APLICATION GUIDELINES FOR DRY-TYPE DISTRIBUTION POWER TRANSFORMERS

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Abstract **- A large number of distribution transformers, currently utilized in low voltage (LV) power systems are of dry-type design. This includes, the IEEE Class II ventilated dry-type design with 3-phase kVA ratings in the approximate range of 500 kVA - 2.5 MVA and primary voltage ratings ranging from 4.16 kV to 34.5 kV and the secondary voltage ratings of 600 V and below. This paper presents a comprehensive review of dry-type transformers design and provides some application guidelines including insulation system characteristics; BIL; losses, overloading, and loss-of life; and price.**

Keywords: ***Distribution Transformers, Low Voltage Power Transformers, Cast-Coil Design and Dry-Type Transformer***

I. INTRODUCTION

In the 1930's, the dry-type distribution transformers for indoor applications that met the fire-resistant requirement were built with Class B (130°C) insulation. Many dry-type transformers during the 1950's, instead, used Class H (180°C) insulation for operation at higher temperatures. Since, air has a poor dielectric strength and thermal conductivity, these transformers were sealed in nitrogen gas to increase operating voltage and cooling efficiency. The ventilated dry-type transformers with 150°C *winding temperature rise* (or 220°C *absolute temperature* and Class C insulation) were also introduced in the same period.

In the 1990's and at present, dry-type transformers are safe, reliable, cost effective, and have low maintenance cost and fire risk. In many commercial and industrial (C&I) applications, they are replacing liquid-filled transformers (primary voltages up to 34.5 kV and ratings up to 2.5 MVA are very common). These applications include power plants, utilities, hospitals, schools, multi-story buildings, paper and steel mills, mining, oil and gas refineries, chemical plants and subway system.

It is to be recognized here, that electric utilities own about 90% (~ 40 million) of all liquid-filled distribution transformers. Dry-type transformers, on the other hand, are primarily utilized by the commercial and industrial (C&I) customers (~12 million). The common secondary voltages are 277/480 V (3-phase, 4-wire, grounded Y) or 120/208 (3-phase, 4-wire, grounded Y) or 120-240 V (1-phase, 3-wire).

Utilities, for the most part, have already established their own loss evaluation criteria[1][2] *(popularly called the Total Owning Cost or "TOC" method and identified by "A" and "B" factors)* before buying their transformers. With the introduction of improved materials and manufacturing techniques, as a result, *utility-owned* distribution transformer efficiencies have steadily improved from the 1950's to the 1990's. Manufacturers responded by tailoring their products to the *energy evaluation factors* specified by customers, a practice that continues to this day.

Electrical contractors or agents (who are not the users and paying for the electricity bills), on the other hand, are currently responsible for most C&I purchase of dry-type transformers. As such, most of the *non-utility* distribution transformers, contrary to the utility owned units, are purchased on the *lowest first-cost basis* without evaluating the cost of energy consumed by the units. Thus non-evaluated transformers may have as high as ~ 50% more losses than the utility owned transformers.

A cursory examination of the energy efficient transformer industry suggests that manufacturers of dry-type transformers will be more affected than manufacturers of liquid-filled transformers because greater number of dry-type transformers are not currently loss evaluated.

II. TRANSFORMER CORE AND COIL CONSTRUCTION

Core: In standard dry-type transformer design, *Core* is usually cut from high permeability *cold-rolled-grain-oriented silicon steel,* with the high-resistance, inorganic *coating put onto the steel during the manufacturing* process. Since, air has poor thermal conductivity, large clearances and cooling ducts are required for dry-type transformers than compared to the liquid-filled transformers. This then causes the core windows and also the cores of dry-type transformers larger than the corresponding oil-filled transformers of equivalent rating. The larger coil, which results from larger core size, also implies a higher leakage reactance. In order to keep the reactance down, the volt/turn (or the core flux) is generally assumed lower in this design. The maximum flux density, in a dry-type transformer, is typically adjusted between 1.5-1.6 T (Tesla) by core loss, leakage reactance, and noise level, compared to approx. 1.8 T for liquid-filled transformers.

Since the introduction of the *amorphous core* about 15 years ago, the trend of using silicon steel core in case of dry-type transformers has changed. Typical amorphous alloy compositions used for transformer cores contain about 80% iron and 20% of a mixture of metalloids, such as, boron and silicon. The amorphous core substantially reduces the core loss (by 41%) and the magnetizing current (by 87%), compared to the standard laminated silicon steel core design. At 60 Hz, the core loss of an amorphous material is less than 0.2 W/kg at 1.4 T, which corresponds to 30% of the core loss of an M-2 steel core. Also saturation of the amorphous core material occurs at about 1.58 T, which is less than the saturation point of silicon steel. Table I compares core losses in silicon steel core v. amorphous core of typical distribution transformers.

Table I
Comparison of Core Losses in Silicon Steel Core and Amorphous Core of Typical Distribution Transformers

Rating (kVA)	Core Losses (Watts)	
	Silicon Steel Core	Amorphous Core
500	1,900	510
750	2,700	700
1,000	3,400	850
1,500	4,500	1,125

Note: Core losses can vary widely by designs.

Coil: In distribution transformer design, *low voltage (LV) windings* are usually placed nearest to the limb of the core. This is a result of common practices in which the core is grounded and taps are provided for voltage regulation. As a practical matter, the LV winding indeed is easier to insulate from the ground core. The *high voltage (HV) windings* are then placed concentrically around the LV winding. The taps that are provided are usually connected to the HV winding (much simpler design). Most transformers have circular coils. However, LV windings can be constructed as sheet windings in a spiral form or disc windings.

A detailed discussion of the selection of *conductor materials (copper v. aluminum)* is beyond the scope of this paper. Among others, the three most important issues that are considered include resistivity (or conductivity), coefficient of thermal expansion (and contraction) due to temperature variation and the corresponding insulation cracking and loss-of-life evaluation during overloading and loading cycle, and the cost. There are pros and cons to the use of either copper or aluminum. As such, both materials are widely used in dry-type transformer winding design and it is a choice to be made (primarily based on cost) by the purchaser of the transformer.

III. TRANSFORMER CLASSIFICATION AND COST COMPARISON

Dry-type transformers are classified into the following *five categories* by their insulation potting process:

- The *Standard Dip and Bake* unit has the coils dipped in varnish tank under atmospheric pressure. The maximum operating temperatures range from 105°C (Class A) to 180°C (Class H) depending on the resin material.
- The *Vacuum Pressure Impregnation (VPI)* units have become the standard for use in normal applications, indoor or outdoor. The VPI units are constructed with 220°C (Class C) materials.
- The *Vacuum Pressure Encapsulation (VPE)* units are also constructed with 220°C (Class C) materials and are given additional environmental protection by means of a vacuum pressure encapsulation of silicone resin.
- The *Encapsulated (Sealed)* unit adds few additional steps beyond VPE process (thicker coating) to ensure total sealing.
- The *Cast-Coil* unit has the coils encapsulated in epoxy by molding process. Due to maximum temperature limit of 200°C on premium type epoxy, the 150°C temperature rise units (220°C hot-spot temperature) are not available in cast-coil design.

Dry-type transformers are generally self-air-cooled (AA). Cooling fans increase the forced-air rating (FA) to 133% of the self-cooled rating for standard ventilated dry-type design and between 140-150% for encapsulated- and cast-coil unit.

Many manufacturers consider distribution transformers of these ratings and voltage to be more "standardized" and consequently the market is fairly price competitive. The ability to customize the design of each transformer is greatly assisted by the improved transformer design programs and computing power of present day workstations. Price increases from the cheapest dip-bake type to the most expensive cast-coil design. The VPI-unit prices are equivalent to the most expensive silicone-filled transformers.

Table II provides a (typical) price comparison for some commonly used distribution transformers. Present prices of amorphous core transformers are about 25 to 30% greater than those of comparable silicon steel core transformers. In 1997 amorphous core costs were about US $ 1.50 per pound compared to the silicon steel costs ranging from US $ 0.70 - $ 1.15 per pound with the variation depending on the grade or quality of the silicon steel. Following the Total Owning Cost (TOC) method of loss evaluation technique[1][2], at present, the typical pay off period for more expensive amorphous core transformers is between 4-8 years.

Table II
Price Comparison (13.8 kV- 480/277V Transformer)

Description	kVA 500	kVA 1000	kVA 2000	Average $/kVA
Oil fill 65°C	$12,500	$15,000	$22,000	14.1
R-Temp 65°C	$15,000	$18,000	$24,000	16.3
Silicone filled 65°C	$17,500	$21,000	$30,000	19.6
VPI 150°C	$15,000	$20,000	$30,000	18.6
VPE 150°C	$18,000	$23,000	$36,000	22
Fully Cast Coil 80°C	$37,000	$46,000	$64,000	42

Note: The first three rows are for liquid-filled transformers.

IV. INSULATION CHARACTERISTICS AND BIL

The two most important properties that determine the insulation quality, the corresponding transformer life, and the reliability are the absolute temperature limit and the impulse withstand capability.

- The insulation and its temperature limit is normally designated by Letter Code O, A, B, F, H and C. Insulation class may also be specified by the limiting temperature in degree Celsius (°C) rather than a letter, an IEC practice. Table III shows the insulation class letter code and its temperature limitation as defined by the ANSI/IEEE Standard.

Table III
Insulation Class Classification by Letter Code and Its Temperature Limit

Insulation Class	Limiting Absolute Temperature °C
O	90
A	105
B	130
F	155
H	180
C	220

Most commonly used dry-type transformers are available in three different designs with *average winding temperature rise* of 80°C (Class F), 115°C (Class H) and 150°C temperature rise (Class C). The 150°C temperature rise (Class C) design is the standard for most manufacturers regardless of the actual winding temperature rise. Transformers manufactured with temperature rise specified at 80°C and 115°C are designed for energy saving purpose at premium price. This also allows transformers to operate at high temperature and kVA rating with higher load loss.

- Basic Impulse Insulation Level (BIL) capability is one of the key issues that need to be addressed in the proper applications of dry-type transformers. Some manufacturers readily recommend that users should apply better surge protection for dry-type transformers. Standard BIL level values and optional BIL levels are available in IEEE C57.12.01-1998 Table 4[3] (also reproduced below). The BIL of VPI / VPE ventilated dry-type transformers is generally lower than that of the oil-filled transformer of the same voltage rating. However, the BILs of encapsulated- and cast-coil transformers are comparable to the oil-filled counterparts. The BILs of dry-type VPI and VPE transformers can be increased to equivalent liquid-filled transformer BILs with typically 10-15% unit price increase for primary voltages 15 kV and below. When transformer BIL is increased, normally the size and weight are increased, and both no-load and load losses are increased slightly. Table IV, which is self-explanatory, provides the BIL comparison (both standard and optional) of the dry-type transformers with the standard oil-filled design.

Table IV
Comparison BIL Rating in kV[3]

Nominal Voltage (kV)	Ventilated Dry-type (kV) Std.	Ventilated Dry-type (kV) Option	Encapsulated Cast Coil (kV) Std.	Encapsulated Cast Coil (kV) Option	Std. Oil-Filled Std.	Std. Oil-Filled Option
1.2	10	20, 30	10	30	30	45
2.5	20	30, 45	45	60	45	60
5.0	30	45, 60	60	75	60	75
8.4	45	60, 95	75	95	75	95
15.0	60	95, 110	95	110	95	110
25.0	110	125, 150	125	150	150	-
34.5	150	200	150	200	200	-

V. OVERLOADING AND LOSS-OF-LIFE

Manufacturers commonly state that certain transformer types (e,g. solid-cast winding) can be overloaded for short periods with no loss, or limited loss-of-insulation life. When comparing installations for transformers loaded within their nameplate rating and for transformers loaded in excess of their rating, it may be difficult to obtain equivalent reliability.

The cumulative life of insulation is primarily dependent on the operating hottest-spot temperature and the corresponding duration. This relationship is given by the Arrhenius Reaction Rate Theory. Figure 1 from reference [4] depicts these insulation life characteristics for the three major insulation classes (F, H, and C). Table V also provides the information on the allowable average winding temperature rises, the corresponding hot-spot allowances and the maximum temperature limit.

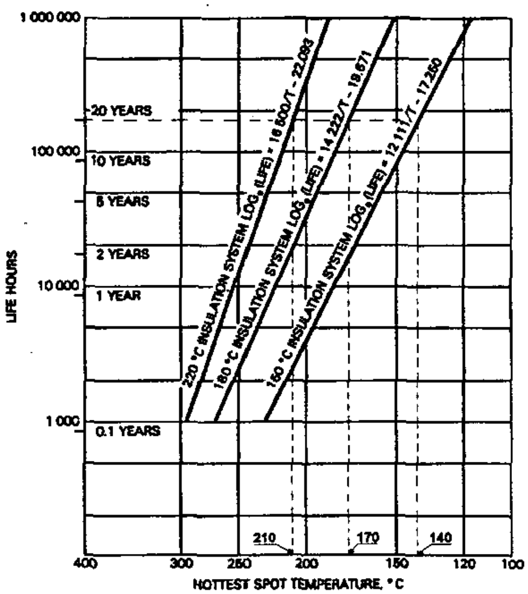


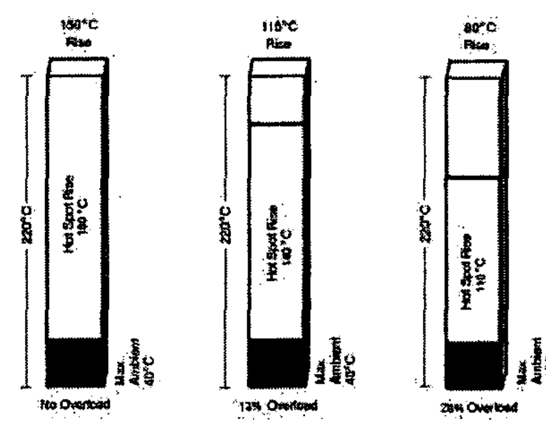
Figure 1. Life Expectancy Curve[4]

Table V[4]
Insulation Class and Hottest-Spot Temperature

Insulation Class (°C)	Avg. Winding Temp. Rise (°C)	Hottest-spot Temperature @30°°Ambient
150 (F)	80	140
180 (H)	115	170
220 (C)	150	210

IEEE standard C57.96-1999[4] gives the recommendation for the overloading capability of dry-type transformers having impregnated insulation systems that have 80°C (Class F), 115°C (Class H) and 150°C (Class C) average winding temperature rises. It also provides methods to calculate the estimated loss-of-life for hottest-spot profile for such dry-type transformers, whereas, the Annex A applies to solid-cast and/or resin-encapsulated epoxy windings.

According to Figure 1, for Class C (220°C) insulation, if the transformer is running on a continuous basis at the hottest-spot temperature, the insulation life expectancy is approximately 10 years. However, in reality, the transformer doesn't run at full-load for its entire life due to the varying load cycle. Running at a reduced load extends the life expectancy. The normal life of transformers is estimated between 20-30 years. Presently, most manufacturers use the 220°C insulation system as a standard design practice even if the average winding temperature rise is below 150°C. The use of 220°C insulation system allows 80°C and 115°C average winding temperature rise transformer capacities to increase by 13% and 28% respectively from the self-cooled rating. With addition of cooling fans the capacities can be increased by an additional 33% from the new self-cooled ratings. This practice normally allows for the growth and available overloading capacity. This overloading capacity of such designs has been graphically depicted in Figure 2.



Avg. Winding Temp. Rise	Overload Rating w/o Fans	Overload Rating w/ Fans
150°C	100%	133%
115°C	113%	150%
80°C	128%	170%

Figure 2. Overloading Capability of Transformer with 220°C Insulation System

According to the IEEE Standard[4], the absolute winding hottest-spot temperature is the sum of the ambient temperature, and the hottest-spot temperature rise and is given by the equation (1).

$$\theta_{hs} = \theta_a + \Delta\theta_{hs} \quad (1)$$

where; θ_{hs} = hottest-spot temperature, θ_a = ambient temperature (30°C) and $\Delta\theta_{hs}$ = hottest-spot temperature rise.

The hottest-spot temperature rise is directly related to loading. For continuous overload, it can be calculated as follows:

$$\theta_{hs} = \theta_a + (\Delta\theta_{hs,r})\,K^{2m} \qquad (2)$$

where, subscript r denotes rated loading, $\Delta\theta_{hs,r}$ = hottest-spot temperature rise at rated load (110°C, 140°C and 180°C for 150°C, 180°C and 220°C Insulation Class, respectively) and K is the loading in per-unit, and m is the empirical constant: m = 0.8 for self-cooled, m = 1.0 for forced-cooled, and m = 0.7 for sealed self-cooled design.

The concept of using a constant hottest-spot allowance (Figure 3) value of 30°C allowance at rated loading for all insulation classes (F, H and C) as mentioned in the previous revision of IEEE standard has been superseded by the use of hottest-spot temperature rise over ambient, $\Delta\theta_{hs}$. The hottest-spot temperature rise can be found from:

$$\Delta\theta_{hs} = \Delta\theta_w + \Delta\theta_g \qquad (3)$$

where; $\Delta\theta_w$ = average winding temperature rise, and $\Delta\theta_g$ = hottest-spot allowance. According to the new standard, the hottest-spot allowances are 30°C, 25°C and 30°C for 80°C, 115°C and 150°C average winding rise unit, respectively.

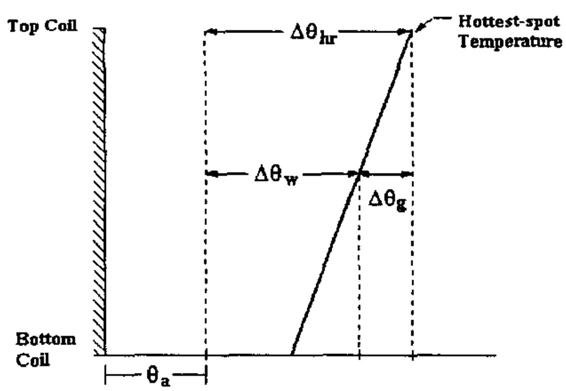


Figure 3. Temperature Gradient

It has been known for quite sometime form experience that the hottest-spot allowance ($\Delta\theta_g$) varies with coil-length, duct-width and average winding temperature rise ($\Delta\theta_w$). Pierce's[10][11][12] investigations for higher average winding temperature rise (150°C or Class C insulation) show similar results. It also revealed that the assumption of a single constant 30°C hottest-spot allowance in ANSI/IEEE standard is not accurate and shall be revisited. In his experiments, the hottest-spot temperature exceeds permissible 220°C limit due to large winding thermal gradients.

Based on the detail experimental results, Pierce proposed to eliminate the 115°C and 150°C average winding temperature rise class and instead, added a new 120°C temperature rise class with 60°C hottest-spot allowance. This will then reduce the insulation system to only two classes, as summarized in Table VI.

Table VI
Proposed Limits of Temp. Rise 220°C Insulation Class

Average Temp. Rise (°C)	Hottest-spot Allowance (°C)	Hottest-spot Temperature (°C)
80	30	150
120	60	220

If this proposal is accepted, the cost of dry-type transformer may increase and the loading capability of the existing 150°C transformer has to be reduced by 13% to accommodate the new 120°C average temperature rise criteria.

VI. NOISE LEVEL

Higher transformer noise caused by *magnetostriction* is an unwanted characteristic of the dry-type design. Dry-type transformers are commonly used indoors, and thus the transformer generated noise is an important consideration and has to be suppressed to an acceptable level. This can be achieved by reducing the core flux density, which will increase the transformer cost. Another simple method for noise reduction is to put thick wall to attenuate the noise. Magnetostriction does not only produce air borne noise but also vibration. The vibration can be reduced by isolating core and coils from the fixed support structure with vibration isolation pads and using flexible low voltage and high voltage connections.

As per NEMA standards, liquid-type transformers (with no force air cooling) are about 5 to 6 dB quieter compared to the air-cooled transformer.

VII. CONCLUSIONS

Numerous designs (temperature rise and BIL) of dry-type transformers are available today. End-users have to understand their characteristics and buy the transformers that best fit their applications. The dry-type transformer is safer to be installed in building (NEC Art. 450-23) and has low maintenance cost. Other than cleaning dust and dirt accumulation from the core coils and bushings, dry-type transformers normally require very little maintenance. The environmental condition, price and reliability determine the selection of transformer type. The VPI units work well under harsh service condition. The VPE units are doing well in heavy moisture outdoor locations. The cast coil units can be subjected to severe load cycles, short circuit and exposure to harsh climates.

There are some additional considerations (not discussed in this paper) that should be taken into account during the selection process. This includes maintenance, short-circuit capacity, enclosures and accessories, testing requirements, effects of non-linear loads producing harmonics and service conditions. This paper has presented some basic information regarding various aspects of dry-type transformer and provides some application guidelines.

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