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Recent Trends in Emerging 765kV/800kV Power Transformers

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Abstract*—Bulk power transmission economically over long distances requires upgradation of transmission line voltage from existing 400kV to 765kV EHV (Extra High voltage AC) or 800 kV HVDC (High Voltage DC). This requires large size power transformers with capacity to handle EHV/UHV voltages. The specific modifications are therefore required in procedures of design, manufacturing, testing and site activities of 765kV/800kV transformers in comparison to procedures being practiced for 400kV transformers. Because of massive size and complicated design of such transformers, the modified procedures require consideration of appropriate material, manufacturing process, and benchmarking of on-site Erection & Commissioning (E&C) and Operation & Maintenance (O&M) practices for enhanced reliability. The present paper is unique and useful in the Indian context with the commissioning of 765kV Sipat-Seoni and 800kV Agra-North East lines and recent government emphasis to extend these lines farther. The paper, in addition to have discussion on some aspects of material, manufacturing & design, also brings out results of recent testing of equipment at site during installation & commissioning or while in-service.

***Keywords*—E&C; O&M; EHV; HVDC; SFRA; VFTD; PD**

I. INTRODUCTION

The expansion in transmission network is characterized by upgradation of transmission voltages to the level of 765 kV/±800kV commonly termed/abbreviated as EHV/HVDC. The *EHV* transmission is necessary for bulk power transfer from generating station to the receiving end over long distance with accrued saving on account of line losses and improved transmission efficiency in comparison to power transfer at lower voltage levels. In present power scenario of India, the existing 400kV AC transmission level being upgraded to next transmission voltage level of 765kV AC & ±800kV HVDC for bulk Power Transmission.

The equipment planning at such EHV/HVDC transmission voltages needs meticulous consideration of material and procedure (*in comparison to the existing 400kV transmission system*) due to necessity of upgraded insulation level to bear peak value of transient overvoltage [1].

In India, the operation of Extra High Voltage (EHV) transmission line is aimed at establishing synchronous National Grid (*one Grid - one Nation - one frequency*).

With this objective, the Raichur-Solapur 765 kV Single Circuit line is constructed, and other lines are either being planned are or under construction [2]. Historically, the Era of EHV AC (765 kV) Transmission in India started with commissioning of SIPAT – SEONI line and that of ±800kV HVDC Bishwanath Chariali-Agra bipolar line respectively in the year 2007 and 2015. The design aspects of EHV transmission line including Sag, Line parameters, Corona at voltage level of 765 kV are discussed in [3]. With this growing need of bulk power transfer capability, the emphasis to augment 765kV (EHV AC) transmission networks may be seen in 11th and 12th five-year plans of India [4]. In [5], a comparative study of 400kV and 750kV transmission Line is performed considering respective line parameters, power handling capacity and line losses. The details of standard parameters for large power transformers are provided in IEC standard [6], whereas the detailed study of large power transformers is elaborated in [7]. The primary emphasis in the design of any 765-kV transformer is on its insulation level. A comprehensive review and history of insulation used in conventional oil immersed power transformers vis-a-vis today's insulation technique is elaborated in [8]. The review includes details of materials selection, drying, clamping and oil impregnation procedures, aging effects, and factors important for the manufacturing and operation of reliable transformers. The details of insulation design procedure and optimization method of high voltage transformers with Finite Element Analysis (*FEA*) for various stress conditions at critical locations of a transformer is discussed in [9], whereas the process control requirement with respect to cleaniness and humidity during manufacturing stage of large size transformers are given in [10]. The reliable design and operation of EHV transformer requires selection of appropriate material/design of the Bushings. The optimization of bushing design of 765kV transformer using different insulating materials such as Epoxy Resin, Porcelain, Oil Impregnated Paper, Resin Impregnated Paper and Polymer are elaborated in [11], and reliability aspects of bushings are discussed in [12] and such the reliability aspects of power transformers based on in-service data/failures statistics are discussed in [13] For implementation of ±800 kV HVDC transmission, an appropriate converter transformer is required. The insulation properties of oil-immersed-paper and transformer oil used with these converter transformers need appropriate design, analysis and testing. The quality of insulation on oil impregnated pressboard as used in such converter transformer is tested/checked by performing polarization-depolarization current (PDC) test, frequency domain spectra (FDS) tests, and the results of testing are analyzed and discussed in [14].

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The most critical aspect of any transformer in general, or EHV transformer in particular, is to withstand the mechanical forces that are produced at the time of short circuit whose magnitude is proportional to square of the short circuit current. The effect of these high intensity radial and axial forces are discussed in paper [15].

The design and manufacturing of EHV & HVDC transformers needs state-of-the-art facility and choice of appropriate material. The facility must include advanced manufacturing plant with modern machinary & tools. The paper is aimed to discuss some aspects of material, manufacturing & design, along with testing results of EHV transformers, installed and commissioned at site or while in-service.

This paper is discussed in six sections. The Section II discusses proposed methodology elaborating design requirement, power transfer capability, state of art facility requirement, material requirement etc. The Section III discusses various design and manufacturing constraints of EHV transformers. The Section IV discusses recent trends with regard to emerging EHV technology of 765kV transformer. The Section V discusses results of various recent test conducted in field operations and their analysis. The Section VI discusses the conclusion of the work proposed int this paper.

II. PROPOSED METHODOLOGY

A. Design Requirements

The various types of transformers required for EHV/HVDC transmission are termed as Generator transformers, Auto transformers, and Converter transformers. The generator transformer is connected to generator end to boost up the generating voltage to the desired transmission voltage. Auto transformers are required for regulation purpose and to enhance the voltage of existing 400kV system to the level of 765kV for interconnection and power transfer through synchronous link. The converter transformer is used for converting AC voltage to High Voltage DC (HVDC) transmission at ±800 kV using thyristor converter that works as asynchronous link for power transfer. The generator transformers are generally rated upto 315 MVA capacity, Auto Transformers upto 500 MVA, and converter transformer upto 295 MVA. In addition, the system also uses shunt reactors for reactive power control and normally rated upto 125 MVAr.

B. Power Transfer Capacity

If power is transmitted through synchronous link at constant grid frequency, the power transfer in EHV system is governed by a well-known expression given as eq. (1). The power transfer depends upon voltages V_s, V_r, Load angleδ, and total positive sequence reactance X. Neglecting the line resistance, power transfer equation can be written as:

$$P = V_S \times V_r \times \sin\frac{\delta}{L \cdot X}$$

(1)

Where,

P - Power (in MW);
V_s - Voltage at Sending end (in kV)
V_r - Voltage (line-line) at receiving end (in kV);
δ - Load angle or angular difference between V_s & V_r
L - Length of line in km
X - Per Meter positive sequence reactance of the Line

The incentive of shifting from 400kV transmission to EHV transmission at 765 kV may be seen in terms of the saving on account of power loss during transmission. For 400 km, 400kV transmission line, the computed loss comes out to be 590MW and same reduces to 308MW when power is transmitted to enhanced voltage level at 750kV for same system parameters [4]. The power loss with transmission line Current I and line resistance of R_L can be given as

$$P_L = 3 \times I^2 \times R_L \qquad (2)$$

C. State-of-Art Facility Requirements

For the manufacturing of EHV transformer; advanced manufacturing machinery, sophisticated tools and precisely controlled ambience with effective cleanliness & housekeeping is required. The windings rooms of EHV transformers must have sufficient space and height with precisely controlled humidity to get recommended partial discharge performance. The EHV transformers are large in size, which requires sophisticated process control to the level of 6 Sigma [4], that include flow of incoming materials and parts, adequate tools & test bed facilities and EOT cranes capacity as per Table I.

Table I: EOT Cranes capacity required for Job handling

Description	400kV, 275MVA, 1-Phase (HV AC)	765kV, 275MVA, 1-Phase (EHV AC)	765kV, 500MVA, 1-Phase (EHV AC)	±800kV system, 1-Phase Converter transformer (HVDC)
Transport Weight (Approx.)	180 Ton	215 Ton	235 Ton	310 Ton

As a part of quality plan, the manufacturing and testing of such large EHV transformers require stringent process control and checks at various stages from beginning to the end in order to ensure reliability at component and system level.

D. Materials

Precisely speaking, all static and rotating electrical machines require three types of material classified as: conducting, insulating and magnetic. For design and manufacturing of EHV transformers, the copper is universally accepted as current carrying conducting material. Various types of Copper for winding material used are: Paper Insulated Copper Conductor (PICC), Continuously Transposed Conductor (CTC), Bunched PICC, Glued CTC, or Glued PICC [17]. In all the transformers, the magnetic lines of forces are the media of transformation of voltages from one level to another. hence core material with maximum flux density and low specific losses have to be used for size reduction and optimum efficiency.

All EHV transformer design therefore uses CRGO (cold-rolled grain oriented) steel as magnetic material. The variant of the CRGO core material give different specific losses in Watts/kg, therefore the core material that have low specific losses are natural choice for EHV transformers design. The Table II enlists core material with corresponding specific losses specified at 1.7 Tesla as per industry practice.

Table II: Specific losses of Core material in EHV design

Grade	Typical losses at 1.7T
Normal Orient Core e.g M4	1.3 Watts/Kg
High –B e.g. MOH	1.03 Watts/Kg
Domain Refined Laser Scribed e.g. ZDKH	0.85Watts/Kg

Obviously from Table II, the laser scribed core steel incurs minimum core losses, hence the latest trend is to use this material in design of EHV transformers.

The transformers also require Insulating material with high dielectric strength for providing insulation among the possible live parts such as windings, tanks etc. The EHV transformer uses insulating oil, pressboard, paper and mixed dielectric e.g. oil and cellulose material for providing insulation between live parts. In order to reduce Insulation failure due to flashover, a low permittivity matched pressboard polymethylpentene fibre with cellulose fibre, is used with EHV transformers [16].

In addition, the EHV transformer also requires ferrous and non-ferrous materials for manufacturing of other sub-assembly such as tank, conservator, and radiator etc. High tensile strength non-magnetic steel is used for clamp plate for higher capacity transformer for stray loss control and improved over fluxing capability.

All these materials require extreme care and whether controlled storage to add reliability to EHV Transformers.

III. DESIGN CONSTRAINTS

A. Material Constraints

In EHV transformers, the design of the magnetic and electric circuit is based on the considerations of rating, operation & transport constraints. The transformer core acts as a magnetic circuit that provides low reluctance path to the magnetic lines of forces. The magnetic flux mutually link with primary and secondary winding which acts as electrical circuits for voltages transformation. The optimum value of the flux density of magnetic material and optimum value of current density of conducting material put constraint respectively on Transformer magnetic and electrical loading that in turn decide its efficiency and physical size. In addition, the leakage flux between the windings and fringing effect at winding-end-portion is higher for higher rating transformers and must be given due consideration. For CRGOS, saturation may occur at the magnetic flux densities exceeding 1.9 tesla [17].

Though insulation design contributes to nearly 10% cost of the EHV transformer yet is a prime constraint that governs life and reliability of the Transformer. The dielectric strength and tanδ of the insulating material is one of the key design parameters. Insulation system in EHV transformer comprises of mixed dielectric i.e. oil and cellulose material. A sound insulation design of transformers refers to understanding of electric flux distribution to minimize non uniform dielectric fields and to avoid creepage stress. As an example, a typical plot of electric field of a coil-end region of a transformer is shown in Fig. 1. According to the nature of the field, insulation area can be divided into three zones 1, 2, and 3 as discussed below.

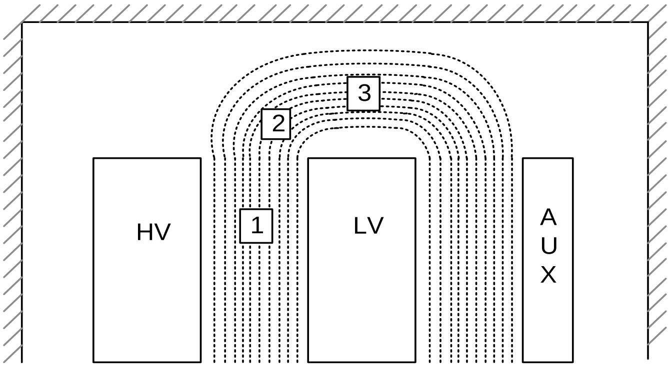


Fig. 1. Typical field plot of coil end region in a transformer

Referring to Fig. 1, the vertical lines of forces with uniform field can be observed in Zone 1. The number and thickness of the barriers (pressboard) in this zone are decided by the stress withstand capability of the oil gaps. The Zone 3 in Fig. 1, has non uniform Field with horizontal distribution of magnetic lines of forces. Obviously, the oil gaps in this zone are larger than in Zone 1, therefore the placements of barriers and static rings are critical to make field strength uniform in this zone. The Zone 2 is the most important from Insulation design consideration. This is certainly a zone of high gradients and is subject to both puncture and surface creep stresses. The above field plot is shown for coil end region and similar study is to be performed for winding conductors. An optimized design is therefore needed to have uniform distribution of electric field at EHV in different zones. Important Insulation design considerations are:

- Knowledge of exact position of the equipotential lines
- Avoiding electrodes placement at very sharp corners or shielding.
- Selection of suitable diameter Lead conductor from the point of view of thermal and electrical stresses withstand capability.
- Division of highly stressed zone into number of thin barriers of solid insulations.
- Shape of the applied voltage (Waveform).
- Volt – time characteristics of insulation
- PD inception characteristics of insulation
- Shape and surface condition of electrodes
- Use of moulded insulation items with contours which are made in accordance with the shape of the equipotential lines

The proper insulation design facilitates elimination of local high stresses due to winding connections, crossovers, transpositions, improvement in oil processing and impregnation, elimination of voids, etc

B. Percentage Impedance Constraints

EHV transformers must be designed for optimum value of percentage impedance as Low percentage impedance yields higher short circuit currents and higher percentage impedance results in increased eddy losses in windings and stray loss in structural parts. The higher short circuit current also causes increased mechanical forces that in turn compel to use lower design value of current density thus increasing the material in use and corresponding cost. On the other hand, the higher percentage impedance, results in increased losses leading to higher temperature rise of winding & oil, requiring extra cooling arrangement [16]. Hence a judicious compromise of designed value of percentage impedance is to be made. A typical value of 16% impedance is generally adopted. The percent impedance of transformers installed in parallel must be between ±7.5%, else this will increase circulating currents significantly.

C. Voltage Regulation Constraints

In 765kV EHV transmission system, the transformers should maintain the voltage within the range 722.925/√3 kV ± 5.5% at Neutral end, thus putting a constraint on voltage regulation. The voltage regulation is defined as change in the magnitude of secondary voltage if the system load is removed keeping primary side voltage constant. The Voltage regulation is expressed as:.

$$\mathrm{Re}\,gulations(pu) = \frac{V_{2oc} - V_2}{V_2} \qquad (3)$$

V_2 - secondary terminal voltage at a specific load,
V_{2oc} - secondary terminal voltage when the load is removed

Voltage regulation is an important performance parameter of a transformer that determines power quality of electricity supplied to consumers. The voltage variation is controlled by tap changing tapings of transformers. In 765kV transmission system, the transformers are provided with total 23 taps, ranging from +807.075/√3 to 722.925/√3 kV i.e. ± 5.5% at Neutral end. Similarly, in ±800kV system, Converter transformers are provided with total 35 tap positions i.e. +512kV to -376kV.

D. Thermal Constraints

The power losses in a transformer decides its temperature rise that causes thermal stress and puts constraints in the design of EHV transformer. The transformer losses include: winding copper losses, eddy current losses in conductors, and stray and magnetic losses caused by magnetic field.

The Copper-loss in transformer also includes stray loss caused by stray fluxes in the mechanical structure and widening conductor apart from the I^2R or load losses. The stray loss is therefore one of the major source of increased temperature in peripheral area of main tank and magnetic flux crossing iron parts. It is therefore utmost necessary to accurately measure and optimize these stray losses to reduce thermal stress. To minimize heating caused by stray losses, a shielding on the tank wall by means of Magnetic shunts are provided as shown in Fig. 2. In addition, to minimize winding copper losses due to load component, the conductor current densities must be kept within limit for all tapping ranges.

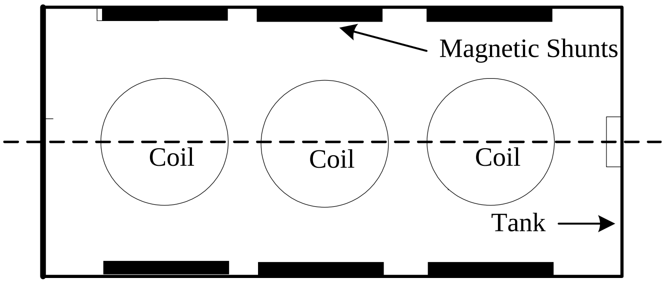


Fig. 2. Fixing of magnetic Shunts on 3-phase transformers

The losses in active part of the transformer rises temperature of oil inside, which in turn controls the ageing of the insulation.

For larger MVA rating & size, the transformer is subjected to significantly high magnetic & thermal stresses. In order to cater for various operating conditions of EHV Transformers at continuous full load/overload, the maximum temperature rise is limited to approximately 50ºC.

E. Short Circuit Withstand Constraints

The most severe mechanical stress occurs in a transformer, when it is subjected to a sudden short circuit. Since the currents flowing through the windings at that time are enormous, thus the forces generated which are proportional to square of currents, are also enormous. Much work has been done to accurately calculate and analyze these forces [15].

$$\text{Radial Forces, } F_r = \frac{2 \times \pi^2 \times (NI)^2 \times D_m \times 10^{-7}}{h} \qquad (4)$$

$$\text{Axial Forces, } F_a = \frac{2 \times \pi^2 \times A \times (NI)^2 \times D_m \times 10^{-7}}{h_{eff}} \qquad (5)$$

Where,

B – Magnetic field density, D_m – Mean diameter of the winding,

f - Frequency (Hz), h - Height of the winding ,

N - Numbers of turns of the winding , NI – Ampere - turn of the winding

"A" is the length of the tap section and it is expressed as a fraction of the total length of the winding, h_{eff} is the effective length of the path of radial flux and value of the h_{eff} varies for each arrangement of tapping.

Minimum cross-section required to withstand the heat generated due to the short circuit is given in eq. (6) [3]:

$$S = \frac{I_{SC} \times \sqrt{t}}{K} \qquad (6)$$

$$K = \sqrt{\frac{\omega.C.\Delta\theta}{0.24 * \rho}} \qquad (7)$$

S : Cross - section of conductor (mm),

Isc : Standard SC current (A),

t : The persistence time of SC current (s),

K : Constant coefficient related to the conductor material,

ω : Specific weight of the conductor (gr/cm3),

C : Specific heat of conductor metal (Calorie/g °c),

$\Delta\theta$: The conductor temperature rise (°c),

ρ : Specific resistance of the conductor (ohm - m/mm2)

The problem does not yield easy solution due to the transient and dynamic nature of the phenomenon. The windings must be mechanically strong to withstand mechanical stress during short circuit. This requires precise design to estimate stresses in the winding so that clamping structure can be made rigid enough to cater these short circuit forces in axial direction as well copper conductor & winding design as radial forces. For short circuit proof design, epoxy bonded CTC conductors and work harden copper conductors are used in winding [16].

F. Transformer Tank Structural Design Constraints

The structural design of transformer tank requires stress analysis of the combined behavior of plate and shells with stiffeners, which involves a realistic estimate of boundary conditions. For computing the stresses and displacements at a few selected points, the classical method is handy. However, for computing the stresses and displacements in global sense, the classical method is not sufficient due to very complex geometry and one has to make use of rigorous methods such as finite element method.

Structural Design of main tank and its structural parts have to withstand stresses during different loading conditions such as full vacuum, air pressure and oil pressure. These stresses are experienced during processing of transformers, oil pressure, lifting by crane, hauling, jacking etc. as well as under seismic conditions. The vacuum test is performed under 760 mm of Hg and pressure test is performed at 14psi approx. for measured deflection within specified limit. The successful design testing enhances the reliability of critical areas of structural parts [17].

G. High Voltage Bushing

Power transformer's reliable operation mainly depends on the sound operation of their high voltage bushings. High voltage bushings are the direct link between power transformer and switchgear.

A new technology of epoxy resin impregnated crepe paper insulation or Resin Impregnated Paper (RIP) bushings are increasingly being used due to its advantage over Oil Impregnated Paper OIP bushings. These new RIP bushings have several advantages namely behavior under various conditions of operation, overall dielectric and thermal performance, positioning the bushing at any desired angle and cheaper in cost. These bushings are very sensitive to moisture and therefore must be tested for proper value of tan δ before installation.

The design of a bushing depends on the various voltages and over-voltages that it has to come across during service. Bushing being a weak link in the transformer, permissible value of tan δ for the bushing is limited to 0.005 [12]. It is necessary in large bushings (greater than 300 kV) with high current, to pay attention in the design to the dissipation of the conductor losses which may be several times the dielectric loss. The transport and storage of RIP bushings for maintaining proper value of tan δ puts constraint to be addressed suitably. Another site constraint is put by the length of these bushings, which is significantly higher 765/800kV transformer. Table III enlist length of the Bushing for 400kV, 765kV and 800kV Transformers.

Table III: Bushing Lengths of Transformers

Description	Bushing Length (in mm)
HV Bushing (for 400kV Transformer)	6500
HV Bushing (for 765kV Transformer)	11000
HV Bushing (for 800kV Converter Transformer)	12500

IV. RECENT TRENDS

A. Manufacturing Technology and Procedure

The manufacturing of 765/800 kV Class of transformer requires very precise workmanship. Therefore, the manufacturing works must be equipped with advanced tools and machinery such as:

- Higher capacity of shop floor tools and plants
- Horizontal and vertical winding machines,
- Platforms for core building,
- Vapor phase drying ovens,
- Pressing arrangement of winding,
- Cranes,
- Air casters,
- Test station,
- Dust free clean and weather-controlled rooms for windings and active part assembly.

To have precise control on manufacturing process of such large EHV transformers, it is mandatory to prepare a detailed document referred as quality assurance plan (QAP), which should include:

- The quality checks for every possible process-step of transformer manufacturing,
- Statistical analysis of number of deviations from desired goal parameters to elevate manufacturing processes to a 6-sigma level.
- Various checklists stating all compulsory technical parameters need be filled up during manufacturing process.
- Maintain desired humidity in the workshop atmosphere along with highest level of effective cleaning by monitoring periodical dust level very precisely [10].

B. Shipment, Receipt and Storage

The EHV/HVDC transformers of 765/800 kV are large in size and weight, therefore requires transport by Rail, Sea and Road, and are shipped without oil. During shipping, following preparation is mandatory:

- The tank is filled with inert gas like nitrogen gas / dry air and mounted with a pressure-gauge & stop-valve to enable measured values to be recorded upon receipt.
- The transformer at the site should arrive with positive pressure, indicating that moisture did not enter the transformer during shipping.
- Measurement of dew point of nitrogen / dry air inside the tank to determine the dryness of insulation.
- Mounting Impact recorder during delivery of transformer for analyzing successful transportation. Transformers are designed to withstand mechanical shocks of the order of 3G impact in all three directions. Any impact of 3G or greater must be reported immediately to manufacturer.

Upon receipt transformer is checked for *(i)* Pressure of Nitrogen/dry air, (*ii*) Dew Point of Nitrogen/dry air, (*iii*) Core-Yoke-Ground isolation test *(Insulation Resistance at 500 Volt), (iv)* Insulation Resistance of Winding at *5kV*

A very significant and vital test, 'Sweep Frequency Response Analysis (*SFRA*)' has been developed to determine any possible physical distortion within active part of the transformer. The *SFRA* being a relative analysis test is recommended to be done initially at factory and later at the site in order to diagnose any abnormality in the signatures.

If the transformer cannot be installed immediately upon arrival and oil filling is impractical, it should be stored with transformers tank under positive nitrogen/ dry air pressure. The maximum length of time under this storage method should not be more than 3-6 months. If the transformer need be stored longer than the prescribed limit for Short Term Storage, the storage can be performed with oil filling.

C. Erection, Testing and Commissioning

The site activities also play a vital role in making successful and trouble-free charging of 765kV transformers. Special care is taken to adhere all operational checks as prescribed by manufacturer during bushing erection as they are sensitive and dimensionally large in length as per Table III. These bushings shall always be lifted by using crane having outriggers in such a way that none of its part touches ground or any other object while being lifted. Crane selection should be based on bushing weight at following height:

- Roller height +
- Transformer height +
- Working height above tank 1000mm for connection & fitting +
- Bushing height

Measures to maintain effective dryness of the insulation of active part while opening the main tank for erection activities:

- Dry air purging during erection to prevent moisture ingress to peep in, when main tank of transformer is opened.
- A rigorous dry out process of tank either by vacuum or injecting dry air/nitrogen gas at dew point of (-) 50ºC or better and purity 99.999% or better,.
- Hot oil circulation till desired parameters are achieved. It must be filled under vacuum only
- Particle size reduction/rinsing by fine filters should be carried out so that particles of size ≥4 micron in the oil can be maintained within desired limit. The limiting value of particles of size ≥4 micron should be according to Scale-10 as per ISO 4406 [18].

Final commissioning tests of 765/800kV Class transformer are performed after the transformer has been filled with oil and the oil temperature is cooled down to a value less than 40°C and measured values of capacitance and tan delta of bushings at variable frequencies are within prescribed limit.

As per existing practice for Tan δ test of bushings is to be performed at power frequency i.e. 50 Hz for 400kV Class transformers. The latest practice for performing test of bushings for 765kV/800kV transformers is to be done at variable frequency starting from 15 to 400Hz. Once the transformer has become ready for charging, a pre-charging and post charging DGA test of oil is mandatory.

In addition to above, installation of such high voltage transformer has to be performed strictly under the well laid down field quality plan (FQP) with established recommendations and guidelines as given by the manufacturer.

D. In-Service Online Monitoring and Control

For large power transformers, following online monitoring system is in place for its effective and optimum utilization:

- Dissolved gases and moisture content measuring system.
- Systems for gradual removal of moisture in oil,
- Fiber optic temperature monitoring system for internal temperatures of core, winding etc. using optical fiber sensors fitted inside transformer main tank,
- Bushing tanδ,
- Partial discharges inside transformer

For bushing on-site condition monitoring, some monitoring/diagnostic methods are used and essential for ensuring healthiness/preventing bushing terminal failure. These diagnostic methods are ranked according to their "effectiveness" in indicating bushing failures as per Fig. 3 [12]:

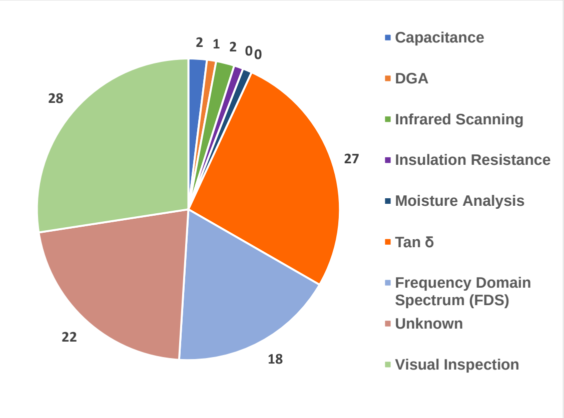


Fig. 3: Bushing Failure Diagnostic methods

In addition to above, a combined monitoring and control can be achieved by integrating all field data for optimum utilization of transformers that include: Control of cooling banks, tap changer operation, estimation of remnant life for allowing overload, dynamic loading, over-load management etc. The system provides state-of-art communication with IEC 61850 and MODBUS protocols for communication of the monitored parameters to the control room. The block diagram of key architecture of composite monitoring system is shown in Fig.4.

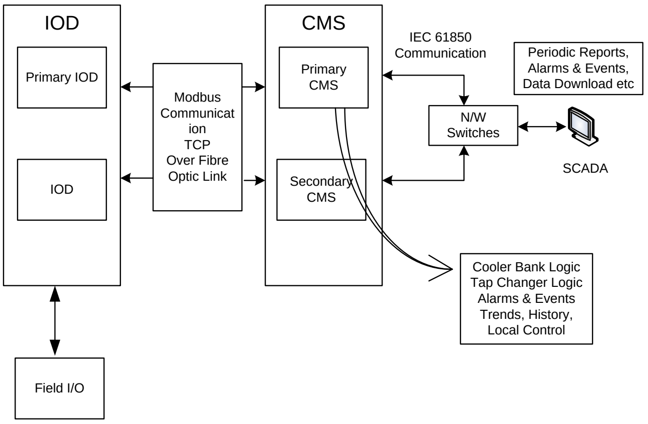


Fig.4: Block Diagram of Composite Monitoring System

Apart from monitoring of data, the control of operation of fan, pumps, tap changer is exercised online from control room. One such set of data is shown in Fig. 5.

Fig. 5. Monitored Data at Control Room

This depicts Binary I/O, the page will display the status of digital input and digital output (IOD). Green indicates logic low and Red indicates logic high.

V. RESULTS ANALYSIS

The present paper, in addition to have discussion on some aspects of material, manufacturing & design constraints, also brings out results of recent testing of equipment at site during installation & commissioning or while in-service. The following diagnostic test are conducted on 765/800kV class transformer and results are discussed underneath.

A. Variable Frequency Tan δ Test (VFTD) of Bushings

The installation of these transformers at site requires good health of bushings, which is very sensitive to moisture ingress. Tto test healthiness of the bushing, a Tan δ test at different frequencies are conducted. Following is the result of site measurement of 4 bushings (*Da*, *Db*, *A*, *B*) in a 800kV Converter Transformers shown in Fig. 6

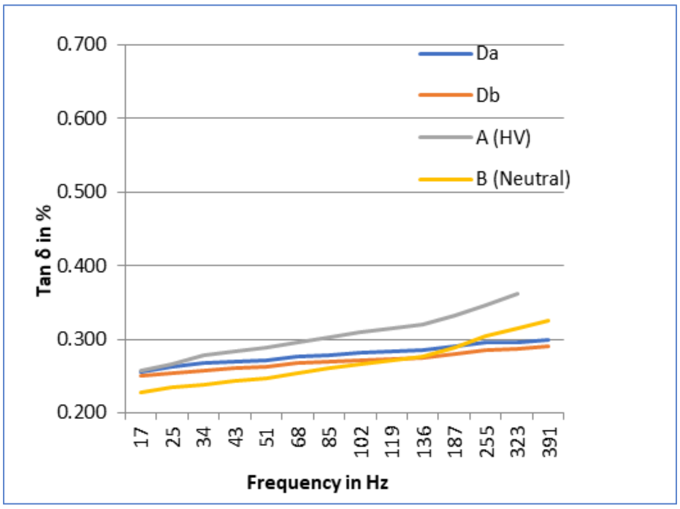


Fig. 6. Variable Frequency Tan δ Plot

In Fig. 6, the test results for measurement of tan δ of 4 bushings of 800kV converter transformers are obtained by varying the frequency in the range of 17 to 391 Hz. Conventionally, the tan δ for bushing health used to be measured at power frequency of 50 Hz only, and corresponding to this frequency the tan δ results of all 4 bushings are within prescribed limit of 0.5% [12], although they have variation in lower and higher frequency zone.

For all 04 bushings above, the measured values are well within the limit of 0.5%, and may be judged as healthy conventionally. But, as per recent trends of *tan δ* measurement of all EHV bushing must maintain the yardstick limit of 0.5% for entire range of frequency [11] or as per OEM manual. For the cases, where *tan δ* is within limits at power frequency but exceeding in lower or higher frequency range, then it may be inferred that the same is prone to malfunction and may cause trouble in the long run.

B. Sweep Frequency Response Analysis (SFRA) of Transformer

The SFRA test at different frequencies were conducted on a 1-Phase 765kV Generator Transformers using Omikron FRA analyser and results are shown in Fig. 7.

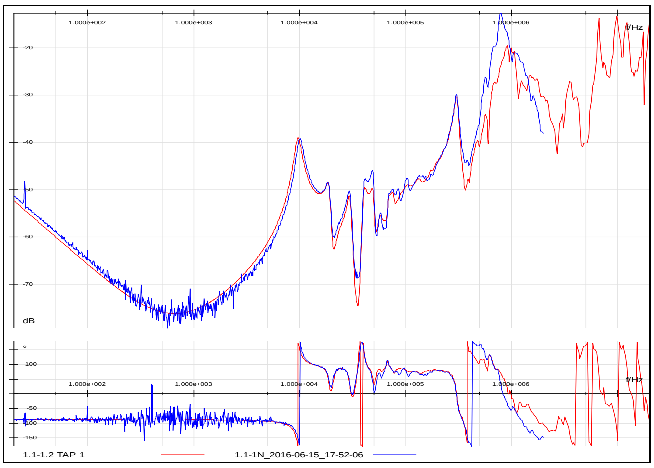


Fig. 7. SFRA Plot of 765kV Transformer HV-N

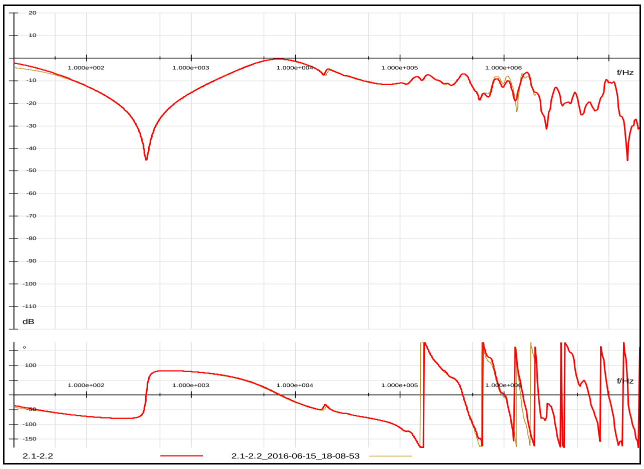
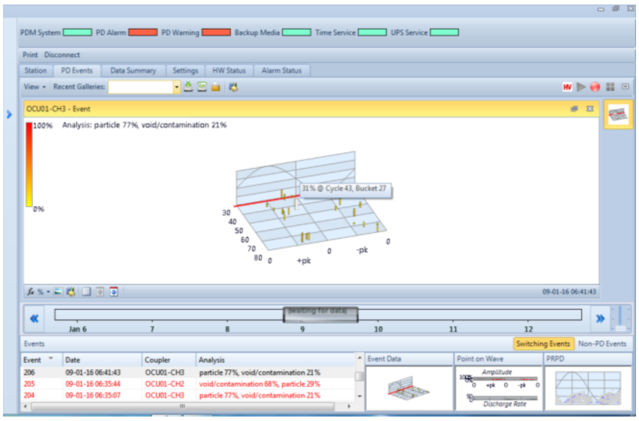


Fig. 8. SFRA Plot of 765kV Transformer LV-N

The SFRA test is diagnostic in nature. It is therefore conducted first at factory before dispatch and then repeated at the site before installation and commissioning. These SFRA signature plots before dispatch and on-site are then compared for connection between HV-N (*High Voltage winding to Neutral)* and LV-N (*Low Voltage winding to Neutral).* If these two plots are found to be matching, it confirms that transformer active part assembly remains intact even after movement/transport. The SFRA Plot of 765kV Transformer for connection between LV-N is shown in Fig. 8. However, there may be slight Electromagnetic (*EM*) noise distortion caused by induction effect of nearby charged lines, which need be ignored while analyzing the plots.

C. Partial Discharge (PD) Measurement

In Ultra High Frequency Coupler (*UHF*) *PD* detection method, an antenna is inserted in the transformer tank through an oil valve. The *EM* waves generated by partial discharges are picked up by the antenna and a broadband filter is used to pick or select a suitable frequency area between 500 to 1000 MHz The result of *PD* measurement conducted on 765kV Auto Transformer using Qualitrol DMS PD monitoring system. Fig. 9 shows a result coming from a UHF sensor mounted on the transformer.



Analysis: particle 77%, void/contamination 21%

09-01-16 06:41:43

Event	Date	Coupler	Analysis
206	09-01-16 06:41:43	OCU01-CH3	particle 77%, void/contamination 21%
205	09-01-16 06:35:44	OCU01-CH2	void/contamination 68%, particle 29%
204	09-01-16 06:35:07	OCU01-CH3	particle 77%, void/contamination 21%

Fig. 9. SFRA Plot of 765kV Transformer HV-N

In the measurement, there is no PD alarm or PD warning indication observed as shown in Fig.9.

If PD is suspected in the measurement, some pulses that represents some PD pulses continuously then these have to take it into consideration.

In PD analysis there are lot of false signals that are created while analyzing, so there is no fixed % or permissible limit. Following type of signals are generally ignored as they mislead the true analysis -

- Noise if seen in any of sensor.
- Random/man made signals.
- Any signals less than 15% amplitude or no event created.

If PD observation from PD analyzer is misleading then expert analysis from OEM is always obtained.

VI. CONCLUSION

In this paper the emerging technology of 765 kV transformer and its ancillary issues in view of upcoming 765kV EHV AC/ ± 800kV HVDC transmission network in India is presented. Considering complex requirements and constraints of 765 kV class of transformer, a recent trend in its design and manufacturing that include selection of conducting, magnetic and insulating material and analysis of magnetic field distribution for appropriate placement of barriers are discussed. The paper also brings out state of art practices in shipment, testing and commissioning and the systems being used for online In-Service Monitoring and Control. In addition to addressing design, manufacturing and other aspects, the paper also discusses results of recently adopted new testing and diagnostic techniques such as Variable Frequency Tan δ Test (VFTD) of Bushings, Sweep Frequency Response Analysis (SFRA) of Transformer, and Partial Discharge (PD) Measurement through Ultra High Frequency Coupler (UHF) on such EHV transformers of 765kV/800kV rating. Looking at the dimension of the country, the power transmission at 1150/1200 kV is in pipeline, hence a similar work on transformers for such ultra-high voltage class may be taken up and presented.

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REFERENCES

1. D. Thukaram, H. P. Khincha and P. Shyamala, "Comparative Studies of Transient and Steady State Analysis for a Typical 765kV/400kV EHV Transmission System in Indian Power System," *2006 International Conference on Power Electronic, Drives and Energy Systems*, New Delhi, 2006, pp. 1-6.
2. National Electricity Plan (V0l-II), 2016
3. A. Netake and P. K. Katti, "Design aspect of 765kV transmission system for capacity enhancement," *2015 International Conference on Circuits, Power and Computing Technologies [ICCPCT-2015]*, Nagercoil, 2015, pp. 1-9.
4. D. Mehta, P. Kundu and A. Chowdhury, "Extending the power transmission capability to 765 kV through emerging EHV/UHV transformers," *2014 9th International Conference on Industrial and Information Systems (ICIIS)*, Gwalior, 2014, pp. 1-6.
5. Rohit G. Kanojiya, Pranay S. Shete, Nirajkumar S. Maurya, Nitin P. Choudhary, "Preliminaries Comparison Based on Performance of 400KV and 750KV Double Circuit Transmission Line", International Journal of Engineering Research & Technology (IJERT), ISSN: 2278-0181, Vol. 3 Issue 3, March – 2014
6. IEC 60076, Power transformers — Specification — Part 3: Insulation levels, dielectric tests and external clearances in air.

7. K. Karsai, D. Kerenyi, L. Kiss, Large Power Transformers, ELSEVIER,vol.25, 1987.
8. Christoph Krause, —Power Transformer Insulation – History, Technology and Design, IEEE Transactions on Dielectrics and Electrical Insulation Vol. 19, No. 6; December 2012.
9. W. Ziomek, K. Vijayan, D. Boyd, K. Kuby and M. Franchek, "High voltage power transformer insulation design," *2011 Electrical Insulation Conference (EIC).*, Annapolis, MD, 2011, pp. 211-215
10. ISO 14644, Clean Rooms and Associated Controlled Environments
11. Avila Priya F, Kalaiselvam K, Poongothai K, Arun R and T. Prabakaran, "Electric field calculation and material optimization of 765kV bushing using FEA," *2015 International Conference on Computation of Power, Energy, Information and Communication (ICCPEIC)*, Chennai, 2015, pp. 0064-0070.
12. CIGRE document on "Transformer Bushing Reliability", WG A2.43, Ref-755, 2019
13. A Technical Brouscher, "Transformer reliability survey", ELT_284_6, CIGRE WG A2.37, Year 2016
14. Hao Wu, Lilan Liu, Teqing Liu, Zongren Peng, Xiaolu Lv and Jintao Liao, "The effect of moisture and temperature on the oil-immersed-paper used in EHV converter transformer," *2016 IEEE International Conference on Dielectrics (ICD)*, Montpellier, 2016, pp. 577-580.
15. K. Dawood, G. Komurgoz and F. Isik, "Computation of the Axial and Radial forces in the Windings of the Power Transformer," *2019 4th International Conference on Power Electronics and their Applications (ICPEA)*, Elazig, Turkey, 2019, pp. 1-6.
16. S.V. Kulkarni, S.A. Khaparde, Transformer Engineering- Design, Technology, and Diagnostics, Marcel Dekker, 2004.
17. Transformers, Authors of BHEL Bhopal, Published by TMH, 2nd Edition, Reprint 2004.
18. ISO 4406, "Hydraulic fluid power-fluids-method for coding the level of contamination by soild particles", 2nd Edition :1999 (E)

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