OPTIMIZING TRANSFORMER SPECIFICATION BASED ON APPLICATION AND RATING

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Abstract – In today's fast-paced world, technology is evolving rapidly and impacting every field. When it comes to transformers, the fundamentals haven't changed, but there are several new innovations that can aid with maintenance, protection and increasing the life of the asset. IEEE C57.12.10 provides standard requirements for power transformers. Beyond the standard requirements, user specification can cover a wide range of design parameters and options. Applying the same requirements for the entire range of transformers on a project may lead to gold-plating and increased cost. On the other hand, critical applications may require more careful consideration and investment. Example of some common questions that may arise- Should one specify high temp fluids or stay with mineral oil? Should sealed type or conservator type preservation system be specified? How far can one deviate from standard impedance before it has a significant impact on cost? Is standard Basic Insulation Level (BIL) adequate or is enhanced BIL required? Should maximum core flux density be specified? Should one specify online monitoring? This paper will explore many of the parameters and options that can be selected and specified by users taking into consideration recommendations from IEEE and transformer industry best practices. The goal is to provide guidance based on rating and application that may enable users to optimize and bring the best value for their project.

Index Terms —Basic Insulation Level (BIL), Continuously Transposed Conductor (CTC), Disc Winding, Factory Acceptance Test (FAT), Helical Winding, Layer Winding, Mineral Oil, Ester Fluid, On-Load Tap Changer (OLTC), Sheet Winding,

I. INTRODUCTION

Transformers utilized in process industry broadly fall under the few major categories summarized below. There may be other specialty type transformers (example- transformers for VFD applications etc.) which will not be covered in this paper. Categories listed below would cover 70 to 80% of applications.

A. Utility Transformer

A Utility transformer is required when power to the process facility is derived from an offsite utility transmission system (typically 69 kV and above). These transformers are generally large power (above 50 MVA) outdoor units and step down to 34.5 kV or 13.8 kV for further distribution within the facility. Small or medium facilities may have one or two utility transformers and larger facilities may have four to eight utility transformers. These transformers may be supplied from an outdoor utility switchyard or Gas Insulated Substation (GIS).

B. Generator Step Up (GSU) Transformer

If a facility has on-site generation, then a GSU transformer is required. These transformers are step up type and will either deliver power through an MV bus (13.8 kV and above) for distribution within the facility (captive application) or HV bus (69 kV and above) for connection to the utility (exporting power offsite).

C. Substation Power Transformer

Process facilities may have multiple substations with MV switchgear (13.8 kV or 4.16 kV) supplied from substation power transformers. These transformers are typically above 5 MVA and less than 25 MVA. There may be two to four such transformers in one substation.

D. Distribution Transformer

Bulk of the transformers in the process facility will be 2.5 MVA and below supplying power to various LV MCCs (600 V and below). It is not uncommon to have four to eight such transformers in one substation. Manufacturers often have standardized designs and shorter manufacturing lead times for this range of products.

This paper will focus on requirements and specification for above listed applications. Key parameters traditionally specified by users related to insulating fluid, preservation system, core & coil, tap changer, and testing are covered in Section II through VI. Section VII addresses online monitoring and bushings. Section VIII will summarize the recommendations of this paper that will aid the user to select options and accessories based on application and rating.

II. SELECTION OF INSULATING FLUID

There are several alternatives to mineral oil that are becoming increasingly popular as cooling medium in transformers. These fluids fall into the classification of high temp fluid or less flammable fluid (fire point > 300 °C per ASTM D5222), thereby significantly reducing the risk of pool fires. Ester fluids (natural or synthetic) are less flammable, also have the advantage of being biodegradable (derived from vegetable oil) and minimize impact to the environment in the event of spills. Viscosity of ester fluids is higher than mineral oil. Additional cooling accessories may be required to limit the temperature rises within the limits specified in the standards. Transformer cost may increase by approximately 5% to 10% for ester fluids when compared to mineral oil. However, this cost may be offset when considering elimination of fire walls and reduction in space for the transformer yard due to tighter clearances permitted by ester fluids as shown in Table I.

TABLE I
MINIMUM SEPARATION DISTANCES BETWEEN ADJACENT TRANSFORMERS

Fluid Vol in gallons	**Clearances from other transformers or non-combustible substation wall**	
	Less Flammable Fluid (ft)	**Mineral Oil (ft)**
<500	5	5
>=500 and <=5,000	5	25
>5,000 and <=10,000	5	50
>10,000	25	50

(Source- Factory Mutual data sheet 5-4 Table 8)

Transformers up to 2.5 MVA can be generally designed with fluid volume less than 500 gallons. This should be confirmed with the manufacturer up front. Transformers above 2.5 MVA and up to 100 MVA will typically have fluid volume greater than 500 gallons but less than 10,000 gallons. Thus, clearances can be significantly reduced with less flammable fluids for medium and large power transformers above 2.5 MVA. For transformers 2.5 MVA and below, mineral oil can be considered since it will be cheaper. However, for consistency and ease of maintenance, the user may choose to specify the same insulating fluid for all transformers within the facility.

Natural ester cooling fluid is more commonly used over synthetic ester fluid for smaller size transformers. Table II lists the common properties that can be compared between mineral oil and natural ester which affects the design and maintenance of the transformers at the typical transformer operating temperature.

TABLE II
MATERIAL PROPERTY COMPARISON

	Mineral Oil	**Natural Ester**
Oil – Dielectric constant	2.2	3.2
Solid Insulation – Dielectric constant	3.2 to 4.4	3.4 to 4.6
Viscosity (in centistokes, cSt)	3.5 cSt	12 cSt
Water saturation level	450 mg/kg	2600 mg/kg

Distribution transformers used in process facilities can use natural ester fluid without much change in design. But larger utility transformers, GSU transformers and substation power transformers will have larger footprint.

Dielectric constants affect the stress distribution in transformer in such a way that stress in ester fluid reduces and stress in solid insulation increases. Increases in viscosity of the fluid causes changes in top oil temperatures, winding rise, hot spot temperature rises and core hot spot temperature rise. This is illustrated in Table III below.

TABLE III
IMPACT ON TEMPERATURE RISE AND ELECTRICAL STRESSES

Parameter	**Changes shown for Natural Ester as compared to Mineral Oil**
Top Oil Temperature Rise	Up to 5 °C increase
Average Winding Rise	Up to 5 °C increase
Winding Hot Spot Rise	10 - 20 °C increase
Core Hot Spot Rise	6 - 10 °C increase
Electrical Stress (in cooling medium)	5 to 7% reduction
Electrical Stress (in solid insulation)	Approximately 35% higher stress values

Power frequency breakdown voltages are comparable between mineral oil and natural ester fluid. However, lightning impulse withstand properties and surface creep properties under non-uniform field conditions (example- winding corners etc.) was not very well understood by the industry until recently. Refer also to papers published in IEEE [2] and [3].

Fig. 1(a) and 1(b) below shows the difference in stress distribution in mineral oil and natural ester fluid respectively.

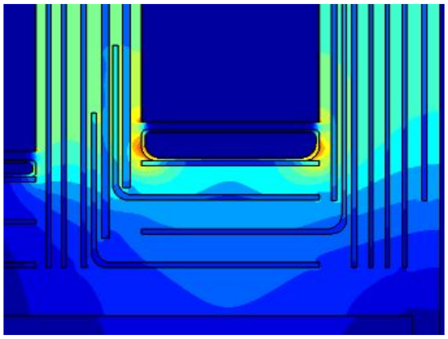

Fig. 1(a) Electric Field for Mineral oil

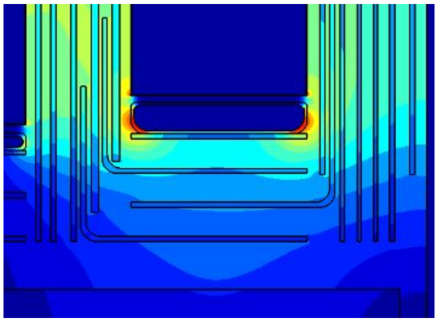

Fig. 1(b) Electric Field for Natural Ester fluid

In these plots, the highest stress is represented in red color and lowest stress is represented in dark blue color. The stress progressively decreases from Red to Blue as shown below-

Red >> Yellow >> Light Blue >> Dark Blue

Due to smaller difference in permittivity's of solid and liquid insulation for ester fluid, there is a shift in stress distribution in active part of the transformers from liquid to solid medium. With mineral oil design, stress in corners of winding geometry is concentrated in fluid medium. On the other hand, in natural ester design, concentration is in paper covering of the winding and shield ring. As a result of this characteristic, the natural ester fluid is typically limited to transformer applications up to 230 kV.

III. TYPE OF PRESERVATION SYSTEM

Broadly there are two types of fluid preservation system for application of transformer discussed in this paper which are sealed tank design and conservator type design. Typical tank fluid preservation system used for smaller size transformer is sealed tank system with dry air or nitrogen blanket system. Conservator fluid preservation system is preferred for units of larger size. Conservator design can be with or without an air cell bladder and will have a dehydrating breather. Table IV provides the size-based preferences of oil preservation system.

Sealed tank design has less interaction with atmospheric air. The gas space above the oil level can be of dry air or nitrogen medium. Pressurized nitrogen tank design with pressure regulator can maintain the positive pressure and allows more variation of temperature. Sudden change in load and ambient temperatures generates gases which gets collected at the top for sealed tank design. With increased moisture content in oil, bubble formation can get as low as 140 °C. Combining this effect with dissolved gasses in oil severely affects the dielectric design of the insulation system, therefore this application to be restricted above 138 kV class. Sealed tank design typically requires lower maintenance and there is no assembly of components, oil filling and oil filtration during initial installation.

In conservator design with air cell bladder, there is no interaction with atmosphere directly unless there is damage to the bladder. However, in conservator design without air cell bladder, interaction between oil and atmospheric air happens through dehydrating breather. The latter type of conservator is not common and not recommended. Typical volume of conservator is 10% of oil volume in main tank and volume can change if the ambient temperatures are high. The conservator type design has gasketed flanges with more possibility of leaks, requires more maintenance and assembly/ oil filling during initial installation.

TABLE IV
PREFERRED PRESERVATION SYSTEM

Size	Type	Advantages and disadvantages
Up to 10 MVA	Sealed tank	Dry air or nitrogen blanket preservation system preferred.
Above 10 MVA and up to 50 MVA	Sealed tank or Conservator Design	Dry air or pressurized nitrogen blanket preservation system with regulators preferred for small & medium ratings. Advisable to consider conservator design if there is expected load variation for larger rating in this range.
Above 50 MVA	Conservator design	Free breathing tank design with bladder cell provides low interaction with atmosphere.

IV. CORE AND COIL CONSIDERATIONS

A. *Core Flux Density (typical value for each application)*

Electrical steel material has a long history of development. Domain refined laser scribed silicon steel with high permeability have been used by the industry for the transformer application discussed in this paper. General practice in specification writing is to detail the application of the transformer and loss guarantee. Transformer designers design to required application based on the site condition and meet the guaranteed no load losses. Typical transformer designs these days have flux density of 1.68 to 1.73 T using laser scribed high permeability electrical steel. Core flux density relation is given below,

$$B_m(T) = \frac{(Coil\,Voltage/Turn)}{4.44\ X\ Frequency\ X\ Core\ Area} \qquad (1)$$

Specifying core flux density can be relevant if there is expected overvoltage or load rejection in site condition. Overvoltage of such nature can roughly exist for about 3 to 4 cycles. Overvoltage or overexcitation results in spillover of flux outside the core which can cause overheating of metallic structures, windings, lead structures which lead to gassing. Specifying lower core flux density requires larger core diameter which subsequently requires more copper, insulation, oil, and tank. Table V provides typical core flux densities and its impact. In general, generator step up transformer requires 110% over excitation per standards to avoid the core getting saturated during condition specified in the IEEE C57.116.

TABLE V
CORE FLUX DENSITY FOR DIFFERENT APPLICATION

Application	Core Flux density	Impact
Utility, Substation power and Distribution transformers	1.65 to 1.73	None (typical value)
GSU	1.60 to 1.68	5 to 7 % increase in material as compared to other applications.

Flux density is a consideration for designers also when losses are evaluated, and core losses are desired to be optimized due to high $/kW.

B. *BIL (Standard or Enhanced)*

IEEE std C57.12.00 provides line and neutral BIL of the winding based on the system voltages. For a given system voltages, the standard provides minimum and alternate BIL protection levels. Specifying higher winding line end BIL would increase winding to winding clearances, winding to yoke end clearances, lead clearances and finally bushing external clearances which can increase the cost by up to 5% and increase the footprint of the transformer. Bushing insulation level shall be same or greater than the winding insulation level. It is recommended to increase the bushing creepage requirement rather than opting for the higher BIL to mitigate any environmental considerations such as high dust levels and to keep the same footprint. Insulation coordination study can be performed to verify the adequacy of standard BIL whenever there is high voltage cable between switching station to transformer. Any special utility requirements also need to be considered during selection of the BIL.

C. Winding Configuration

The most common configuration for substation power and distribution transformers, is the two-winding type with HV primary as Delta connected and LV secondary as Wye connected. Per IEEE C57.12.00, unless specified otherwise by the user, these transformers will be Dyn1 where LV lags HV by 30°. Care should be taken if an alternate source from an existing distribution system is also provided to the new facility. In this case, it will be important to select the winding configuration to match the existing system. Substation power transformers will typically have low resistance LV grounding (typically 100 A to 400 A). Distribution transformers are commonly specified with solidly grounded LV winding to permit fastest fault clearing. Sometimes for critical process applications where it is desirable to have an alarm and not trip for ground faults, the LV winding may be high resistance grounded.

GSU transformer where the LV winding is supplied from a generator will typically have Delta connected LV winding and Wye connected HV winding with LV lagging HV by 30° [6]. The HV winding is typically solidly grounded when connected to the utility system or low resistance grounded when connected to the main MV bus for distribution within the facility.

Utility transformers up to 138 kV are commonly specified as two-winding type with HV winding Delta connected and LV winding as Wye connected. When there are four utility transformers, replacing with two three-winding transformers can be considered and may be more cost effective. For 230 kV and above, a wye connected HV winding with a buried delta stabilizing winding could be alternatively considered by the user. Refer to paper presented in 2019 PCIC conference [1] for more information.

D. Winding Type

Sheet or Foil winding is constructed with thin sheet of conductor that has large width to cover the entire height of the winding as shown in Fig 2. This type of winding is used for low BIL application up to 75 kV and can provide large cross-sectional area of conductor for high current. Layers are separated by layer insulation and occasional axial ducts for cooling purpose. Leads are of bus bars or flexible jumpers brazed to winding ends as shown. This construction is used in both oil and dry type transformers.

Layer winding construction also known as barrel winding has several turns in each layer with turns axially located, and layers separated by layer insulation as shown in Fig 2. Depending on the number of turns, construction can be unidirectional or bidirectional as determined by the manufacturer. Voltage stress in unidirectional winding is lower than the bidirectional design. Transient voltage distribution is good for layer winding construction. There is no radial spacer in layer winding which makes it weaker against short circuit forces.

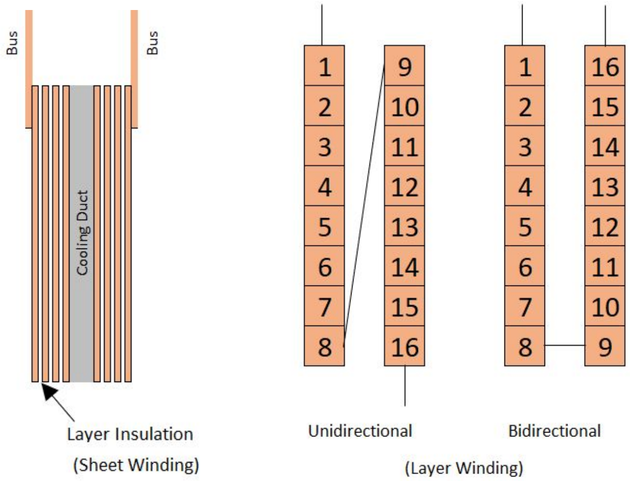

Fig. 2 Sheet and Layer Winding

Helical winding is type of disc winding with only one turn per disc and wound laterally around the core as a helix with radial spacer between them. This construction is used when current is high, and the number of turns is low. Number of strands in each turn can be from 5 to a large number which can be handled during manufacturing. When the number of strands is high enough, it is typical in industry to use Continuously Transposed Conductor (CTC). The CTC cable is continuously transposed and hence does not require further transposition when used for construction of the helical winding. The winding hotspot is reduced due to lower eddy and circulating current losses.

Disc type of construction is used when current is low but with higher number of turns typical of high voltage winding. Radial spacer between discs provides oil flow path. When there is more than 1 pull or strand, the wires change position relative to each other in every disc as shown in Fig. 3. Therefore, transposition is not required for limiting circulating current in winding. Both helical and disc type of construction provides high capability to withstand short circuit forces.

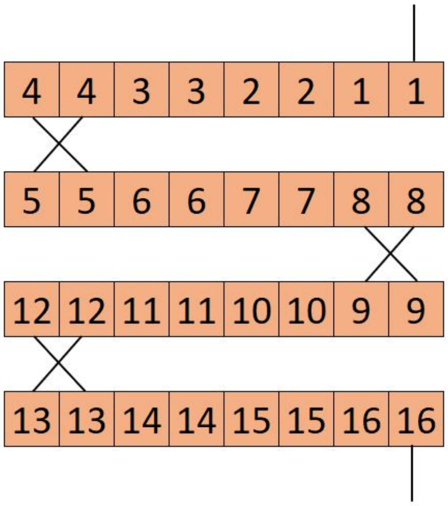

Fig. 3 Disc Winding

TABLE VI
WINDING CONSTRUCTION

Type of construction	Benefits
Sheet Winding	1) Utilized up to 2.5 MVA in size on low voltage side with maximum of 5 kV. Mostly applicable to distribution transformers.
Layer winding	1) Utilized up to 5 MVA in size and 34.5 kV. Mostly applicable to distribution transformers.
Helical Winding	1) Used as low voltage winding and low side regulation winding for Utility, GSU and Substation transformers. 2) This can be magnet wire or continuously transposed conductor (CTC).
Disc winding	1) Typically used for high voltage winding and high side regulation winding for Utility, GSU and Substation transformers. 2) This can be magnet wire or continuously transposed conductor.

E. Impedance Specification

IEEE C57.12.10 provides recommended impedance value for self-cooled rating based on HV winding BIL and whether there is an OLTC or DETC. It also states that user should perform a system study to determine the proper value of impedance. The selected transformer impedance will impact the voltage and short circuit fault level of the downstream bus. As a starting point, the user may utilize the recommended impedance values from the IEEE C57.12.10 for conducting the initial system studies. Typically, for distribution transformers and substation power transformers, the IEEE C57.12.10 values yield satisfactory voltage and short circuit levels at downstream buses. Cases where there are multiple sources (example- if transformers operate in parallel with downstream bus tie closed) or there are large motor loads may require special consideration and adjustment of transformer impedance value. Utility transformers will generally require adjustment and fine tuning for arriving at final values. But users often wonder how far one can deviate from the IEEE C57.12.10 values without causing significant cost impact. Alternatively, the user may want to consider higher short circuit rating for the downstream switchgear (example- 40 kA instead of 31.5 kA).

Manufacturers typically will not have any issues designing for an impedance value that is one level higher or lower than the IEEE C57.12.10 recommended impedance value (Example- selecting 6.5% impedance for 200 kV BIL without OLTC in lieu of the IEEE C57.12.10 recommended value of 7%). Any further deviation from the recommended value will require consultation and discussion with the manufacturer.

The IEEE C57.12.00 allows up to ±7.5% tolerance for two winding transformer and ±10% for three winding transformers on percent impedance. Deviation from the standard impedance for a transformer could change the design cost and footprint of the transformer. Pattern of impedance variation to active part material cost is shown for typical 10 MVA transformer in Fig. 4. Cost is optimum for certain percentage impedance for a given rating of transformer. Until a certain point, cost increases is linearly with change in impedance. But deviating more than 15 % from standard impedance (two level deviation from the IEEE C57.12.10 value) can increase the cost drastically. Loss evaluation for no load and load loss can also change the optimum point for impedance to material cost.

The effect of impedance change on design parameter is given in Table VII. With the increase in impedance, the leakage flux and stray losses will increase, however the short circuit forces will be lower. On the other hand, lowering the impedance causes reduction in leakage flux and increase in short circuit forces. Such variations will impact the overall material cost as reflected in Fig. 4 and Table VII.

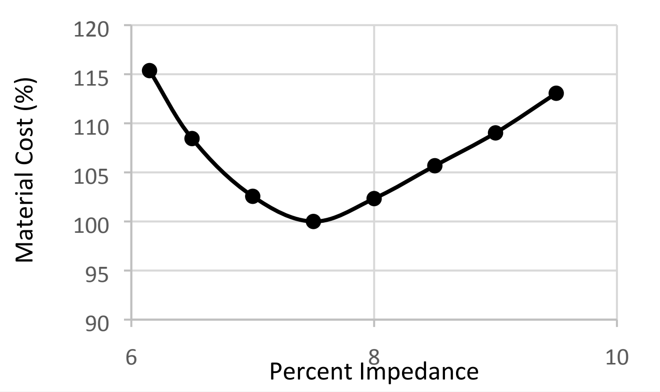

Fig. 4 Impedance Versus Cost

TABLE VII
EFFECT OF IMPEDANCE ON DESIGN AND COST

%Z	Leakage flux & Stray Losses	SCF	Order of Magnitude Cost factor
+15	↑↑↑	↓↓↓	1.07 X
+10	↑↑	↓↓	1.04 X
+7.5 %	↑	↓	1.03 X
Standard impedance	Reference point		1.00 X
-7.5 %	↓	↑	1.03 X
-10%	↓↓	↑↑	1.06 X
-15%	↓↓↓	↑↑↑	1.11 X

V. TAP CHANGER TYPE AND LOCATION

As per the IEEE C57.12.10, DETC will be provided as standard accessory unless an OLTC is specified by the user. Typically, an OLTC may be required for the utility transformer to regulate the voltage levels on the MV buses within the facility. This can be validated based on system studies (load flow and motor starting). For large motor starting, the operator can temporarily boost the pre-start bus voltage by adjusting the OLTC tap and then restore the bus voltage following successful motor start. If the utility transformer is provided with an OLTC or in the case of onsite generation connected to the MV bus where the generator voltage can be controlled, it is not necessary to provide OLTC for other substation power and distribution transformers. Sometimes for three-winding transformers, an OLTC may be provided on each LV winding to achieve better regulation for the respective load bus. However, due to higher currents on the LV side, it may be necessary to provide a separate series transformer when the current exceeds 2500 A which will significantly increase the cost and complexity. The most economical solution is to provide the OLTC on the neutral end of Wye connected HV winding. In case of Delta connection, a split HV winding may be provided with the OLTC in the middle to reduce oscillations and stresses. Refer to paper presented in 2019 PCIC conference [1] for more information on the selection and location of OLTC.

VI. FACTORY ACCEPTANCE TESTS (OTHER THAN ROUTINE)

The IEEE C57.12.00 identifies routine, design and other tests for distribution transformers, Class I power transformers and Class II power transformers. Tests identified as “other” is to be specified as needed by the end user. Some of the key tests in this category are described below:

A. Temperature Rise Tests at Minimum and Maximum Ratings

This is a design test for the first unit of a new design. When the user specifies this test on additional transformers (substation power, Utility and GSU application), it is recommended to have the shutdowns for hot resistance measurements on all three phases at the maximum rating and determine the winding temperature rises to identify the hottest phase. For testing at the minimum rating, the shutdown and measurements are not required on every phase and can be limited to the hottest phase. Temperature rise tests are time consuming and reducing the number of shutdowns can help reduce the overall duration of the FAT. Thermal imaging during the temperature rise test provides a good visual indication of hot spots and localized tank heating. For large units such as GSU transformer and Utility transformer, it may be worthwhile performing the test on every unit even if it may be a duplicate design.

B. Short Circuit Capability

Unless specifically required by the end user, it not common to require a short circuit test. Generally, the manufacturer can provide calculation/ simulation to demonstrate the short circuit withstand capability of the unit. Type test reports of similar unit (from standpoint of BIL and core/coil construction) may also be available and can be requested by the user.

C. Lightning Impulse Test

Typically, it is not necessary for distribution transformers unless there are overhead distribution lines within the facility. Substation power transformers, utility transformer and GSU transformer are good candidates for the lightning impulse test.

D. Switching Impulse Test

This test is standard for transformers 345 kV and above. It is recommended at lower voltages (69 kV and above) if the transformer is directly connected to Gas Insulated Switchgear (GIS). Typically, it is performed after the lightning impulse tests are completed.

E. Sweep Frequency Response Analysis (SFRA)

This test is an important tool to identify any shifting or movement internal to the tank during transportation. An initial test is done in the factory and serves as a fingerprint to which subsequent results can be compared in the field. If the transformer will be shipped without the fluid, it is best to perform the test in shipping configuration as well as completely assembled configuration with fluid. It is usually not necessary for smaller distribution transformers or substation power transformers up to 15 MVA. Above 15 MVA, it can be considered and is strongly recommended for critical applications such as Utility and GSU transformer.

F. Partial Discharge Measurements

PD measurements are done at the end of the induced voltage test. It is a routine test for Class II power transformers 69kV and above. This test is useful to detect breakdown of the dielectric that could lead to insulation failures when the unit is placed in service. It is usually not measured for distribution class transformers and is recommended for substation power, Utility and GSU transformers.

G. Dielectric Frequency Response (DFR)

DFR test can be performed for liquid filled transformers to detect the condition of the solid and liquid insulation and contaminations in liquid insulations. The IEEE C57.161 provides guidance regarding the application, test configuration and interpretation of the results. This is an optional test that provides additional information regarding moisture content and user can evaluate based on criticality of the application. More common method in the field is dew point measurement.

VII. MISCELLANEOUS ITEMS

Active part design has not changed over the years, but there are innovations related to on-line monitoring and bushing technology that is helping to improve the life of the transformer.

A. Online monitoring

Online monitoring of transformers allows for better trending and continuous monitoring of key parameters in between the periodic sampling (typically every 6months to a year) and offsite analysis of the insulating fluid. Such monitoring in real time greatly enhances the ability to identify any warning signs of transformer failure and take corrective action in a timely manner. Below are some of the methods that can be seen for larger and critical applications:

1. Hotspot temperature monitoring of winding and core temperatures with fiber optic sensors can reveal the temperatures at various locations inside active part. This can be used to estimate the performance of unit with variation in load and the ageing rate of the transformer.
2. Dissolved Gas Analysis (DGA) monitoring to detect fault gases generated due to field condition, stray gassing and overheating from loading. This can also include loss of life tracking, moisture in insulation and oil. DGA monitor can help in enabling condition-based maintenance plan to extend the transformer life. Single gas monitoring (H_2 gas + moisture content) can be considered for smaller transformers whereas more comprehensive multi-gas monitoring can be considered for larger transformers.

3. Bushing monitoring system to monitor the condition of the power factor and capacitance to detect the partial discharge activity. Change in bushing capacitance during its life can be compared with name plate capacitance to determine the bushing condition.

B. Bushings

Bushings have progressed in its construction in last few decades. Some of the developments include ester impregnated bushings and resin impregnated synthetic bushings.

VIII. RATING AND APPLICATION BASED SPECIFICATION

In this paper, common requirements for specification by end user was reviewed. The Table VIII below summarizes the recommendation for various specification parameters based on rating and application.

TABLE VIII
RECOMMENDATIONS

Parameter	**Distribution**	**Substation Power**	**Utility**	**GSU**
Insulating Fluid	Mineral Oil or Natural Ester	Natural Ester	Natural Ester up to 100 MVA and 750 kV BIL; Mineral Oil above 100 MVA	
Preservation System	Sealed Tank	Sealed Tank	Sealed Tank up to 10 MVA; Sealed Tank or Conservator Tank above 10 MVA and up to 50 MVA; Conservator Tank above 50 MVA	
Tap Changer	DETC on HV Side	DETC on HV Side	DETC or OLTC on HV Side	DETC on HV Side
BIL	Standard	Standard	Standard or enhanced	Standard
Winding Config	Dyn1	Dyn1	Dyn1	Yd11
Winding Type	HV: Layer, LV: Sheet	HV: Disc LV: Helical or Disc	HV: Disc, LV: Helical	HV: Disc, LV: Helical with CTC
Core Flux Density (T)	1.65 to 1.73	1.65 to 1.73	1.65 to 1.73	1.6 to 1.68
Impedance	Standard	Standard	User Specified	User Specified
Factory Acceptance Test	Routine	Routine + Lightning Impulse +SFRA above 15 MVA	Routine + Lightning Impulse + Switching Impulse + Temp Rise (with thermal imaging) + SFRA	Routine + Lightning Impulse + Temp Rise (with thermal imaging) + SFRA
Online Monitoring Devices	Typically, not specified	DGA monitoring, for critical applications	DGA Monitoring + Bushing Monitoring	DGA Monitoring

IX. CONCLUSION

The paper provides guidance for the user to select and specify options/ parameters for transformers used in process facilities based on the type of application and rating. Cost impacts due to various options was also discussed to aid the user to make decisions when developing the specification. Such consideration can help avoid overspecification for non-critical applications while ensuring that the larger transformers or critical applications are not compromised.

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XI. VITAE

Shankar Nambi received his B.S. in Electrical Engineering from the University of Mumbai and M.S. in Electrical Engineering from Clarkson University. He has over 23 years of engineering experience and has worked on several projects in Oil & Gas, Mining & Metals and Power Generation. He is a registered Professional Engineer in the States of Texas and Maryland. He is also a member of the IEEE PES Transformer Code Committee. He is currently working with Bechtel Energy, Inc. as an engineering supervisor and specializes in transformer applications.

Balakrishnan Mani has received his B.E in Electrical and Electronics Engineering and Master's in High-Voltage

Engineering from Anna University, Chennai, India. He worked with KNR Engineers and Consultants in Chennai, India on transient analysis of gas insulated substations for two years before joining Virginia Transformer. Since 2011, he has served as a product development engineer, leader and currently working as Product Development Manager. His expertise includes 3D and 2D finite element analysis of static devices, design, development and testing of large power transformers. He works on various FEA programs for electromagnetic analysis and electrostatic stress analysis and its validation.

John K John received his B.S with Honors in Electrical Engineering from University of Kerala and Post Graduate Diploma in High Voltage Engineering from College of Engineering, Guindy, Madras (now Chennai). He has over 45 years of experience in Transformer Industry, including initial training from Hitachi, Japan on High voltage Transformers. He joined Virginia Transformer in 1993 and currently the Corporate Director of Engineering & Development of Virginia/Georgia Transformer. John is a senior member of IEEE and active IEEE Transformer Committee member.