ABSTRACT

This article focuses on refurbishment / reconditioning for extension of life-expectancy of old transformers of EHV (extra high voltage 66 kV class and above) class, which were continuously in service for more than 20 years in the State Transmission Utility of Madhya Pradesh in India. The salient feature of this article for moisture refurbishment of old transformers was by adopting the criterion "% relative saturation of water in oil." This selection criterion is different from the conventional practice in vogue of observing the deterioration trend of IR (Insulation Resistance) and PI (Polarization Index) values and the DGA (Dissolved Gas Analysis), etc. The reconditioning of all such old EHV transformers, precisely 205 units, was taken up "online" in a big way, avoiding long downtimes and frequent load shedding, etc., keeping in view dissatisfaction amongst the consumers at large. This project was completed over a period of five years.

KEYWORDS:

moisture content, Karl Fischer titration, oil filter plant / machine, IR and PI

ACRONYMS:

EHV (extra high voltage), ppm (parts per million = mg/kg), % RS (percentage of relative saturation, OEM (Original Equipment Manufacturer), IR (insulation resistance) and PI (polarisation index) = ratio of IR value measured after 10 minutes to IR value measured after 1 minute (it does not have a unit of measure)

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Transmission utilities should endeavor to extend the life expectancy of the transformer to 35–40 years, adopting good practices of maintenance for the transformers

Online refurbishment of old transformers - selection focused on the percentage of relative water saturation in oil

1. Introduction

The useful life of AC and DC substations is defined by the Central Electricity Regulatory Commission, Government of India vide notification No. L-1/236/2018/CERC, dated 7 March 2019, as only 25 years [1].

However, transmission utilities should endeavor to extend the life expectancy of the transformer to 35–40 years, adopting good practices of maintenance for the transformers, as they are the most expensive and vital equipment in a power utility. The old power transformers were identified for online reconditioning, adopting the following criteria:

a. rendered continuous service for over 20 years,
b. percentage of relative water saturation r in the transformer oil: > 15 % [2],
c. deterioration trend in IR and PI values.

Besides enhancing the life expectancy of old transformers, this process also resulted in many intangible benefits to the utility and the end-users, through the reduction in the outage, load curtailment, loss of revenue, cost of transformer replacement, leading to better consumer services and greater satisfaction. This includes as many as 205 of old EHV transformers of the total fleet of around 600 units. In addition, EHV Transformers were successfully refurbished for moisture over a period of five years in the Transmission Utility in the state of Madhya Pradesh in (India).

The authors have narrated the procedure adopted for identifying the old EHV transformers which needed refurbishment / reconditioning through the percentage of relative saturation, which is different from the conventional method of deteriorating IR & PI values, DGA values, etc., and carried out online

> **The most dangerous enemy of the transformer is the moisture / water in excess in the transformer oil and in the winding insulation**

refurbishment / reconditioning project successfully over a period of 5 years.

2. Causes of deterioration of both solid and liquid insulations

Deterioration of overall insulation is attributed to the following:

i. Increase of moisture contents in the oil above 20 ppm.
ii. Increase in water contents in the winding beyond 4 % [2].
iii. Continuous overloading of transformers beyond 80 °C to 140 °C leads to loss of life to half for every 6 °C beyond 80 °C as stipulated in the IS: 2026 (Part-7):2009 (IEC equivalent IEC 60076-7:2005) [3], resulting in a fall in DP value nearing 200.

3. Water, the deadly enemy of the transformer

The most dangerous enemy of the transformer is the moisture / water in excess in the transformer oil and in the winding insulation. The moisture content of the oil in the transformer in service is governed by the IS:1866-2000 / IEC 60422 / IEEE std. C57.106 -2013 [4].

3.1 How does water get into the transformer?

i. Inadequacy in the drying-out process during work operations of OEM (original equipment manufacturer).
ii. Leakage / seepage from gaskets and welding spots at various locations.
iii. Inhaling atmospheric air while oil volume shrinks during cold and moist nights and also during off-peak hours of the day and due to negligence of the maintenance staff for untimely replacement of the fused silica gel granules with dry silica gel granules.

3.2 Reason for the increase of water contents in oil

Most of the practicing substation engineers / managers wonder how the moisture content of the oil increases, while every precaution against entry of atmospheric moisture into the transformer is taken care of, as narrated in paragraph 3.1.

Earlier, only silica gel breathers were provided for the duty, as mentioned in paragraph 4.1 (iii), but in the present scenario, air cells are provided, which act as a barrier between the atmospheric air and transformer oil.

4. Solid insulation in the transformer

The paper is a major solid dielectric material used for conductor wrappings, such as barrier boards, spacers, and clamps (in compressed or resin-bonded forms). The major constituents of the paper are cellulose (90 %), lignin (about 6 %), and the remainder (about 4 %) [5].

The structural formula of cellulose is as shown in Fig. 1.

The three most common degradation factors for cellulose have been identified, and they are thermal, oxidative, and hydrolytic. When cellulose is subjected to a temperature of 200 °C, the beta linkages (glycosidic bonds) tend to break and open the glucose molecule rings and thereby lose mechanical strength. The by-products of this reaction are [5]:

a. free glucose molecules,
b. moisture,
c. CO & CO_2,
d. organic acids.

The presence of oxygen promotes oxidation, and cellulose molecules have a tendency to oxidize. The reaction of oxidation on the cellulose causes the glycosidic bond to weaken, and it can cause the scission of the cellulose molecule chain. The oxidation of hydroxyl produces carbonyl (aldehydic) and carboxyl (acidic) compounds. Moisture is also a by-product of this oxidative reaction.

Table 1. Guidelines for interpretation of moisture percentage by dry weight of paper

% Moisture by dry weight in paper	Condition
0–2	Dry paper
2–4	Wet paper
>4.5	Excessively wet paper

*Note: Table 8 in IEEE standard 62-1995, chapter 6.3.12

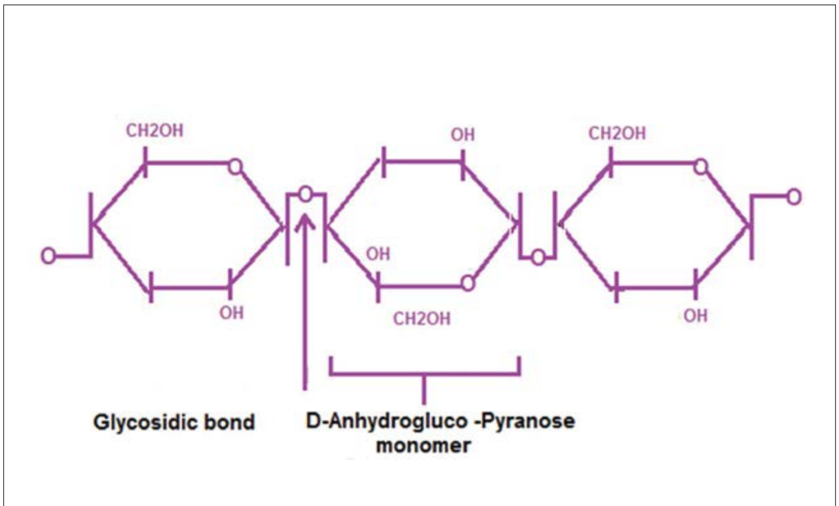

Figure 1. The structural formula of cellulose $(C_6H_{10}O_5)n$

The moisture produced, as explained above, is also transferred to the oil.

5. Water content in paper insulation of the winding

In any mineral oil-filled power transformer, the amount of paper insulation is considered to be approximately 4 % of the total weight of the winding with paper insulation. Since paper is highly hygroscopic, it is bound to contain some water from its manufacturing stage unless otherwise it is properly dried at the OEM's (original equipment manufacturer) works.

Guidelines for interpretation of moisture percentage by dry weight of paper as per IEEE 62-1995 are shown in Table 1 [6].

5.1 Weight of water in paper insulation of winding (sample calculation)

A transformer of 20 MVA 132/33 kV EMCO made had failed after rendering service for over 20 years was written off for auctioning in the Madhya Pradesh State Transmission Utility (India). The calculation of the weight of water the paper insulation must have contained is calculated in Table 1(a) [6a].

6. Phenomena of water migration (water dynamics)

There is always some moisture present in the transformer as the paper is very hygroscopic and has a greater affinity to water. Most of the moisture present would be in paper only.

Water migrates between the paper and liquid insulation in a transformer with changes in the load and the temperature.

In any mineral oil-filled power transformer, the amount of paper insulation is considered to be approximately 4 % of the total weight of the winding with paper insulation

Consequently, the concentration of water-in-oil alone expressed in ppm (parts per million) does not provide sufficient information to arrive at an adequate evaluation of the dryness of the insulation system. Relative saturation provides a better evaluation under a wide range of operating conditions and temperatures [7].

7. Percentage of water saturation in oil

The quantity of dissolved and dispersed water in mineral oil is significant for two reasons: (i) the presence of polar water molecules in the mineral oil adversely affects the dielectric properties of the mineral oil, and (ii) the amount of moisture in the oil can be reflective of the amount of moisture in the paper insulation. The solubility in mineral oil is temperature-dependent and acidity-dependent. Therefore, a statement as mg/kg of water in the oil without temperature information would not be adequate. The calculation of the percentage of water saturation (mg/kg water/mg/kg of water at saturation) x 100 has greater significance as it indicates the possibility of free water formation in the oil [7].

Free water in oil

"Free water" that exists in the form of droplets if the water content in oil exceeds the saturation level. In cellulose materials, free water may exist in macropores. In addition, the following are the basic reasons for increasing the water contents in oil [8]:

a) Residual moisture in the thick structural components not removed during factory drying-out or moistening of insulation surface during assembly.
b) Inhaling atmospheric air through fused silica-gel while oil volume shrinks during cold and moist nights and during off-peak hours of the day, resulting in the poor dielectric strength of the oil.
c) Aging (decomposition) of cellulose and oil.

The solubility in mineral oil is temperature-dependent and acidity-dependent, which means that the information on the mg/kg of water in the oil without temperature information is not adequate

Table 1(a) 20 MVA 132/33 kV transformer

No.	20 MVA132/33 kV transformer (written-off for auction)	Calculation	Weight
1	Weight of core and winding		18100 kg
2	Weight of copper winding with insulation 40 % of WT of the core-coil assembly	18100 x 0.4	7240 kg
3	Weight of paper insulation at 4 % of weight of copper winding with insulation	7240 x 0.04	289.6 kg
4	Weight of water present in the paper considering as 5 % as per Table 1	289.6 x 0.05	14.48 kg

Table 2. Water saturation of oil in %

% of water saturation in oil	Condition
0–5	Dry insulation
6–20	Moderate to wet. Lower numbers indicate fairly dry to moderate levels of water in the insulation, whereas values towards the upper limit indicate moderately wet insulation.
21–30	Wet
> 30	Extremely wet

Table 2 gives general guidelines for interpretation of data expressed in % of saturation [7].

7.1 Formula for solubility of water in oil and specimen calculation

The following calculation is based on the formula from IEEE Std. C57.106-2002 [8].

$$\mathbf{Log_{10}\, S_o = (-1567/K) + 7.0895}$$

Where:

- S_o is the solubility of water in mineral oil.
- K is the absolute temperature in Kelvins (°C + 273)
- °C is the oil temperature in Celsius at the time of sampling.
- % saturation = 100 (mg/kg of water)/S_o

7.2 Specimen calculation

Water content = 16 mg/kg,
The temperature of top oil = 30 °C
The temperature in Kelvin = 30 °C + 273 = 303 K

$$Log_{10} S_o = (-\frac{1567}{303}) + 7.0895 =$$
$$= -5.1716+7.0895=1.9197$$

$$S_o = 82.775$$

Therefore % saturation
$$= (-\frac{16}{82.775}) \, 100 = 19.32 \%$$

8. Criteria for selection of old transformers for refurbishment

1. Transformers that have served for over 20 years.
2. Deterioration in IR and PI values.
3. Water saturation in oil if found >*15 % [2].

*Note: this figure is selected looking at Table 2, indicating guidelines for interpretation of % saturation of water in oil.

8.1 Selection of transformers for refurbishment

A sample list of a few old transformers that have rendered continuous service for over 20 years with the calculated RS % is shown in Table 3.

Table 3. A sample list showing transformers that have served for over 20 years with moisture contents of the oil at the sampling temperature

No.	Substation name	Name of transformer	Transformer serial No.	Water content	Temperature in °C	Calculated R.S. %	Remarks
1	132 KV S/s Patan	40 MVA 132/33 KV BBL	473372	16	46	9.24	CAL at 50 °C
2	132 KV S/s Patan	20 MVA 132/33 KV GEC	1328571	18	38	14.87	CAL at 40 °C
3	132 KV S/s VFJ	40 MVA 132/33 KV BBL	4733/21	15	52	8.67	CAL at 50 °C
4	132 KV S/s VFJ	5 MVA 33/11 KV Kirloskar	50008304	36	36	29.75	CAL at 40 °C
5	132 KV S/s VFJ	5 MVA 33/11 KV Accurate	18343/25	30	54	17.34	CAL at 50 °C
6	132 KV S/s Kymore	16 MVA 132/33 KV NGEF	2800034714	21	50	12.13	CAL at 50 °C
7	132 KV S/s Kymore	20 MVA 132/33 KV BHEL	6004548	27	51	15.60	CAL at 50 °C
8	132 KV S/s Kymore	5 MVA 33/11 KV UE	183775	38	48	21.95	CAL at 50 °C
9	220 KV S/s Jabalpur	40 MVA 220/132 KV BHEL	6004131	20	50	11.56	CAL at 50 °C
10	220 KV S/s Jabalpur	40 MVA 220/132 KV BHEL	6004129	24	52	13.67	CAL at 50 °C

8.2 Calculation of % saturation of water in oil with true values

A sample case calculation of water saturation percentage in oil in respect of 20 MVA, 132/33 kV BHEL transformer bearing serial number 6004548 at 132 kV, substation, Kymore, listed under number 7 in Table 4, is depicted below.

The water content of oil at 50 °C, as reported by the oil testing laboratory, is 27 ppm.

$Log_{10}S_o = (-\frac{1567}{K}) + 7.0895$, where:

- S_o is the solubility of water in mineral oil,
- K is the absolute temperature in Kelvins (°C + 273),
- °C is the oil temperature in Celsius at the time of sampling,
- % saturation = (ppm/S_o) x 100,
- Oil temperature = 50 °C and moisture content in the oil 27 ppm,
- K = 50 + 273 = 323 °K

Therefore,

$Log_{10}S_o = (-1567/323)7.0895 = 2.2382$
$S_o = 10^{2.2382} = 173.06135$,

Therefore,

$\% \text{ saturation} = \frac{ppm}{S_o} \times 100 =$

$(\frac{27}{173.06135}) \times 100 = 15.601\ \%$

Since *15.601% > 15 %, this transformer is identified as suitable for refurbishment.

*Note: 15 % saturation of water in oil was taken as the benchmark for the selection of old transformers for reconditioning.

9. Filter plant with a brief description of its salient feature

Before going into details of the method / technique adopted for the online filtration process, it is imperative to know

A detailed real-world case study with all relevant data for the selection of the transformers for the refurbishment is presented

more about the filter machine (a machine in which removal of all suspended particles such as dust, rust, scales, colloidal carbon oxidation sludge, etc., up to < 1 micron is done, as well as degassing and dehydration of transformer oil under vacuum, circulation of heated oil and filling of treated oil in the transformer tank, and de-acidification by evaporation and absorption method). The flow diagram of a conventional filter machine of 500 GPH (it shows the capacity of the machine to handle the oil in gallons per hour) is shown in Fig. 2.

Before going into details of the method / technique adopted for the online filtration process, it is imperative to know more about the filter machine

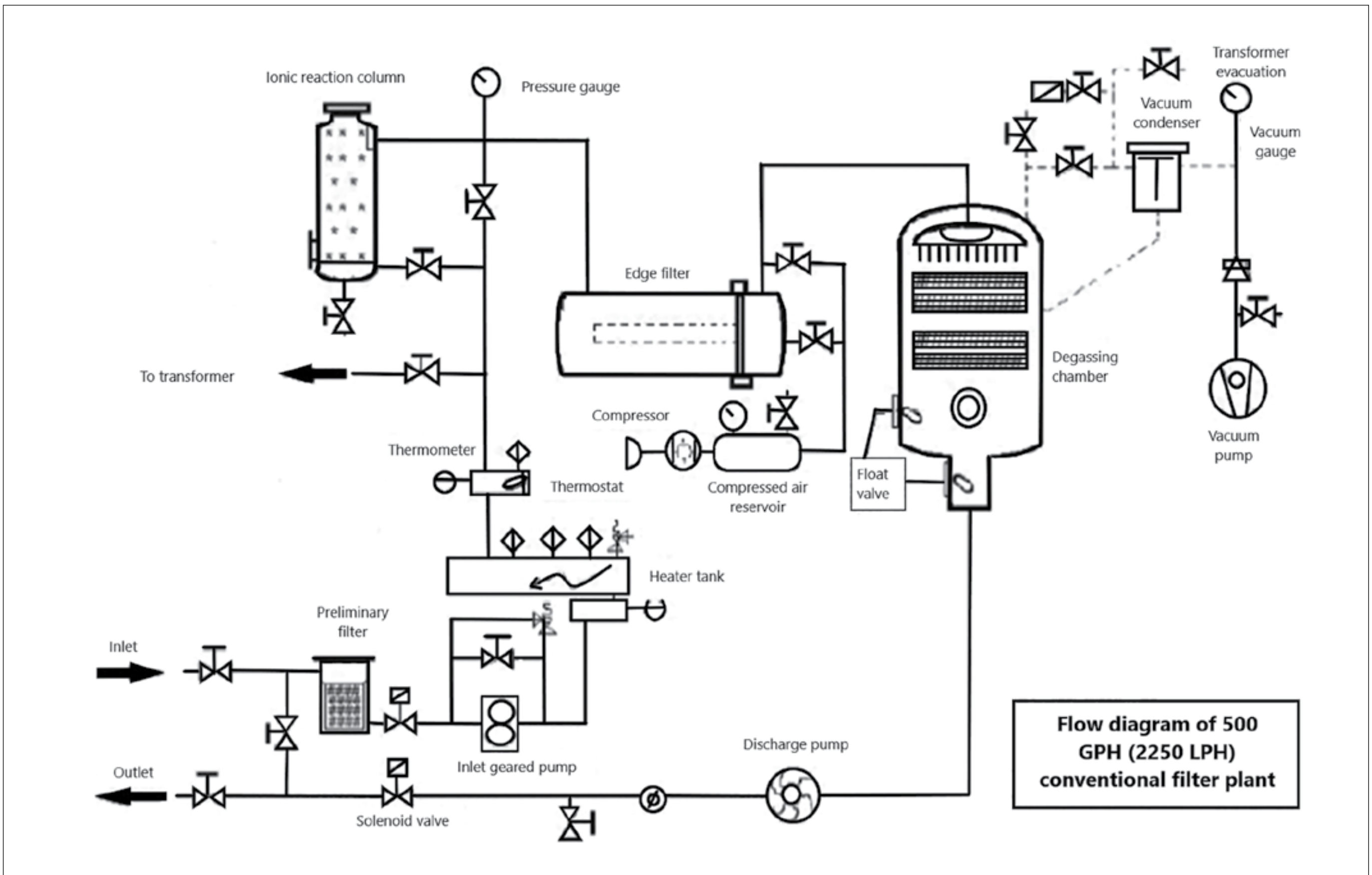

Figure 2. Flow diagram of 500 GPH (2250 LPH) conventional filter machine

A detailed schematic and description of every part is given for the conventional filter machine of 500 GPH

Various components of the filter machine / plant and their functions are:

1. Preliminary filter:
   A preliminary filter is at the oil inlet and is provided with a magnetic strainer and a perforated sheet. The magnetic strainer prevents magnetic particles from entering the gear pump. This perforated sheet prevents particles of over 1 mm in size from entering the gear pump. This is used for the filtration of rough particles and to arrest magnetic particles. This protects the inlet gear pump.
2. Oil inlet pump:
   This is a positive displacement type of gear pump. This pump functions by forcing the oil through the filter at required pressure and flow rate. The input side oil is cool and more viscous there. In this case, it is preferable to use a gear-type pump.
3. Heater tank:
   A heater tank is made up of mild steel welded structure and is thermally insulated with mineral / glass wool. The electric heaters provided are of the indirect type, and their design is such that overheating or localized heating is eliminated.
   Thermostats are provided to prevent any overheating. Its operation is automatic. Thermostats are provided to maintain the desired temperature. The total power is 48 kW for a 2250 LPH and 200 kW for a 6000 LPH machine, divided into three groups. Heater groups are interlocked with the inlet pump, and it is not in the ON position unless the inlet pump is working. This heater tank operates by heating the oil at a required temperature (from 45 °C to 60 °C).
4. Thermostats:
   Four thermostats are provided on the heater tank to control the oil temperature. They operate automatically. One of them is used for the temperature setting as a safety, and the others are used for controlling the temperature and heating. The safety thermostat is provided to take care of any accidental rise in the temperature of the oil, and if that happens, the heaters are switched off. This thermostat is set at a slightly higher temperature than that of controlling thermostats. These thermostats range from 30 °C to 110 ° C.
5. Thermometers:
   Two dial-type thermometers are provided on the plant. One is located at the inlet of the heater tank to indicate the temperature of incoming oil, and the other at the outlet of the heater tank to indicate the temperature of outgoing oil.
6. Edge filter:
   It consists of two chambers, one for incoming dirty oil and the other for outgoing clean oil. Several candles made of filter packs are held under the spring compression in the dirty oil tank. The spring pressure can be adjusted by tightening or loosening of the nuts. These candles consist of stacked ring-type filter paper. Oil enters the candles in the radial direction and flows towards the clean oil chamber in the axial direction. Filters are easily replaceable.
   This is useful for the removal of sludge content in the used oil. It has an oil inlet, outlet, drain, and air pressure connections for the clearing purpose. This is a very fine filter, and it filters oil of more than 1 micron-sized particles.
7. Air compressor:
   It is provided for the edge filter clearing by passing the compressed air. This compressor can also be used for spray painting and other purposes.
8. Ionic reaction column:
   It consists of activated alumina (20/200 kg). If the initial acidity of the oil is higher as compared to IS: 1866-2000 [9] or IEC 60422-2013 [10], then this column can be taken in the oil circulation to reduce the acidity of the oil.
9. Oil discharge centrifugal pump:
   This is a mechanical seal-type oil discharge pump. This pump is provided at the outlet of a degassing column, and it can draw oil from the degassing chamber held under vacuum and feed it to the transformer. The output-side oil is hot, and its viscosity is low, so we prefer to use a centrifugal-type pump.
10. Solenoid valve at the inlet and outlet:
    One solenoid valve at the inlet and one at the outlet are provided. Valves at the inlet and outlet automatically open the moment the oil inlet and outlet pumps are switched on. In case of a power failure, these valves are capable of preventing the oil from entering into the plant and thus avoiding the possibility of mixing the processed oil with unprocessed oil.
11. Degassing chamber:
    A shower arrangement is provided in the degassing chamber. The oil comes out of the shower arrangement in the form of a shower and falls on the cage filled with Raschig rings. The purpose of Raschig rings is to expose the incoming transformer oil to optimum surface area for efficient degassing and dehumidification. In addition, sight glass with an illuminating lamp is provided for observation of the oil flow.
12. Float switch (high-level):
    It is provided to prevent the rise of the oil level in the degassing chamber to trip the inlet pump.
13. Float switch (low-level):
    When the oil level in the degassing column (low-level) falls to a specific level, the low-level float switch opens the circuit and trips off the discharge pump, thereby preventing it from dry-running.
14. Vacuum pump:
    A rotary oil-sealed vacuum pump WSVP 9060 (for 2250 LPH)/SR 2500 B (for 6000 LPH) is provided for evacuation off the plant.
    For 6000 LPH machine, two vacuum pumps are installed. The first pump creates a vacuum in the first stage, and the second is for the second stage of degassing the column and transformer.
15. Oil sampling valve:
    Processed oil samples can be collected from this valve.
16. Vapour condenser:
    One of vapor condenser (baffle type) is provided in the plant to protect the vacuum pump and to trap the vapors of transformer oil and moisture. An oil drain line is provided and connected to the degassing chamber to collect the oil trapped inside a vapor trap.
17. Oil hoses:
    Two nitrile rubber hoses, each 15/20 meters long and with a flanged end

connection on both sides, are provided. One is for the oil inlet and the other for the oil outlet. Oil hoses are capable of handling transformer oil of up to 100 °C (max.) and full vacuum.

*Note: In the 6000 LPH filter plant, two vacuum pumps and two root pumps are installed. Vacuum pumps are to create a vacuum, and root pumps are provided to create a fine vacuum in the second stage. One water-circulating (cooling) pump is also installed to cool the vacuum and root pumps.

10. Removal of water from windings

10.1 Traditional hot oil circulation

The traditional technique of circulation of hot oil through the transformer is widely used in many countries around the world. This technique has some limitations:

(i) The transformer needs to be taken out of service, as many cycles of oil circulation must be carried out, and that can take a few weeks.
(ii) It removes moisture mainly from the oil, but the removal of moisture from paper is very low, as 99 % of water is in the paper and around 1 % is in the oil.
(iii) Once the transformer is put back in service, the heat generated in the winding due to the increase in load results in migration of moisture from the paper to oil, and thus moisture content in oil increases.

10.2 Process of online filtration

With the constraint as narrated in paragraph 10.1, the only option is to resort to "online filtration." A filter plant of adequate capacity is connected to the loaded transformer. At higher temperatures, the moisture released by winding migrates to oil, which is further removed by the filter plant. As moisture is released from winding at a very slow rate, there is no possibility of substantial improvement in the breakdown voltage of oil during the process. This process may take from a few weeks to months, depending on the quantity of water in the transformer and its temperature during the load conditions. As a precautionary measure, heaters of the filter plant are kept off during the whole process.

A filter plant is connected to the loaded transformer since the higher temperatures help in releasing the moisture, which is further removed by the filter plant

10.2.1 Process

(i) The complete quantity of oil from the transformer was decanted (drained-out in some vessel / tank), and sludge cleaned off the bottom. After the cleaning, a vacuum of (-)740 mm Hg to (-)759 mm Hg (1 torr) was applied to the transformer and maintained for 24 hrs.
Note: Vacuum is applied for extracting the moisture from the winding. The periods for which the transformers, kV category-wise subjected to vacuum, are as follows:
  - 132 kV transformers: 24 hrs
  - 220 kV transformers: 48 hrs
  - 400 kV transformers: 72 hrs.

(ii) Meanwhile, filtration of oil from the oil tank was carried out, and the transformer oil was decanted.
(iii) After 24 hours of vacuum, the oil was filled through the bottom filter valve of the transformer.
(iv) After the oil was filled up, the filter machine was connected in such a manner that the oil-outlet (delivery) hose pipe of the filter machine was connected to the top filter valve of the transformer, and the oil-inlet (suction) hose pipe was connected to the bottom filter valve of the transformer.
(v) Air was released from all the pockets provided on the top cover and the Buchholz relay.
Note: Operations mentioned in the items from (i) to (v) are offline activities, and these are essential prior to perform the online filtration process.
(vi) The transformer was switched on and observed for any abnormality without load.
(vii) After observing that no abnormality had taken place, the transformer was subjected to load.
(viii) On-load filtration of the transformer was carried out until the moisture content had come down to almost 10 ppm.
Percent saturation turned out to be equivalent to 10.72 as per the formula stated in Cl:7.1.
(ix) After 15 days of filtration, an oil sample was collected and tested for moisture content. If an increment in ppm is noticed in the oil sample, then online filtration of transformer is carried out until moisture content in the oil is reduced to 10–12 ppm. It is to mention here that online filtration of transformer eliminates water particles from the winding.
(x) After a lapse of three months, the online filtration activity was over, and a sample was taken for the moisture contents test.

11. Sample test results

Results of a 20 MVA 132/33 kV transformer, serial number 6004548, at 132 kV substation, Kymore, were as follows:

a) IR &PI values of 20 MVA 132/33 kV BHEL transformer, serial number 6004548, before filtration in MΩ (with oil temperature 46 °C and multiplying factor 0.43, which is the factor to convert the measured IR value to 60 °C, is shown in Table 4 [11].

Table 4

	R 15 in MΩ	R 60 in MΩ	Converted in MΩ	PI
HV-E	111	132	56.76	1.18
LV-E	104	126	54.18	1.21
HV-LV	145	171	73.53	1.17

The sample and test results for the selected transformers show much better values of the IR and PI parameters after filtration

b) IR &PI values of 20 MVA 132/33kV BHEL transformer (sr. No. 6004548) after online filtration in MΩ. (O.T. 50 °C and M.F. 0.560) is shown in Table 5 [11].

Note

i. IR value: This is known as the insulation resistance of any equipment measured with an instrument called Megger. In the instant case, it is measured with 5 kV DC Megger (static).
ii. HV-E: The insulation resistance of HV terminal (HV-neutral lead removed and keeping all LV terminals earthed) to earth is measured.
iii. LV-E: The insulation resistance of LV terminal (LV-neutral lead removed) to earth (keeping all HV terminals earthed) to earth is measured.
iv. HV-LV: The insulation resistance of the HV terminal (HV-neutral lead removed) and LV terminal (LV-neutral lead removed) is measured.
v. Why conversion of IR value to 60 °C is necessary: The basic phenomenon of insulation is that the IR value decreases with temperature. In order to compare the IR values of transformers taken at different oil temperatures, the Transmission Utility has defined a chart of the multiplying factor to convert the IR value to a base temperature of 60 °C [11]. It is said as per this chart that the multiplying factor for the IR value, if measured with a temperature of the oil at 60 °C would be 1. **Sample calculation**: IR value measured between HV and earth of a transformer at the oil temperature of 45 °C, say it is 250 MΩ. The value of the multiplying factor at 45 °C = 0.40 (as per the chart). Therefore, the converted IR value to 60 °C base would be 250 x0. 40 = 100 MΩ.
vi. PI ratio: IR values recorded at 60 s to IR value recorded at 15 s.

Table 5

	R 15	R 60	Converted	PI
HV-E	184	236	132.16	1.28
LV-E	181	254	142.24	1.4
HV-LV	270	372	208.32	1.37

Note:
a. Since this is a ratio, it does not have units and has no bearing on the transformer oil temperature.
b. Table 6 shows the PI values and their significance.

Table 6. Polarization index values and their significance

Polarization index	Insulation condition
< 1.0	wet
1.0–1.1	poor
1.1–1.25	fair
1.25–2	good
> 2	very good (dry)

Note:

i. Ppm: acronym for "parts per million", i.e., 1 part/1,000,000 parts or (mg/kg). The traditional method used is Karl Fischer moisture-titration. It is a laboratory test.
ii. BDV: acronym for "breakdown voltage". This is a kit used for accessing the breakdown voltage of insulating oil. Low BDV indicates a rise in the moisture content of the oil.
iii. The BDV kit used in the present scenario is automatic. It has the following main components:
   - It is an AC equipment of 50 Hz,
   - Voltage range: 80 to 100 kV,
   - A 400 ml vessel,
   - A pair of electrodes, mushroom-shaped, cylindrical or spherical. The gap maintained between the pair of electrodes is 2.5 mm.
   - Rate of rise in voltage is 2 kV/s.

Table 7. Moisture contents and breakdown voltage (BDV)

Parameter	Before filtration	After filtration	% RS at OT 40 °C
PPM	23 ppm	13 ppm	10.72
BDV	60 kV	76 kV	

Method:

a. A 400 ml vessel made of transparent (acrylic) material is cleaned and rinsed with the oil to be tested.
b. Verify the gap between the pair of electrodes. The gap should be 2.5 mm.

c. Fill the oil sample under test in the vessel up to the mark.
d. LT AC supply is applied to the kit.
e. Once the kit is energised it provides 2 kV/s to the pair of electrodes and automatically increases the voltage by 2 kV/s.
f. Some chattering sound is heard before the breakdown of the oil insulation.
g. Voltage at which the breakdown of the oil insulation takes place indicates the BDV.
h. Modern kits measure the BDV for 3–5 values of the breakdown voltage, and then the final result is indicated on the equipment screen, and it is the average of 3–5 readings.

Recommended values – the generally adopted recommended limiting BDV values are:

- 40 kV for 72.5 up to 145 kV class transformers,
- 50 kV for ≥ 145 kV class transformers,
- > 60 kV for 420 kV class transformers.

Note: The voltage classes shown above are the highest power frequency system voltages.

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[5] IEEE Std. C57.152-2013, *IEEE guide for diagnostic field testing of fluid filled power transformers, regulators and reactors (Annex-E)*

[6] IEEE Std. 62-1995 (Cl. 6.3.12);

[6A] Schedule "A" of Survey report on 20 MVA failed transformer in 400 kV, substation, MP Power Transmission Co. Ltd. Katni

[7] IEEE Std C57.106–2002, *IEEE guide for acceptance and maintenance of insulating oil in equipment,* (Cl. 4.5)

[8] CIGRE report 349, Working Group A2, 30 June 2008

[9] IS:1866–2000, *Code of practice for electrical maintenance and supervision of mineral insulating oil in equipment*

[10] IEC 60422-2013, *Mineral insulating oil in electrical equipment supervision maintenance*

[11] IR value conversion factor chart followed in MP Power Transmission Co. Ltd.

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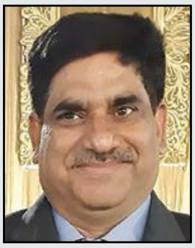

R. K. Agrawal holds a bachelor's degree (Hons) in electrical engineering from GEC Bilaspur and is currently working on position of the executive engineer (testing Dn-I) at MPPTCL Jabalpur. He has 30 years of experience in maintenance and testing of EHV Substations in MPSEB / MPPTCL. He has commissioned several EHV substations, transformers, reactors, etc., up to the voltage class of 400 kV in MPPTCL / MPSEB. Mr. Agrawal has been recognised for excellent jobs done and felicitated by the CMD MPPTCL, with certificates of merit and many other awards.

J. J. L. Kapil is a retired assistant engineer, 220 kV S/S, Jabalpur in June 2017, holding a diploma in electrical engineering.
Among his commendations, MD MPPTCK has felicitated Mr. Kapil in recognition of his hard and sincere work and for preventing many incidences. He was responsible for the upkeep of 3x40 MVA 220/132/33 kV Mitsubishi transformer bank (1-Ph. units), which are still in service after 53 years.