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A COMPLETE ANALYSIS OF TRANSFORMERS REGARDING CONSTRUCTION AND TESTING

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ABSTRACT

This paper thoroughly presents a complete study on transformer equipment as well as construction and testing of transformers. This is an observed study of several months' internship project done in a factory.

Keywords: *EMF, Lamination, Core, Vector Group, Tap Changer*.

1. INTRODUCTION

A transformer is a device that transfers electrical energy from one circuit to another through inductively coupled conductors - the transformer's coils. [1] A varying current in the first or primary winding creates a varying magnetic flux in the transformer's core and thus a varying magnetic field through the secondary winding. This varying magnetic field induces a varying electromotive force (EMF), or "voltage", in the secondary winding. This effect is called inductive coupling. If only a fraction of the flux produced by one coil links the other, the coils are said to be loosely coupled. In this case, the operation of the transformer is not very efficient. In order to increase the coupling between the coils, the coils are wound on a common core.

In an ideal transformer, the induced voltage in the secondary winding (V_s) is in proportion to the primary voltage (V_p) and is given by the ratio of the number of turns in the secondary (N_s) to the number of turns in the primary (N_p) as follows:

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

2. TRANSFORMER RATING

The nameplate of a transformer provides information on the apparent power and the voltage handling capacity of each winding. From the nameplate of a 1.5-MVA, 11/0.415-KV transformer we can say that it's nominal or full load power rating is 1.5 MVA or it can deliver 1.5 MVA on a continuous basis. If it is a step down transformer then primary voltage is 11 KV and secondary voltage is 415 V. Now the current can be calculated just putting the power/voltage for each winding.

DISTRIBUTION TRANSFORMER

Figure 1

3. MAJOR COMPONENTS OF A TRANSFORMER

Following are the major components of a transformer:

1. Core
2. HT (High Tension) coil
3. LT (Low Tension) coil
4. Tap Changer
5. Main Tank
6. Radiator
7. Bushing
8. Buchholz relay
9. Conservator

Transformer core and windings are kept in the main tank which is filled with the transformer oil. In figure-1, we could see the radiators just outside of the main tank. These are used to make the circulation of the transformer oil for cooling when it's heated. Bushing is the part of a transformer where the bus-bar is connected. This is located over the main tank. Buchholz relay is a safety device mounted on some oil-filled power transformers and reactors, equipped with an external overhead oil reservoir called a conservator. The Buchholz Relay is used as a protective device sensitive to the effects of dielectric failure inside the equipment. When the oil is heated then the volume of the oil is increased due to the gas generated inside for the decomposed oil. This increased oil flows to the conservator and gets stored temporarily. If the heat is excessive then the Buchholz relay operates and gives signal to the relay of the circuit breaker to trip.

CORE OF TRANSFORMER

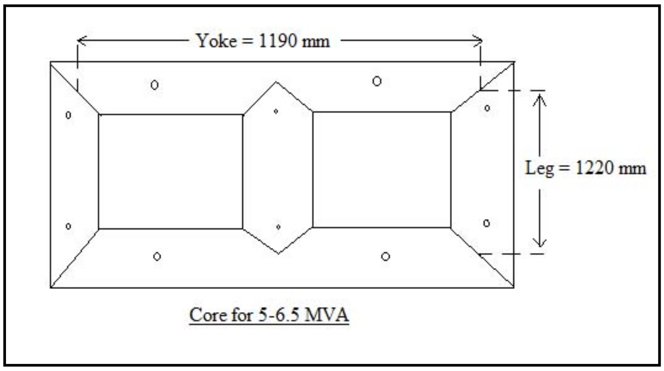

Figure 3

4.IMPORTANT RAW MATERIALS

Following are some important raw materials needed in the production of a transformer:

1. Silicon Steel
2. Copper
3. Transformer Oil
4. Aluminum
5. Silica Gel
6. Mild Steel Sheet
7. Stainless Steel Sheet

5. CONSTRUCTION AND MANUFACTURING

TRANSFORMER MANUFACTURING FLOW CHART

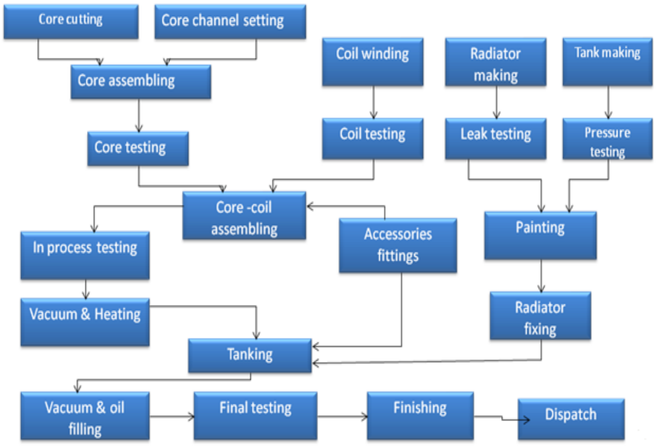

Figure 2

5.1 CORE & LAMINATION

An Auto Core Cutting unit is needed where cores are cut to give the right size for thetransformer. There is a PLC (Programmable Logic Controller) which actually controls the machine which cuts the core of desired size and number. The technicians just set the required size and number of cores through the software of PLC and the machine does the rest. The yoke and leg size for 5-6 MVA transformers are shown in figure-3. The size varies with rating of transformer. Thickness of a single core can be either 0.23 mm or 0.3 mm. Cores are mainly CRGO (Cold Rolled Grain Oriented) steel with silicon lamination. Grain-oriented electrical steel usually has a silicon level of 3%.

The reason for laminating the steel cores with silicon is for limiting the eddy currents. Silicon significantly increases the electrical resistivity of the steel, which decreases the induced eddy currents and narrows the hysteresis loop of the material, thus lowering the core loss. Steel is a very good conductor of electricity, and it can be swept by the magnetic field as well. If laminations are not used, the steel core would provide a place for the magnetic lines to produce (induce) current, and that current flowing in the core would heat the core up fast and waste energy. By laminating the cores, the current paths within that core can be broken up and also limits eddy currents.

5.2INSULATORS

The different types of insulators are as follows:

1. Crepe paper (Over copper wire)
2. Press board (Used in between each coil)
3. DPC paper (Over copper wire)
4. Parma wood (Between the channel and coil)

5.3COIL WINDING

Many types of winding are done depending on the client's requirement. These are:

1. Spiral winding: This winding is done mainly in LT (Low Tension) turns as because of reducing the number of turns. This is done spirally around the core and 2 layers are given on it.

2. Disk winding: This winding is done in HT (High Tension) turns as because it can produce large number of turns. Here several numbers of turns are wound like a disk and several disks are covered through the core. For a 5 MVA transformer there are 66 disks with 16 turns in each disk.

3. Cross-over winding: This winding is done mainly in small distribution transformer. Here copper wire is used as a coil which is wound one after another across the core.

4. Foil winding: This is almost same as cross-over winding. But here aluminum foil is used across the core rather than the copper wire.

5.4 TRANSFORMER OIL & COOLING

Transformer oil or insulating oil is usually a highly-refinedmineral oil that is stable at high temperatures and has excellent electrical insulating properties. The scientific name of the oil that is been put in the tank is AscarolPiron. The oil helps in cooling the transformer. Because it also provides part of the electrical insulation between internal live parts, transformer oil must remain stable at high temperatures for an extended period.

To improve cooling of large power transformers, the oil-filled tank may have external radiators through which the oil circulates by natural convection. This is called ONAN (Oil Natural Air Natural). Very large or high-power transformers (with capacities of thousands of kVA or MVA) may also have cooling fans, oil pumps, and even oil-to-water heat exchangers. This type of transformer is called ONAF (Oil Natural Air Forced).

6. VECTOR GROUPS

Vector group defines the primary & secondary side connection type of the transformer. There are many types of vector groups available for a transformer. Some of those are explained here.

1. Dy1/ Dyn1
2. Dy11/ Dyn11
3. Yd1/ YNd1
4. Yd11/ YNd11
5. Dd0/ Yy0
6. Zig Zag

These all have some physical meaning. First symbol/symbols, capital letters: HV winding connection (Mainly primary). Second symbol/symbols, small letters: LV winding connection (Secondary).Third symbol, number: Phase displacement expressed as the clock hour number.

VECTOR GROUPS

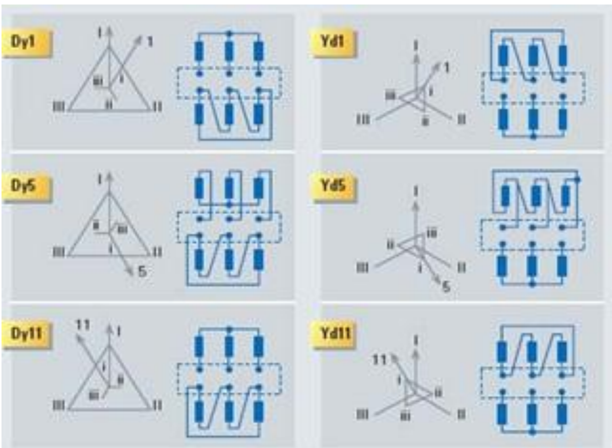

Figure 4

High Voltage / HV (capital letter): Delta – D, Wye – Y, Interconnected star – Z, Neutral brought out - N Low voltage / LV (small letter): Delta – d, Star – s, Interconnected star – z, Neutral brought out – n.

In accordance with IEC, phase rotation is always anti-clockwise. We need to use the hour indicator as the indicating phase displacement angle. Because there are 12 hours on a clock, and a circle consists out of 360°, each hour represents 30°. Thus 1 = 30°, 2 = 60°, 3 = 90°, 6 = 180° and 12 = 0° or 360°.

The minute hand is set on 12 o'clock and replaces the line to neutral voltage (sometimes imaginary) of the HV winding. This position is always the reference point. Because rotation is anti-clockwise, 1 = 30° lagging (LV lags HV with 30°) and 11 = 330° lagging or 30° leading (LV leads HV with 30°).

Dyn1: Delta connected HV winding, star connected LV winding with neutral brought out; LV is lagging HV with 30°. And for Dy1, there is no neutral brought out.

Dyn11: Delta connected HV winding, star connected LV winding with neutral brought out; LV is leading HV with 30°. And for Dy11, there is no neutral brought out.

7.TAP CHANGER

A transformer tap is a connection point along a transformer winding that allows a certain number of turns to be selected. This means, a transformer with a variable turn's ratio is produced, enabling voltage regulation of the output. The tap selection is made via a tap changer mechanism. Tap changers are always connected with the HV side because the size of a switch depends on current it carries. HV side carries lower current. That's why tap changers are connected with this side.

There are two types of tap changers: 1. Offload, 2. On load – Linear, Coarse/fine, reverse or plus/minus.

7.1 OFF LOAD TAP-CHANGER

In this type of tap changer, the load is kept off and hence the name comes.

OFF LOAD TAP-CHANGER

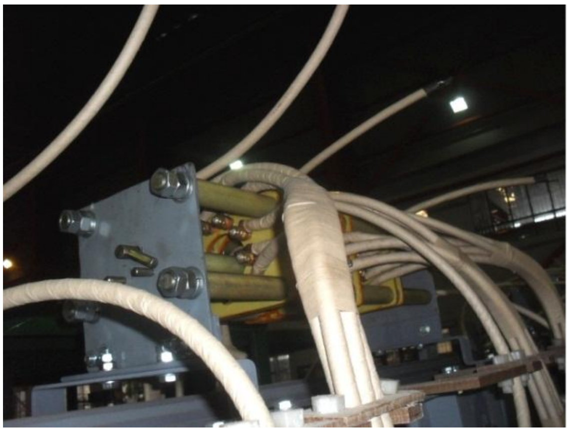

Figure 5

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OPERATION OF AN OFF LOAD TAP-CHANGER

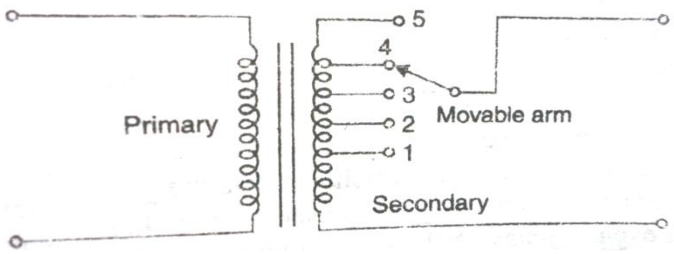

Figure 6

The figure-6 shows the arrangement where tappings have been provided on the secondary. As the position of the tap is varied, the effective number of turns is varied and hence the output voltage of the secondary can be changed. Thus referring to figure-6 when the movable arm makes the contact with tap position 1, the secondary voltage is minimum and when with position 2, it is maximum.

During the period of a light load, the voltage across the primary is not much below the alternator voltage and the movable arm is placed on tap position 1. When the load increases, the voltage across the primary drops, but the secondary voltage can be kept at the previous value by placing the movable arm on to a higher tap position.

7.2 ON LOAD TAP-CHANGER

In this system, tap-changing has normally to be performed on load so that there is no interruption to supply. The discussion is shown here with figure-7 and figure-8.

LINEAR ON LOAD TAP-CHANGER

Figure 7

(a) Linear: In figure-8(a), it is seen that even and odd numbers of tap positions are taken from a single winding. Even positions are connected with terminal A and the odd positions are with terminal B.

We can see from the figure that it is working with tap position 2. If it desires to change its position to 3, then the contact of 3 will be connected through the signal from a motor drive unit. Then the magnetic contact of neutral terminal will be moved from switch A to B. Then the contact 2 will be opened as well. That’s how it works.

(a) LINEAR (b) PLUS/MINUS

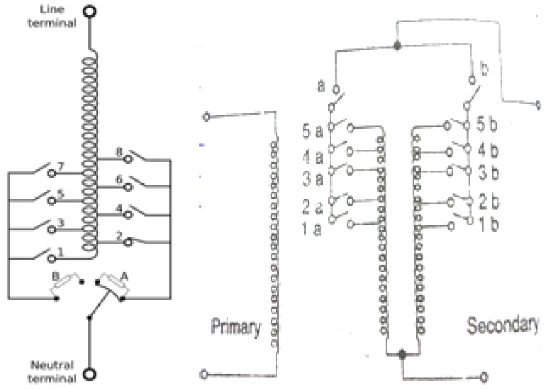

Figure 8

(b) Plus/Minus: In figure-8(b), it can be seen that secondary consists of two equal parallel windings. In the normal working condition, switches a, b and tapping with the same number remain closed and each secondary winding carries one-half of the total current. Referring to the figure, voltage will be maximum when switches a, b and 5a, 5b are closed. However, the secondary voltage will be minimum when switches a, b and 1a, 1b are closed.

Suppose the transformer is operating with tapping position at 4a, 4b and it is desired to alter its position to 5a, 5b. For this purpose, one of the switches, say a, is opened. This takes secondary winding controlled by switch a out of the circuit. Now, the winding controlled by switch b carried the total current which is twice its rated capacity. Then the tapping on the disconnected winding is changed to 5a and switch a is closed. After this, switch b is opened to disconnect its winding, tapping position on this winding is changed to 5b and then switch b is closed. In this way, tapping position is changed without interrupting the supply.

8. TESTING

There are two types of tests done on a transformer.

1. Routine test- No load test, full load test.
2. In process test- Continuity test, Ratio test, Magnetic balance test, Insulation resistance test (Megger).

Now the types of testing will be explained.

Continuity test: This test is done to identify the coil continuity after the completion of coil winding & core coil assembly. It is conducted with the help of a multi meter. An open circuit cannot conduct electricity but a close circuit can conduct electricity, this continuity is the basic concept of this test.

Ratio test: This test is done after core coil assembly under in process test. ATRM-200, Automatic Transformer Ratio Meter (ATRM) can directly measure the ratio of the HT & LT winding of the transformer. [2] The picture of ATRM is shown in figure-9.

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AUTOMATIC TRANSFORMER RATIO METER

Figure 9

It gives the values of the ratio for both the LT and HT windings. We can also check the results just using the basic formula of transformer which is V_1 / V_2 or I_2 / I_1 as well which can be done by using ratio meter where the value of currents of three phases are recorded.

Magnetic balance test: The test is conducted to identify the magnetic imbalance. A two phase supply of 220V is applied across two phase, another phase is kept open. The voltage is then measured twice, each between one of the first two phases and open phase. The sum of these two voltages should give the applied voltage. The observed results while doing this test are shown in table-1.

Table 1: Magnetic Balance Test.

Supply Voltage (V)		Measured Voltage (V)		Sum of measured Voltage (V)	Measured Current (mA)	
V_{an}	241.7	V_{bn}	196	239.6	I_a	1.91
		V_{cn}	43.6			
V_{bn}	238.5	V_{an}	119	239	I_b	1.55
		V_{cn}	120			
V_{cn}	238.8	V_{an}	47	237	I_c	1.98
		V_{bn}	190			

It's clearly visible that the results are satisfactory. After all these tests are done, then the whole active part of the transformer is put into the Vacuum Drying Plant. It is kept there for 3 days with a continuous heating temperature of 100^0 C to clean the moistures in it.

Insulation resistance test (Megger test): A DC voltage 2.5 KV or 5 KV is given and reading is taken after 15 and 60 seconds. In this test, the insulation of LT-E (Earth), HT-E and HT-LT is checked. Table-2 shows some observed results doing this test on a power transformer of 15 MVA and 33/11 KV.

Table 2: Insulation Resistance Test.

Time (Seconds)	Insulation Resistance (Mega Ohms)		
	LT-E	HT-E	HT-LT
15	1.5 GΩ	3.83 GΩ	4.15 GΩ
60	3.03 GΩ	7.93 GΩ	9.15 GΩ

The insulation resistance should be increased with time because of the increased amount of current which will create more heat. Here the desired result was to reach at 2 GΩ after 1 minute. The result is well above the expectation. That's why the test result is satisfactory. After these in process tests the transformer tank is filled with oil and then the routine tests are done on it.

8.1NO LOAD TEST

[3] The secondary of the transformer is left open-circuited. A wattmeter is connected to the primary winding. An ammeter is connected in series with the primary winding. A voltmeter is optional since the applied voltage is same as the voltmeter reading. Rated voltage is applied at primary.

NO LOAD/ OPEN CIRCUIT TEST

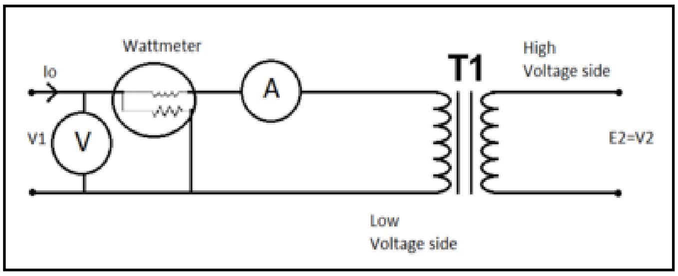

Figure 10

If the applied voltage is normal voltage then normal flux will be set up. As the Core loss is a function of applied voltage, core loss will occur. Hence the core loss is maximum at rated voltage. This maximum core loss is measured using the wattmeter. Since the impedance of the series winding of the transformer is very small compared to that of the excitation branch, all of the input voltage is dropped across the excitation branch. Thus the wattmeter measures only the core loss.

It should be noted that the iron losses consist of the hysteresis loss and the eddy current loss. This test measures the combined loss. Although the hysteresis loss is less than the eddy current loss, it is not negligible. The two losses can be separated by driving the transformer from a variable frequency source since the hysteresis loss varies linearly with supply frequency and the eddy current loss varies with the square.

Since the secondary of the transformer is open, the primary draws only no load current which will have some copper loss. This no load current is very small and because the copper loss in the primary is proportional to the square of this current, it is negligible. There is no copper loss in the secondary because there is no secondary current.Current, voltage and power are measured at the primary winding to ascertain the admittance and power factor angle.This test is done to measure the core loss when a rated voltage is applied. Test results for following specification where 3 watt meter method is used are shown in table-3.

For 20 / 28 MVA, 33 / 11 KV, Power Transformer
Test Frequency = 50 Hz
Applied Voltage =11 KV

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Table 3: No load Test.

Test Voltage (KV)	No- Load Current I_0 (A)	Watt Meter Reading - W1 (KW)	Watt Meter Reading – W2 (KW)	Watt Meter Reading – W3 (KW)	Remark
V_{an} = 6.36	I_a = 1.20	1.53	3.33	8.53	CT Ratio = 2 PT Ratio = 55
V_{bn} = 6.39	I_b = 0.98				
V_{cn} = 6.28	I_c = 1.36				

No load loss (W1+W2+W3) = 13.39 KW.
Another method of determining the series impedance of a real transformer is the short circuit test.

8.2FULL LOAD TEST

The test is conducted on the high voltage (HV) side of the transformer where the low voltage (LV) side or the secondary is short circuited. The supply voltage required to circulate rated current through the transformer is usually very small and is of the order of a few percent of the nominal voltage and this voltage is applied across primary. The core losses are very small because applied voltage is only a few percentage of the nominal voltage and hence can be neglected. Thus the wattmeter reading measures only the full load copper loss.

SHORT CIRCUIT/ FULL LOAD TEST

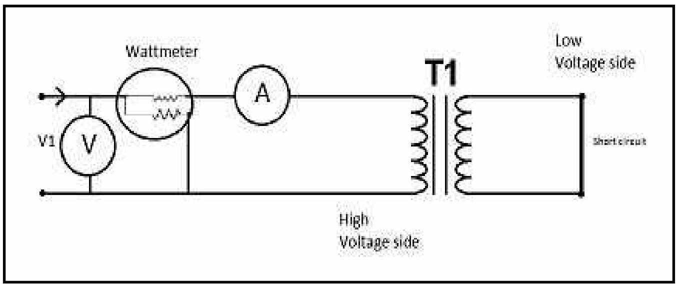

Figure 11

This test is also done in the same manner. But here the rated current is given to measure the copper loss. The short circuit test on power transformer should be performed maintaining the following steps:

- At first it is needed to isolate the power transformer from service.
- Then HV/LV jumps are removed and neutral from earth/ground needs to be disconnected.
- LV phases are shorted and these short circuited terminals are connected to neutral.
- HV side is energized by LV supply.
- Current in neutral, LV line voltages, HV voltage and HV line currents are measured.

OPEN CIRCUIT/ SHORT CIRCUIT TEST PANEL

Figure 12

Another type of test which is called the high voltage test/ impulse test is done. It is basically done to test whether the transformer withstand the high voltage during heavy thunder occurs. This is basically done by a 500 KV high voltage transformer.

9. CONCLUSION

Transformer is an electrical device without which our modern life is simply unimaginable. In our country lot of factories have been developed to manufacture transformer and export to abroad as well. They just bring the equipment from China or India and assemble here in our country to produce distribution and power transformers. I think this paper will present a clear outlook for those who wish to work with such type of production.

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