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Altitude Correction Factor for Oil Immersed and Dry Type Transformers as Per IEC and IEEE Standards

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ABSTRACT: Equipment designed and applied in North America follows ANSI/IEEE standards whereas the same equipment when designed and applied in Europe follows IEC standards. Requirement for altitude correction arises due to variation in air density (temperature and pressure) and humidity at an altitude greater than 1000m above mean sea level. Failure to understand importance of altitude correction while selecting electrical equipment may result in temperature rise, insulation deterioration, aging, and even failure of the selected equipment. This report aims to provide a study of the important attributes along with their necessities as they play an important role in determining the altitude correction factors of Oil Immersed and Dry Type Transformer as per IEC and IEEE standards. An effort has also been made to make specific comparison with respect to some of the transformer attributes amongst IEC & IEEE and a very high level comparison summary may be found in the concluding section.

KEYWORDS: Altitude correction factor, Oil and Dry type transformer,Density, Temperature rise, Dielectric strength.

I.INTRODUCTION

Requirement for altitude correction arises due to variation in air density (temperature and pressure) and humidity at an altitude greater than 1000m above mean sea level. Failure to understand importance of altitude correction while selecting electrical equipment may result in temperature rise, insulation deterioration, aging, and even failure of the selected equipment.

EFFECT OF ALTITUDE ON PRESSURE, TEMPERATURE, HUMIDITY and DENSITY**:** As altitude increases, air becomes thinner and density reduces. Air is comprised of various particles which have different mass and hence exerts different weights in the direction of the earth's surface because of the gravitational pull from the earth. As pressure is force per unit area, it turns out that the number of particles in air at a particular altitude is lesser than the number of air particles at a relatively lower altitude in a unit volume of air and hence pressure on air particles reduces with increasing altitude. Relationship between density, pressure and temperature is given below:

$$\mathbf{P = R\ r\ T}$$

Where, **P** is pressure, **r**is density, **T** is temperature and **R** is the specific gas constant. For dry air, R is 287 J K^{-1} kg^{-1}.

This very important relationship is known as the Equation of State. This simply says that the air density is directly proportional to pressure. Therefore, for any given temperature, as pressure decreases, so does the air density. Worthwhile mentioning, that though temperature decreases with reductions in pressure, a decrease in temperature actually has the opposite effect on density, since density and temperature are inversely proportional to each other.This effect however is outweighed by the pressure-density relationship, and as pressure decreases with height, so does air density.

As altitude increases, air becomes thinner and less dense due to the increase in the concentration of water vapour in the air that making the air humid. This reduces the density of the air. Most of the air is made up of nitrogen molecules N_2, a somewhat lesser amount of oxygen O_2 molecules and some other molecules including water vapour. Since density is weight divided by volume, we need to consider the weight of each of the molecules in the air. Nitrogen having an atomic weight of 14, an N_2 molecule has a weight of 28 units. As the atomic weight of oxygen is 16, an O_2 molecule has a weight of 32 units. The molecular mass of air would be around 29.Considering water molecule, H_2O with hydrogen having an atomic weight of 1 approximately and oxygen having an atomic weight of 16.It is very evident that a water molecule weighs lighter than a nitrogen molecule, an oxygen molecule, and air. Therefore a given volume of air containing water molecules would weigh lesser than the same volume of air without any water molecules. Again for any gas, at a given temperature and pressure, the number of molecules present is constant for a particular volume. As such, when water molecules (vapour) are introduced in air, equivalent number of molecules reduces, without the pressure or temperature increasing. As the mass per unit volume of the gas decreases, therefore the density reduces. So combining all of these, there is a reduction of air density at high altitude.Reduction in air density has a deteriorating effect on the insulating as well as heat dissipation property of air.

II.ALTITUDE CORRECTION REQUIREMENT FOR OIL IMMERSED TRANSFORMER

- **IMPACT ON TEMPERATURE RISE LIMIT AND KVA OUTPUT DUE TO HIGHER ELEVATION:**

As per IEC 60076-2,the temperature rise limits given in Table (A) below are valid for transformers with solid insulation designated as Class A (105 °C) according to IEC 60085and immersed in mineral oil or synthetic liquid with a fire point not above 300 °C. Limits refer to steady state conditions under continuous rated power and 20 °C average yearly temperature of the external cooling medium are valid for both Kraft and upgraded paper.

Table (A)

Requirements for	Temperature rise limits (K)
Top insulating liquid	60
Average winding (by winding resistance variation): (a) ON… and OF… cooling systems (b) OD cooling system	 65 70
Hot-spot winding	78

If the temperature of the external cooling medium at site exceeds one or more of the normal service condition given in IEC 60076-2, all the temperature rise limits indicated in Table (A) shall be corrected by the same amount. The obtained values shall be rounded off to the nearest whole number of degrees Kelvin.

As per IEC 60076-2,if the installation site is more than 1,000 m above sea-level but the factory is not, then the allowable temperature rises during the test in the factory shall be reduced as follows:
(a) For a naturally cooled transformer, the limit of top-liquid, average and hot-spot winding temperature rises shall be reduced by 1 K for every interval of 400 m by which the installation's altitude exceeds 1,000 m.
(b) For a forced-cooled transformer, the reduction shall be 1 K for every 250 m exceeding 1,000 m.
Any altitude correction shall be rounded to the nearest whole number of degrees kelvin.

As per IEEE C57.12.00 & IEEE C57.91,the average winding temperature rise,the maximum (hottest-spot) winding temperature rise above ambient temperature at rated kVA and the top insulating liquid temperature rise above ambient temperature for a particular combination of connections and taps as specified in IEEE C57.12.00 is indicated in Table (B) below.

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Table (B)

Requirements for	Temperature rise limits (ºC)
Top insulating liquid	65
Average winding	65
Hot-spot winding	80

Maximum allowable average temperature of cooling air for carrying rated kVA at higher altitude as specified in IEEE C57.91is given in Table (C) below. As such, it may be seen that the temperature rise limits have not been de-rated. Instead the ambient cooling air average temperature has been reduced considerably to take care of the lower heat dissipation.

Table (C)

Method of cooling apparatus	1000 m / 3300 ft.	2000 m / 6600 ft.	3000 m / 9900 ft.	4000 m / 13200 ft.
Liquid-immersedself-cooled	30	28	25	23
Liquid-immersedforced-air-cooled	30	26	23	20
Liquid-immersedforced-oil-cooledwithoil-to-aircooler	30	26	23	20

As per IEEE C57.91, transformers may be operated at altitudes greater than 1000 m (3300 ft.) without exceeding normal temperature limits, provided the load to be carried is reduced below its rating by the percentages as given below in Table (D) for each 100 m (i.e. 330 ft.) above 1000 m (i.e.3300 ft.).

Table (D)

Types of cooling	Derating factor % per 100m (330 ft.)
Liquid-immersedair-cooled	0.4
Liquid-immersedwater-cooled	0.0
Liquid-immersedforced-air-cooled	0.5
Liquid-immersedforced-liquid-cooledwithliquid-to-aircooler	0.5
Liquid-immersedforced-liquid-cooledwithliquid-to-water-cooler	0.0

- **IMPACTS ON CLEARANCES AND DIELECTRIC WITHSTAND CAPABILITY DUE TO HIGHER ELEVATION:**

As per IEC 60076-3,if the transformer is specified for operation at an altitude higher than 1,000 m, the clearance requirements shall be increased by 1 % for every 100 m by which the altitude exceeds 1,000 m. These clearance details are specified in Table 5, 6 and 7 of IEC 60076-3 and the specifics of the clearances corresponds to:
(a) Clearance phase-to-earth and phase-to-neutral;
(b) Clearance phase-to-phase between phases of the same winding;
(c) Clearance between a line terminal of the high voltage winding and a line terminal of a lower voltage winding.

It follows from the above that the recommended values in IEC 60076-3 are in effect minimum values. The design clearances shall be stated on the outline drawing. These are nominal values subject to normal manufacturing tolerances and they have to be selected so that the actual clearances will be at least equal to the specified values.

IEEE C57.12.00 Table 10 contains the minimum external clearances between transformer live parts of different phases of the same voltage. The mentioned external clearances indicated however are applicable to transformers intended for operation at altitudes of 1000 m (3300 ft.) or less. For operation at altitudes in excess of 1000 m, the external clearances shall be increased to compensate for the decrease in spark over voltage at the rate of 1% per 100 m (330 ft.) increase in altitude in excess of 1000 m (3300 ft.).
The dielectric strength of transformers is dependent on air for insulation and as such decreases as the altitude increases due to the effect of decreased air density. As per IEEE C57.12.00, for altitudes above 1000 m (3300 ft.)transformers shall be designed with larger air spacing between terminals using the correction factors of Table (E) to obtain adequate air dielectric strength. The minimum

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insulation necessary at the required altitude is calculated by dividing the standard insulation level at 1000 m (3300 ft.) by the appropriate correction factor from Table (E) given below. Accordingly the correction factors needs to be applied on the Dielectric Insulation Levels as indicated inTable 3 and Table 4ofIEEEC57.12.00 for Class I and Class II Power transformer respectively.

Table (E)

Altitude m/(ft)	Altitude correction factor for dielectric strength
1000/(3300)	1.00
1200/(4000)	0.98
1500/(5000)	0.95
1800/(6000)	0.92
2100/(7000)	0.89
2400/(8000)	0.86
2700/(9000)	0.83
3000/(10 000)	0.80
3600/(12 000)	0.75
4200/(14 000)	0.70
4500/(15 000)	0.67

Note - An altitude of 4500 m (15,000 ft.) is considered a maximum for transformers conforming to this standard.

This has been dealt a bit differently in the IEC world however. IEC 60076-3 does not specifically addresses any separate derating factors for calculation of Dielectric Strength. The decreased rate of heat dissipation resulting out of reduced air density is dealt with by increasing the clearances. Accordingly, is stated that when an oil immersed transformer is specified for operation at an altitude of higher than 1000mtr, clearances shall be designed accordingly and it may then be necessary to select the Bushing design for higher insulation levels than those specified for the internal for the transformer winding. Discussion on Transformer Bushings is beyond the scope of the present text and hence has not been discussed.

III.ALTITUDE CORRECTION REQUIREMENT FOR DRY TYPE TRANSFORMER

- **IMPACT ON TEMPERATURE RISE LIMIT AND KVA OUTPUT DUE TO HIGHER ELEVATION:**

IEC 60076-11 specifiesthe temperature rise of each winding of the transformer, designed for operation at normal service conditions whichare not supposed to exceed the corresponding limitsas specified therein. For ready reference, Table (F) follows.

Table (F)

Insulation system temperature °C	Average winding temperature rise limits at rated current (K)
105 (A)	60
120 (E)	75
130 (B)	80
155 (F)	100
180 (H)	125
200	135
220	150

When the transformer is designed for service where the temperature of the cooling air exceeds one of the maximum values specified in IEC 60076-11, the temperature rise limits shall be reduced by the same amount. The values shall be rounded off to the nearest whole number of K.

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As per IEC 60076-11,for transformers designed for operation at an altitude greater than 1,000 m but tested at normal altitudes depending on type of cooling, the limits of temperature rise given in Table (F) shall be reduced by the following amounts for each 500 m by which the intended working altitude exceeds 1,000 meter.
Natural-air-cooled transformers: 2.5 %;

Forced-air-cooled transformers: 5 %.

Any altitude correction shall be rounded off to the nearest whole number of K.

As per IEEE C57.12.01 and IEEE C57.96,hottest-spot temperature rise and average winding temperature rise above the ambient temperature for continuously rated dry-type transformer windings shall not exceed the limits given in Table (G) below.

Table (G)

Insulation system temperature class (°C)	Winding hottest-spot temperature rise (°C)	Average winding temperature rise by resistance (°C)
130	90	75
155	115	95
180	140	115
200	160	135
220	180	150

Since dry-type transformers are completely dependent on air for dissipation of the heat generated, the effect of decreased air density at higher altitudes is an increase in the temperature rise of the transformers which in turn takes a toll on the transformer insulation. Maximum allowable 24-hr average temperature of cooling air in °C for operation at rated kilovolt-amperes with normal loss of life under unusual altitude conditionsare given in Table (H)as specified in IEEE C57.96for different altitudes. The cooling air temperatures are based on an increase in average winding temperature rise of 0.5% for every 100 m above 1000 m altitude for natural cooling and 1.0% for forced-air cooling.An altitude of 4500 m is considered to be the highest point where a dry-type transformer may be installed IEEE C57.12.01.

Table (H)

Insulation temperatureclass AA,ANV cooling	Rated averagewinding temperaturerise °C	Cooling Air Temperature at various Altitudes			
		1000m	2000m	3000m	4000m
130	75	30	26	23	19
150	90	30	26	21	17
180	115	30	24	19	13
200	130	30	24	17	11
220	150	30	23	15	8
Insulation temperatureclass AA/FA,AFA cooling	Rated averagewinding temperaturerise °C	Altitude			
		1000m	2000m	3000m	4000m
130	75	30	23	15	8
150	90	30	21	12	3
180	115	30	19	7	-5
200	130	30	17	4	-9
220	150	30	15	0	-15

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The data included in Table (H) apply to ventilated dry-type and non-ventilated dry-type transformers only and are not applicable to sealed or gas-filled transformers.

As specified in IEEE C57.96 transformers may be operated in a 30 °C ambient at altitudes greater than 1000 m without exceeding temperature limits provided the load to be carried is reduced below rating by the percentages given in Table (I) for each 100 m that the altitude exceeds 1000 m.

Table (I)

Typeof cooling	% Deratingfactorforeach100m
Self-cooled(AA,ANV)	0.3
Forced-air-cooled(AA/FA, AFA)	0.5

- **IMPACTS ON DIELECTRIC WITHSTAND ABILITY DUE TO HIGHER ELEVATION:**

IEC 60076-11 Table 3 specifies the insulation levels (in kV) applicable totransformers intended for general power distribution in public or industrial systems.When the transformers are specified for operation at altitudes between 1,000 m and 3 000 m above sea-level, but tested at normal altitude, the rated short duration separate source AC withstand voltage shall be increased by 1 % for each 100 m above 1,000 m. Above 3000 m, the insulation level shall be defined by agreement between supplier and purchaser.

IEEE C57.12.01 specifies the standard dielectric insulation levels in Table 5. The dielectric strength of transformers depends wholly or partly on the surrounding air density. When specified for installation and/or testing above 1000 m (3300 ft.), transformers shall be designed with appropriate insulation system to meet the required dielectric insulation test level. To determine this insulation test level, altitude correction factor found in Table 1 of IEEE C57.12.01 may be used which is also added below as Table (J).
To identify the relevant Insulation test levels,when performing dielectric insulation tests, the standard dielectric insulation test level needs to be multiplied by the test correction factor, TCF.

$$TCF = \frac{\text{Correction factor at installed altitude}}{\text{Correction factor at tested altitude}}$$

For altitudes not listed below, the correction factor can be defined by interpolation of the data of Table (J). The corresponding Insulation level needs to be selected from Table 5 of IEEE C57.12.01

Table (J) —Dielectric insulation level correction factors

Altitude		Altitudecorrectionfactorfordielectricstrength
Meters(m)	Feet(ft.)	
≤ 1000	≤ 3300	1.00
1200	4000	0.98
1500	5000	0.95
1800	6000	0.92
2100	7000	0.89
2400	8000	0.86
2700	9000	0.83
3000	10000	0.80
3600	12000	0.75
4200	14000	0.70
4500	15000	0.67

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IV.CONCLUSION

- **Oil Immersed transformer**

A high level comparison of a Hypothetical Oil Filled Transformer of IEEE & IEC is given below. It may be noted that this is just for a Basic Illustration purpose and may not be considered as absolute. There are numerous criticalities and intricacies which need very detailed examination and judgement before selection of a transformer and such High level comparison may not be suitable to fit such purpose.

Oil Filled Transformer 100 MVA, 500kV / 132 kV, ONAF, Elevation 2000 meter					
Transformer Property	Comparison Attribute	Standard Value (At elevation of 1000 meter)		De-rated Value (At elevation of 1000 meter)	
		As per IEC	As per IEEE	As per IEC	As per IEEE
Temperature Rise Limits	Top insulating liquid	60^0C	65^0C	56^0C	NS Note2
	Average winding	65^0C	65^0C	61^0C	NS Note2
	Hot-spot winding	78^0C	80^0C	74^0C	NS Note2
Rating / Capacity	MVA Rating	100 MVA Note1	100 MVA Note1	NS	95 MVA
Clearance	Phase to Phase	3700 mm	3937 mm	4070mm	4331 mm Note3
	Phase to Earth	4200 mm	3937 mm	4620mm	4331 mm Note3
	Phase to Other Winding	2650 mm	3937 mm	2915mm	4331 mm Note3

NS – Not Specified
Note1: Transformer Rating Assumed
Note2: Maximum allowable average temperature of cooling Air considered being 26^0C as per IEEE C57.91
Note3: Rounded off to the next Decimal Number

- **Dry Type transformer**

A high level comparison of a Hypothetical Dry Type Transformer of IEEE & IEC is given below. It may be noted that this is just for a Basic Illustration purpose and may not be considered as absolute. There are numerous criticalities and intricacies which need very detailed examination and judgement before selection of a transformer and such High level comparison may not be suitable to fit such purpose.

Dry Type Transformer 2 MVA, 10 kV / 0.4 kV, AF, Elevation 2000 meter					
Transformer Property	Comparison Attribute	Standard Value (At elevation of 1000 meter)		De-rated Value (At elevation of 1000 meter)	
		As per IEC	As per IEEE	As per IEC	As per IEEE
Temperature Rise Limits Note4	105^0C	60^0C	-	54^0C	-
	120^0C	75^0C	-	67.5^0C	-
	130^0C	80^0C	75^0C	72^0C	67.5^0C
	155^0C	100^0C	95^0C	90^0C	85.5^0C
	180^0C	125^0C	115^0C	112.5^0C	103.5^0C
	200^0C	135^0C	135^0C	121.5^0C	121.5^0C
	220^0C	150^0C	150^0C	135^0C	135^0C
Rating / Capacity	MVA Rating	2 MVA Note1	2 MVA Note1	NS	1.9 MVA
Insulation Note2, Note3	Lighting Impulse Voltage Level	60 kV	60 kV	NS	53.4 kV

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NS – Not Specified
Note1: Transformer Rating Assumed
Note2: For the sake of simplicity and ease of comparison, Short Duration Separate AC Withstand & Low Frequency Voltage Insulation is not included
Note3: Standard exposure to Lightning and Switching overvoltage's considered.
Note4: For comparison purpose temperature rise limits given in table (F) are used.

It might seem that IEC is more Conservative in case of Oil Filled Transformers whereas IEEE is more conservative in case of Dry Type Transformers, however it must be noted that each has its very own and specific attributes. Ultimately the selection amongst of either of these depends mostly on the place of Installation, End user preferences, Certification Requirements and last but not the least, a bit of Biasness!

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