oil. Fuji totally enclose type on-load tap-changer is so designed that the oil of the diverter switch chamber can be filtered or changed without stopping the operation of the transformer. (Fig. 15)

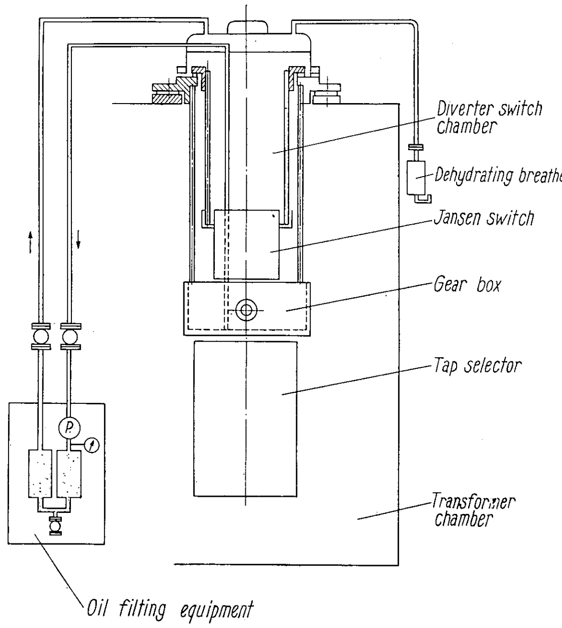

Fig. 15. Oil filting equipment at on-load operating condition of transformer

This oil filtering apparatus without stopping the operation of the transformer was developed by our company. A small oil filer is placed near the transformer and connected to the diverter switch chambers. Thus, the switch oil can be easily filtered whenever it becomes fouled. A small, light filter has been specially designed for this purpose. Care has been taken to prevent breathing air into the pipe. The oil duct is so placed that the fouled oil will be effectively removed from the diverter switch chamber. Also, the pipe is completely insulated in sections near the high voltage sections.

This oil filter has the following specifications:

Oil pump: three-phase, 200 volt

Output: 0.4 KW

Quantity of circulating oil: 16 l/min

Absorbent: Silica gel

	JIS Electrode dielectric strength	Acid value
Before filtering	10 kV/2.5 mm	1.1
after 15 min filtering	28 kV/2.5 mm	0.78
after 30 min filtering	48 kV/2.5 mm	0.61

It is advisable to filter the oil once every 1,000 times of tap changings. For example, when voltage is changed on an average of 30 times a day, oil must be filtered once a month and more frequent filtering is not advisable. If oil is not filtered over a long period, the oil will become fouled and small carbon particles will adhere to the surface of the insulating material inside the diverter switch chamber. The oil cannot be filtered easily as when it is filtered at set intervals. When the oil becomes excessively fouled, it will be necessary to remove all the fouled oil and replace it with new oil after the chamber has been cleaned out. Our on-load tap-changer will give satisfactory service even when it has been operated for several 10,000 times without filtering oil. Consequently, there is no need to become over-sensitive concerning the fouling of oil. Fig. 16 shows the decrease of the dielectric strength of oil as obtained from various tests. When it decreases to below 20 kV/2.5 mm in case of JIS electrode, the oil must be either filtered or replaced.

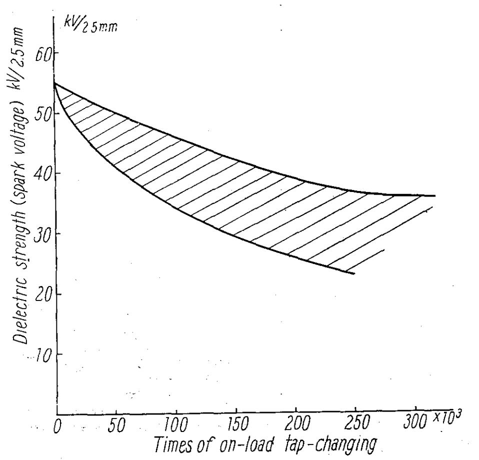

Fig. 16. Dielectric strength of oil in on-load tap-changer

Concerning contacts, as has been explained in Chapter 2, its life corresponds to the service life of the transformer body; therefore, there is absolutely no need for replacement. Furthermore, it is advisable not to touch the contacts since they are manufactured in high precision. Contacts and springs must not be adjusted without first referring to instructions attached to the transformer equipment. Whenever abnormal operation is discovered, the service must be stopped and the trouble reported to the maker.

The motor driven operating mechanism is designed to prevent damage from moisture, dust and gas. The only maintenance required is supplementing the bearing grease, oiling of the moving parts. When coupling of the axle is disassembled for inspection, it must be replaced in the same position and the marks matched. Any errors of disassembly will cause abnormal operation.

The alarming relay system and the explosion vent are installed to prevent accidents due to abnormal pressure in the diverter switch chamber. Also, the oil level relay is installed to show that the surface of the oil has fallen lower than the prescribed position in case of oil filtering or replacing A small oil gauge is placed on the upper part of the cover. The oil inside the diverter switch chamber connects with the outside air through the dehydrating breather. The gas generated by arc at time of switching is released through this breather. This dehydrating breather is similar to that attached to the transformer body. Silica-gel is used as the absorbent. The moisture content is judged by the degree of discoloration of this absorbent.