The Journal of CPRI,
Vol. 12, No. 3, September 2016 pp. 487-496

Technological development of on - load tap changing mechanism in power transformer - a review

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Voltage control is one of the main concerns of power utilities with regard to quality of the power. To maintain load voltage within permissible limits every power transformer is designed with voltage controlling and regulating system. Hence transformers are required to supply with an On-Load Tap Changer (OLTC) which became mandatory. The OLTC voltage regulation is naturally operated by Changing the number of turns in one of the windings of the transformer. This paper presents a review of a differentiated details of conventional mechanical OLTC and electronic assisted tap changer as controller.

Keywords: *Voltage control, On-Load Tap Changer (OLTC), vacuum type, static type.*

1.0 INTRODUCTION

When the load in a power network changes it affects voltage profile on the network. To maintain the voltages within permissible limits, Power transformers are equipped with tap changing system. A tap changer is a device fitted to power transformers for regulation of the output voltage to required levels. This is normally achieved by changing the ratios of the transformer on the system by altering the number of turns in one winding of the appropriate transformer/s. It is very much essential to maintain the network voltage within specified limits. At load centers tap changers offer variable control to keep the input voltage within these limits.

On-load tap changing power transformers are an essential part of any modern power system, since they allow voltages to be maintained at desired levels despite load changes, without interruption of loads.

About 96% of all power transformers above 10 MVA incorporate on load tap changers as a means of voltage regulation.

An on-load tap-changer must not break the supply while the transformer is on load. So it has a 'make-before-break' arrangement with its contacts, shown in Figure 1.

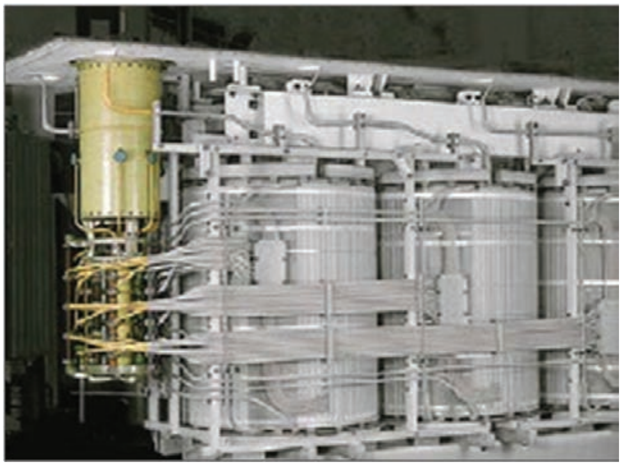

FIG. 1. POWER TRANSFORMER WITH OLTC

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Sequence of operation involved in the operation of OLTC is given in Figure 2

On-Load Tap Changer (OLTC), is the only moving component of a transformer except oil which plays most vital role in power system stability and the quality of power delivered to the customer. An international survey by International Council on large electric system (CIGRE) Working Group 05, 1983 reveals that 41% of power transformer failures are due to on load tap changers. Figure 3 represents power transformer failure due to various components. The consequences of failure of a power transformer are well known. To minimize the failure attention must be paid to new technology development, stringent testing of OLTC and better understanding of OLTC failure. [1]

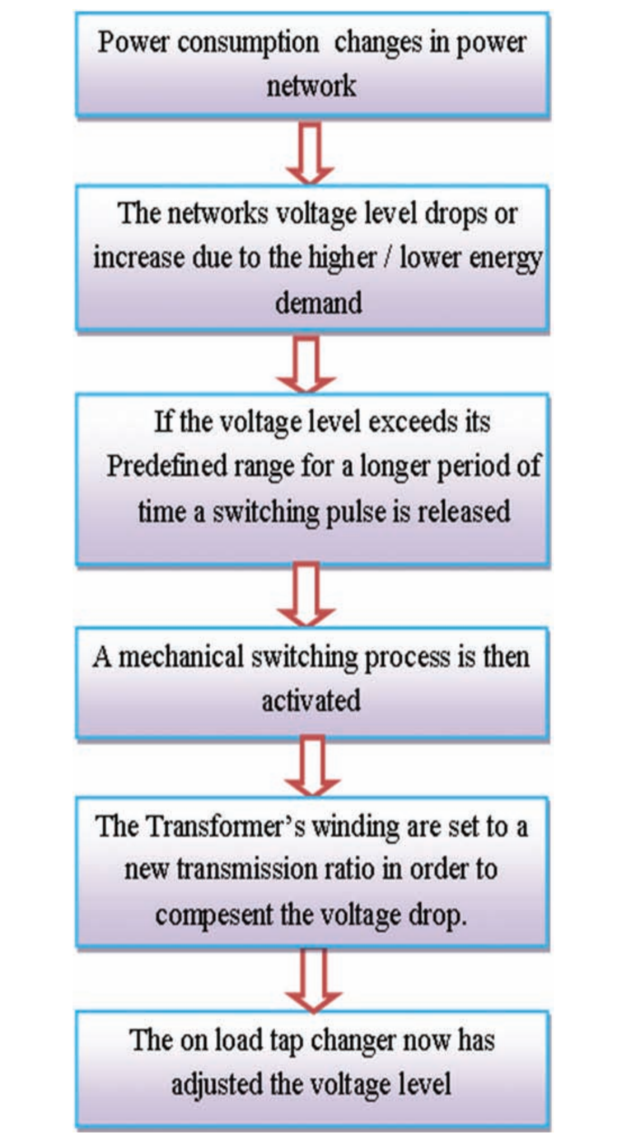

FIG. 2. STEPS INVOLVED FOR OLTC OPERATION

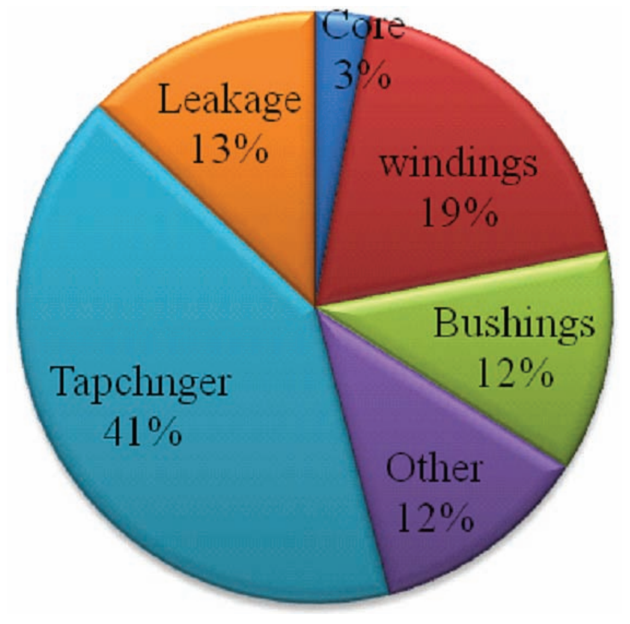

FIG. 3. REASONS FOR FAILURE OF POWER TRANSFORMERS

2.0 SIGNIFICANCE OF VARIOUS COMPONENTS

A conventional tap changer uses the principle of make before break in order to vary the transformer ratio while maintaining the supply to the load. There are two important conditions for an OLTC operation, first being the regulating step must never be short circuited and the second being the load current must never be interrupted. The principle make before break two adjacent taps, the load current is switched to the desired one and the other tap is then disconnected so that it ensures the continuity of supply to the load. The two main switching techniques namely resistance switching and reactance switching employ resistors or impedances during the transition of the load current from one tap to the other. The idea is to limit the circulating current when the two taps are bridged and to transfer the load current to the other tap without any interruption of supply. There are two different types of switches employed in OLTCs namely the selector switch and the diverter switch (Figures 4 and 5). The selector switch first selects the desired tap to switch. Later the diverter switch performs the transfer of load current from one tap to the other.

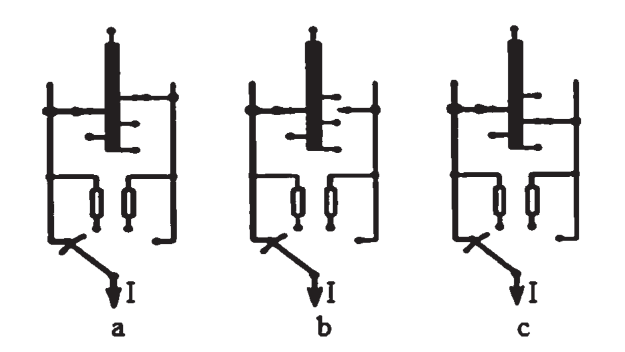

FIG. 4. SWITCHING SEQUENCE OF SELECTOR SWITCH

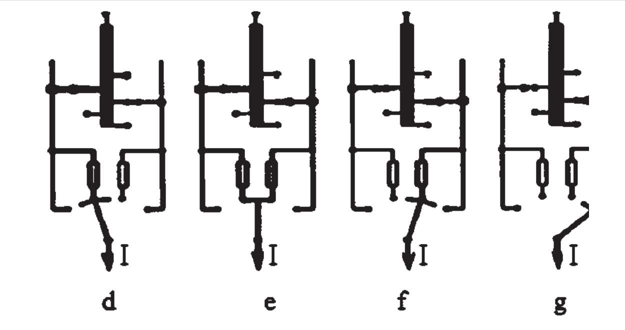

FIG. 5. SWITCHING SEQUENCE OF DIVERTER SWITCH

An OLTC is commonly mounted in the primary side of power transformer. A lower load current at the primary side is preferred to be switched because it may reduce the switching arc. Small switching arc will prolong the contact lifetime and slow down the formation of carbon when oil is used as an insulating medium. Another insulating media is vacuum. It is mostly used in the diverter switch type of OLTC.

There are three different kinds of tapped-winding arrangement according to the type of switching. Linear, plus/minus and coarse/fine switching. Figure 6 shows the different types of winding arrangements are used for tap changer.

OLTCs in linear arrangement add the tapped winding in series with the main winding and thus change the ratio since the number of winding turns is changed. The plus/minus arrangement provides an ability to add or subtract the voltage of the tapped windings from the voltage of the main winding. Then the regulating range can be doubled or the number of the tapped windings can be reduced. The other arrangement is coarse/fine. It connects and disconnects the coarse winding during the operation which has a higher voltage than the fine tapped windings.

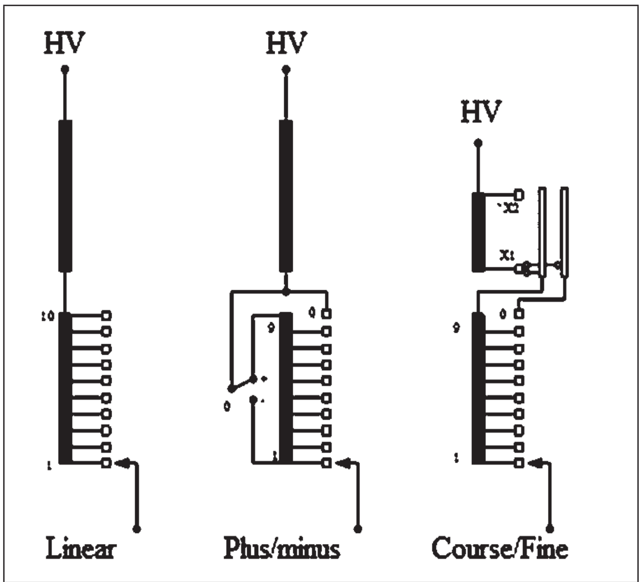

FIG. 6. DIFFERENT TYPES OF TAP WINDING ARRANGEMENTS

Based on their working mechanism during switching the load current, OLTCs are divided into two types (Figures 7 and 8) diverter switch and selector switch type OLTCs. Diverter switch type consists of a tap selector and a diverter switch. A tap selector pre-selects the tap winding without switching any current. Then the diverter switch transfers the load current from selected to the pre-selected tap during the switching operation. The other type of OLTC is selector switch which combines both functions of tap selector and diverter switch. It selects a tap winding while transferring the load current.

Resistance type load tap changers, as the name implies, use a resistive element to limit the circulating current when in the bridging position. Presuming a common 13.8 kV transformer secondary where the voltage change per tap is 5/8%, one step change represents about 50 V. If the resistor is sized as one ohm, it will be required to dissipate 2.5 kW as due only to the circulating current. This point is the basis for the fact that OLTC which use resistors

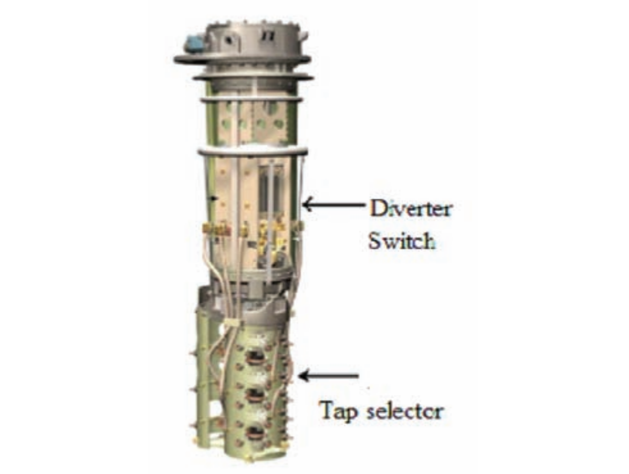

FIG. 7. DIVERTER SWITCH

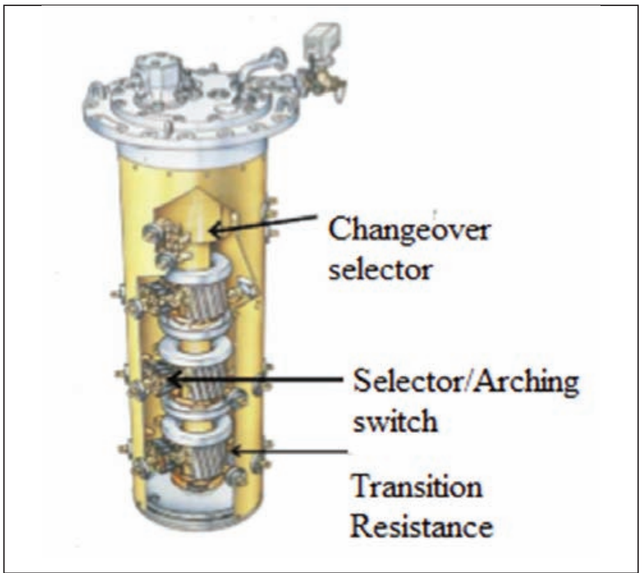

FIG. 8. SELECTOR SWITCH TYPE

transition quickly between steps, the bridging position being in the circuit only tens of milli seconds.

TABLE 1
DIFFERENCE BETWEEN RESISTANCE AND REACTANCE

Sl. No.	Resistanc	Reactance
1	The switching always occur at Upf. Hence voltage across the open selector is not very high.	Switching always occur at Zero power factor
2	I^2R loss is more	I^2R Losses are less compared to resistance Type
3	Resistance are smalla compared to reactor	Reactors are bulky compared to resistor

3.0 OPERATIONAL PERFORMANCE

Operational performance can broadly described in to switching time and Life time switching time: Conventional tap changers require a 20 to 40 s for switching whereas the recently developed vacuum tap changers require 3 to 10 s for their operation.

Life Time: Conventional tap changers have a lifetime of 100,000 operations whereas the recent technology of vacuum switching tap changers have a life time of 500,000 to 600,000 operations

4.0 VACUUM TYPE

Vacuum switching technology also best meets the new application requirements and increased performance demands for OLTCs by end users. Its superiority over competing switching technologies in the low and medium power ranges is based on a number of technical features.

- The vacuum interrupter is a hermetically-sealed system, There is no interaction with the surrounding medium, despite the arc
- The arc (drop) voltage in vacuum is considerably lower than in oil or SF_6, reduced contact wear.
- No aging of the quenching medium, Constant or even improving switching characteristics throughout the entire
- Life span of the vacuum interrupters
- No interaction/oxidation during switching, high rate of recondensation of metal vapor on contacts extends contact life
- Extra ordinary fast dielectric recovery of up to 10 kV/µs , Ensures short arcing times (maximum one half cycle) even in the case of large phase angles between current and voltage or high-voltage steepness dU/dt after the current zero (converter transformers)

Since vacuum type OLTCs are offers better arc quenching property than insulation oil, hence Vacuum based OLTC are more preferable

FIG. 9. VACUUM DIVERTER SWITCH

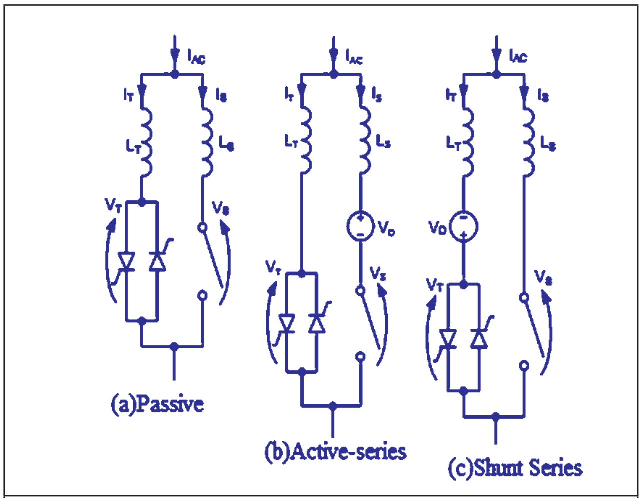

FIG. 10. HYBRID TAP-CHANGER

5.0 LIMITATIONS OF CONVENTIONAL TYPE

In spite of developments in the structure of the on-load mechanical tap-changers, they have considerable limitations. These include

- Arcing in the diverter switch
- Excessive conduction losses
- Mechanical structure is a complicated gear mechanisms of selectors, diverters and switches.
- Mechanical arrangements are slow in response and susceptible to contact wear condition and deterioration of insulating oil, thus requiring regular maintenance

In order to overcome to these limitations new circuits and configurations for tap-changers have been recommended [2].

6.0 STATIC TYPES

These may be classified into two groups

1. Electronically assisted (or hybrid)

2. Fully electronic (or solid-state)

tap-changers.

The circuit for the hybrid tap-changer was presented in [4].

This structure reduces the arcing considerably. However, its major disadvantage is that although two thyristors are on over short periods during the tap-changing process, it is permanently connected to the circuit of the deviation (diverter) switches and it probably is burnt. This may therefore reduce the reliability of the system.

To remove this drawback, an alternative configuration has been introduced in [5]. The main idea in this structure is that two thyristors are connected only during the tap-changing period which enhances the reliability of the system. In [6], a different diverter switch structure has been introduced in which only one resistor-pass has been used.

So far, the recommended structures could reduce the arcing, but the tap-changing process remained too slow, because traditional structure has been employed for the switches. If improvement of power quality is proposed [7], [8] using a tap-changer, quick operation of the tap-changer is desirable. In such a case a traditional tap changer cannot react well, while an electronic tap-changer enables to operate properly.

Shuttle worth *et. al* [9] in their paper had outlined and discussed a new design scheme for tap changing scheme. Instead of using oil-immersed contact and complicated mechanical drive, a vacuum switch and bistable electromechanical actuator were used. These vacuum switches had the advantages of high power handling capability and long life, thus, suitable for the use as the selector. The proposed diverter, consisting of two solid-state switches, was to be connected between each of the selector output leads and star point and in parallel with those two solid-state switches. With this arrangement, the two solid-state switches werere lieved from conduction loss and protected from over-currentdue to through faults during tap changing. However, use of high cost vacuum switches and the permanent connection of solid-state switches to the tap-changer leads to low electrical reliability. Another new structure for hybrid tap-changers has been introduced in [3], where the selection switch parts and diverter switches are not separated from each other. Although it can be concluded that the hybrid tap-changers using solid-state power switches can considerably suppress the arc during the tap-changing process [10], there are still moving mechanical parts present in these tap-changers. This complicates the system and leads to slow operation of tap-changers. Full-electronic tap-changers have therefore been introduced. In the 1990's, a comprehensive study has been carried out in which traditional techniques for limiting the circulating current between the taps, using pass-impedance, has been employed in the electronic tap-changer [13].

The first circuit for a micro controlled based tap changer was presented [14]. In this structure output voltage of the transformer will be sensed by the micro controller and compare with the reference value as per the program. And it will produce appropriate command to trigger the pair of anti parallel thyristors for change in the suitable tapping of transformer. The system stability is improved, because of quick response. Because of static devices, maintenance cost is reduced due to elimination of frequent sparking.

Where the complete mechanical control is replaced with static or semiconductor switches belonging to the thyristor family such as GTO. The GTO switches are capable of controlled turn on and off. These modern GTO thyristors had the advantages of high power handling capability and long life, thus suitable for use as selector. The tap selector consists of bi-directional GTOs connected in anti-parallel. Thus selection of particular tapings is done by switching GTOs in that respective tap. The application of semiconductor or solid state devices in designing the tap changer have advantage of faster response, are almost maintenance free and better performance when compared to conventional tap changers.[15]

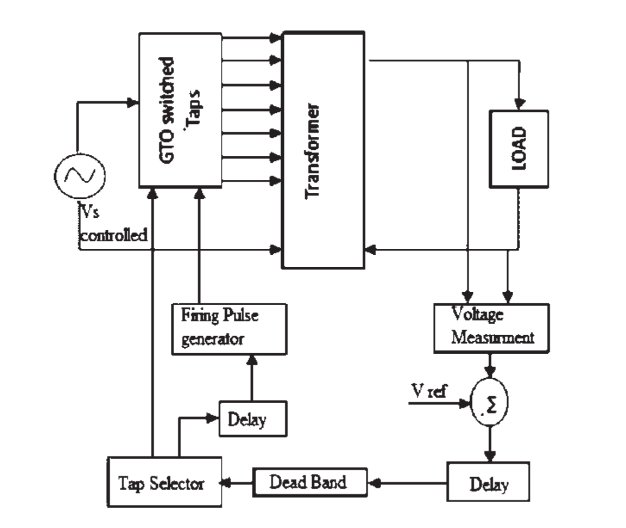

FIG. 11. BLOCK DIAGRAM OF OLTC WITH STATIC SWITCH

7.0 LIMITATION OF STATIC SWITCH

R C Degen eff, O Demirci *et. al* [16][17]. In their paper clearly discussed limitations of static type OLTC, is that cost, efficiency and high conduction loss. Furthermore, as solid state switch is permanently connected in the circuit, some sort of protection against high voltages surge travelling down transformer winding is required.

8.0 REQUIREMENTS OF OLTC CHARACTERISTICS AND PERFORMANCE UNDER SHORT-CIRCUIT CONDITIONS AS PER LATEST IEC STANDARDS

Proper operation of OLTC along with the transformer has to be ensured by some means of testing and making sure it will be intende to perform well. IEC 60214-1: 2014 dealt the testing requirements of OLTC. According to this following type tests shall be performed on on-load tap-changers after their final development or on equivalent.

- Temperature rise of contacts
- Switching tests
- Short-circuit current test
- Transition impedance test
- Mechanical tests
- Tightness test
- Dielectric tests

8.1 Short-Circuit Current Test

All contacts of different design carrying current continuously shall be subject to short-circuit currents, each of 2 s (±10 %) duration. In the case of liquid immersed on-load tap-changers, the test shall be performed in transformer liquid.

The values of the short-circuit test current to be applied shall be as given in Figure 12

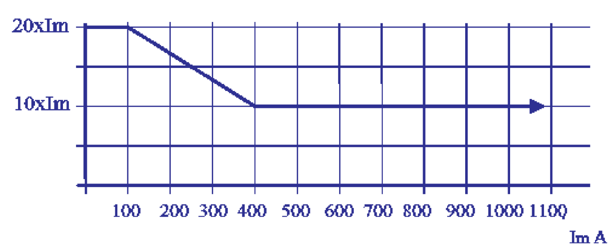

FIG. 12. SHORT-CIRCUIT TEST CURRENT (R.M.S. VALUE) AS A MULTIPLEOF THE MAXIMUM RATED THROUGH-CURRENT (ON-LOAD TAP-CHANGER)

In the case of three-phase on-load tap-changers, it is sufficient to test the contacts of one phase only unless otherwise specified. Three applications shall be made with an initial peak current of 2,5 (±5 %) times the r.m.s.value of the rated short-circuit test current. The contacts shall not be moved between these applications. When there are no facilities for point-on-wave switching and it is not possible to obtain three short-circuit applications with initial peak current 2,5 times the r.m.s. value, the following test may be used. Figure 13 shows OLTC under short circuit test.

8.1.1 Evaluation criterion

Contacts shall not have been damaged, This has to be proven for a diverter switch or selector switch by a no load operation, oscillographically recorded, breaking any created weld. Comparison of this oscillogram with those obtained before the test shall show suitability for service.
For a motor-driven sliding contact such as tap selector or changeover selector contacts, the initial operating torque shall be measured before and after the test and show suitability for service.

Other current-carrying parts shall not show signs of permanent mechanical distortion, which can influence the normal operation of the tap-changer

FIG. 13. MOUNTING ARRANGEMENT FOR SC TEST

8.1.2 After Test Condition

Figure 14 shows the condition of 110/66/33 kV, 200 A On-Load Tap Changer after the test which was carried out at 3.5 kA rms for 2.0 s and 8.75 kA peak.

After test pitting was observed on moving contact of the pre selector switch. Hence pre selector switch did not operate.

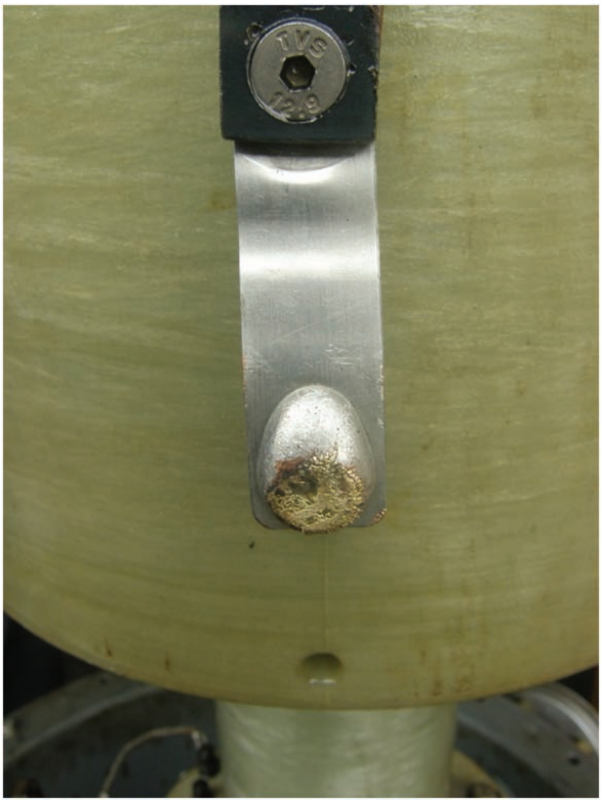

FIG. 14. CONDITION OF SAMPLE AFTER TEST

8.2 Transition Impedance Test

The transition impedance test relates to the allowed rise in temperature of the current limiting resistor in resistance type tapchangers. With the tapchanger mechanism operating without interruption and at normal speed for the full range of operation (commonly 32 steps) and at 1.5 times the tapchanger maximum rated through current, the temperature rise of all components must not exceed 350 K relative to the surrounding oil and must be such as to not damage any components.

8.2.1 Transient current calculations as per annexture 'C' of IEC: 60214-1

The test is performed with current *I*p, the r.m.s. value of which is obtained from

$$I_p = \frac{1}{\sqrt{k}} \times \sqrt{\frac{\sum_{i=1}^{n} \left(I_i^2 \times t_i\right.}{\sum_{i=1}^{n} t_i}} \quad \ldots(1)$$

Where

I_i is the current value loading the transition resistor throughout different steps of the switching sequence.

T_i is the time during which the particular currents Ii are flowing.

k is the coefficient chosen to suit the testing requirements of the resistor

TABLE 2		
SPECIFICATION OF TAP CHANGER		
1	Rated Current(Ir)	800 A
2	Relevant step voltage(E)	1700 V
3	Transient Resistors (R)	1.10 Ω

Test conducted at 1.5 times current of Ir

=800 x 1.5 = 1200

Heavy Duty cycle current

$$I_H = \tfrac{1}{2}\left(Ir + \tfrac{E}{R}\right) = 1373 \text{ A} \quad \ldots(2)$$

Light Duty Cycle current

$$I_L = \tfrac{1}{2}\left(\tfrac{E}{R} - Ir\right) = 173 \text{ A} \quad \ldots(3)$$

t_1 in ms=150
t_2 in ms=150

$$T_{ON} = t_1 + t_2 = 300 \text{ ms} \quad \ldots(4)$$

$T_{off} = 4$ s

K=5

$$\left(I^2 t\right)_H = IR^2 t_1 + I_H t_2 = 49866 \text{ A}^2 \text{ s} \quad \ldots(5)$$

$$\left(I^2 t\right)_L = IR^2 t_1 + I_{L2} t_2 = 22048 \text{ A}^2\text{s} \quad \ldots(6)$$

$$\sum t = t_1 + t_2 = 300 \text{ ms}, \quad \ldots(7)$$

K=5

Tp=5x0.30 = 0.15 s

Heavy Duty Cycle test current

$$I_{pH} = \sqrt{\left(\sum \left(I_2 t\right) H / t_p\right)} = 576.6 \text{ Amps} \quad \ldots(8)$$

Light Duty Cycle test current

$$I_{pL} = \sqrt{\left(\sum \left(I_2 t\right) L / t_p\right)} \quad \ldots(9)$$

Above current values to be used for 16 uninterrupted operation

9.0 CONCLUSIONS

From the above literature study on various technologies developed on load tap changer and testing procedures, the following conclusions are made.

i. Tap changers are very sophisticated and precise mechanical switches. Various suppliers have refined the operation of these switches to meet their particular needs. The user needs to recognize the instrinsic differences among the, resistance type and reactance type in order to fairly evaluate the competitive merits of each.

ii. The OLTC is responsible for a 41% of transformer failures. Even though limitations are in conventional type OLTC, like arching, excessive conduction loss, slow tap changing process, still it is favourable for practicle applications. Due to difficulties in their designs and development of solid state OLTC.

iii. Testing of OLTC as per standards is very important to greately reduce the probability of failuere OLTC. In this short-circuit current test and transresistance test are clearly described as per IEC 60214-1: 2014.

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