BEE CODE

TRANSFORMERS

Prepared for

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1 OBJECTIVE & SCOPE

1.1 Objective

1.1.1 The objective of this BEE Code is to establish rules and guidelines for conducting tests on electrical distribution transformers used in industrial, commercial and such other load centers at site conditions.

1.1.2 The overall objective is to evaluate the energy losses in the transformers at different operating conditions. The energy losses in a transformer consist of relatively constant iron losses and dielectric losses, and variable load losses; which vary with the load.

1.1.3 In general, matching the levels of precision of instruments available during testing at works is difficult and costly. Data from test certificates from manufacturers can be used in majority of the cases. Tests in this code are minimised and simplified so that it can be conducted by easily available instruments under site conditions.

1.2 Scope

1.2.1 This standard covers electrical power distribution transformers of single phase/three phase and oil cooled or dry type but restricted to those having secondary voltages in the L.T distribution range of 415 V/240 V. The ratings covered are 25 kVA and upwards.

1.2.2 The standards applicable for testing transformers a manufacturer's works are as under:

1. IS 2026- 1977– Specifications for Power Transformers
2. IEEE Standard C57.12.90 – 1993: IEEE Standard Test Code for Dry Type Distribution Transformers
3. IEC 60726: Dry type power Transformers
4. IEC 60076: Power transformers - general
5. IEC 61378: Converter transformers

1.2.3 Tests described in this code are as under:

1. Measurement of winding resistance
2. Measurement of no load losses
3. Measurement of load losses
4. Measurement of operating load and winding temperature

2 DEFINITIONS AND DESCRIPTION OF TERMS

2.1 Basic Units and Symbols

The basic units and symbols used in this code are given in Table-2.1. Subscripts are explained in Table –2.2.

Table 2-1: Basic Units and Symbols

Symbol	Description	Units
P	Rated output	kVA
V_1	Rated primary voltage	V
V_2	Rated secondary voltage	V
I_1	Rated primary current	A
I_2	Rated secondary current	A
Z	Impedance	p.u.
I	Line current	A
I_{nl}	No load line current	A
I_{sc}	Line current during short circuit test	A
U	Reading of true r.m.s voltmeter	V
U’	Reading of average reading voltmeter	V
V_{s1}	Applied line voltage during short circuit test	V
W	Wattmeter reading	Watts
E	Energy consumption	Wh
T	Time taken during initial and final reading of energy meter	Seconds
C_h	Ratio of hysteresis loss to total iron loss	p.u
C_e	Ratio of eddy current loss to total iron loss	p.u
T	Operating winding temperature	ºC
P_L	Total power loss at temperature T	Watts
P_{s-L}	Stray losses at temperature T	Watts
P_{cu-L}	Copper losses at temperature T	Watts
R	Winding Resistance	Ω
F	Temperature coefficient of resistance	

Table 2-2: Subscripts

Symbol	Description
m	Measured value
nl	Measured at no load
sc	Measured during short circuit test
L	At actual load
r	At reference temperature
1	Referred to primary
2	Referred to secondary
ph	Per phase value
ll	Line to line value
R	Referred to R phase
Y	Referred to Y phase
B	Referred to B phase

2.2 Definition & Description of terms

Primary winding: The winding where incoming power supply is connected. Usually this refers to High Voltage side in distribution transformers

Secondary winding: the winding where the principal load is connected. Usually this refers to Low Voltage side in Distribution transformers.

No load loss: The losses taking place in a transformer when only primary winding is energized and all secondary windings are open. They represent constant losses in a transformer.

Dielectric loss: The losses taking place in a stressed dielectric medium (insulation) subjected to stress reversals.

Iron losses: The losses taking place in the magnetic core. There are two types; hysterisis losses and eddy current losses.

Hysteresis losses: This loss depends upon the area of the hysteresis loop, which is depending upon the maximum flux density, the type of material and frequency. It is independent of the waveform

Eddy current losses in core: This is loss due to circulating currents induced by voltage in the thickness of core laminations. It depends upon thickness of lamination, path resistance which is depended upon the type of material, R.M.S. flux density i.e. waveform and square of frequency

Eddy losses in a conductor: For a thick conductor, the induced voltage within the conductor cross section due to self linkage and due to current in other conductor varies. The difference in induced voltage in the local path in the thickness of the conductor causes extra eddy current loss. This loss varies with square of current and square of frequency.

Stray losses: All current dependant losses in a winding other than the basic I^2R losses. Stray losses include eddy loss in the conductor, eddy losses in structural paths in close proximity to outgoing conductor and the eddy loss in general in the structural parts. In dry type transformers, the last two mentioned types of stray losses are absent.

Form factor: It is the ratio of the r.m.s. value of a waveform to the average value over one half cycle. For a sine wave the value of form factor is 1.11. For distorted waves with higher peak values, the form factor is higher.

Harmonics: Frequencies other than the main fundamental frequency of current or voltage which are present in a distorted wave as multiples of base fundamental frequency.

Transformer Polarity: This refers to the relative direction of the induced voltages between the high voltage terminals and the low voltage terminals. During the AC half-cycle when the applied voltage (or current in the case of a current transformer) *is* from H1 to H2 the secondary induced voltage direction *will be* from X1 to X2. In practice, *Polarity* refers to the way the leads are brought out of the transformer.

Burden: The load on an instrument transformer is referred to as a “burden”.

Short circuit impedance & Impedance voltage: The impedance voltage of a transformer is the voltage required to circulate rated current through one of the two specified windings; when the other winding is short circuited with the winding connected as for rated operation. The short circuit impedance is the ratio of voltage and current under above conditions.

The resistive component of short circuit impedance, gives a parameter for estimating load losses. These losses include eddy current losses in the conductors and structure as a small portion. Their contribution is materially enhanced due to harmonic currents in load. Exact determination by test is difficult and simplified test at low current suffers from the disadvantage of a high multiplying factor; but it is expected to give representative values.

3 GUIDING PRINCIPLES

3.1 Safety precautions

The tests require operation on the HV side of a transformer. Extreme caution should be exercised in consultation with the plant personnel to see that HV system is deactivated and discharged safely prior to access. Similarly while energizing from LV side, the reach of induced HV side voltage should be restricted to prevent damage to personnel/ equipment through inadvertent access.

Some simple minimum steps for ensuring safety are as follows.

1. Qualified engineers should be conducting the test. Safety work permit should be issued to the person.
2. The transformer should be on normal tap
3. Before conducting the tests, the HT area should be clearly demarcated to set up a suitable physical barrier to prevent inadvertent entry /proximity of personnel in the HT zone.
4. The HT supply should be switched off by the primary breaker visibly and then disconnected by the isolator; followed by disconnection on the LT side.
5. The HT side terminals should be discharged by a proper grounding rod, which is compatible with the voltage level on the HT side.
6. The primary terminals should then be physically disconnected and left open.
7. It should be remembered that application of even 4 volts on the secondary LT side can induce more than 100 volts on the 11 kV HT side, as per transformer ratio. Similarly abrupt breaking of relatively small D.C. currents can give large voltage spikes on the HT side.

3.2 Sources of errors and precautions

3.2.1 Ratio and phase angle errors

For no load test, the circuit power factor is very low. (0.05 to 0.15). Hence more sensitive energy meters calibrated for preferably 0.1 or 0.2 pf should be used. Indicating meters should be so selected as to give an indication in 20% to 100% full scale. Digital meters can give more reliable low end readings.

Electro-dynamic watt meters have a small angle of lag for the pressure coil circuit by which the pressure coil flux lags the applied circuit voltage. This angle of lag should be added to measured angle like CT phase angle error. Electronic energy meters/watt meters may not have this error.

CTs used will have a ratio error within 0.5%. The phase angle of the CT secondary current with respect to real current can be leading by phase angle error ‘cd’ stated in minutes. This error causes a very significant effect on measured power and tends to give a higher reading. It is recommended that the CT’s used should be calibrated to have known ratio and phase angle errors over the working range and for the intended burden of the wattmeter and the ammeter.

Recommendations:

It is recommended to use portable power analysers or digital energy meters calibrated with CTs of suitable range and the errors be known in the entire current range.

3.3 Estimation of transformer efficiency

The total losses in a transformer at base kVA as well as at the actual load are estimated. From the rated output and measured output, transformer efficiency is calculated as follows.

Efficiency at full load = $\left(\dfrac{Rated\ output}{Rated\ output + Total\ losses\ at\ full\ load} \right) \times 100\ \%$

.

Efficiency at actual load =

$$\left(\frac{Output\ power\ at\ actual\ load}{Output\ power\ at\ actual\ load + Total\ losses\ at\ actual\ load} \right) \times 100\ \%$$

Considering the fact that distribution transformers are usually operated at around 50% of the rating, estimation of losses at 50% load can also be done by extrapolation method and efficiency at 50% load can be calculated.

4 INSTRUMENTS AND METHODS OF MEASUREMENTS

4.1 Measurements/estimation of parameters

The measurements of the following parameters are required for transformer loss estimation.

1. Power input
2. Current
3. Voltage
4. Frequency
5. Winding Resistance
6. Temperature of winding

4.2 Power input

A wattmeter or a suitable electronic 3-phase 4-wire energy meter calibrated for 0.1 p.f can be used for measurement of power in no load test and short circuit test. It also gives a power reading or for improved resolution, energy reading over a period of measured time is possible. Modern digital energy meters have indications of voltage, current, power and frequency; hence more convenient for site measurements.

Electronic 3 phase 4 wire energy/power meters of 0-5A range and multiple voltage ranges from 60 V to 500 V with a full-scale indication in the range of 0.1 pf and 0.5-class accuracy is preferred.

Separate single phase energy/power meters can be used but a single 3 phase 4- wire energy meter is more convenient.

CT's of bar primary type 0.5-class accuracy with multiple ranges can be used. The CT's should be calibrated to indicate its ratio error and phase angle error at 10% to 100% current with the specific burden of ammeters and power meters used.

During use, the phase angle error is directly taken from the calibration curve for specific current readings. Ratio error can be taken as constant or the nominal ratio can be taken.

4.2.1 No load loss measurements

No load losses can be measured from the L.V. side using an adjustable three phase voltage source with neutral. It can be derived from mains or a D.G. set. The voltage and frequency should be steady and at rated values and as near as possible to 50 Hz and it should be measured. This test can give a basic value near rated conditions if all precautions are taken.

The L.V. side is energised at the rated tap at rated voltage and power is measured by three watt meters or 3 phase, 4 wire single wattmeter/energy meter. Connections are made as given in figure 4.1 for single phase transformers and figure 4.2 for 3 phase transformers. Due to energisation on L.V. side, PT's are avoided.

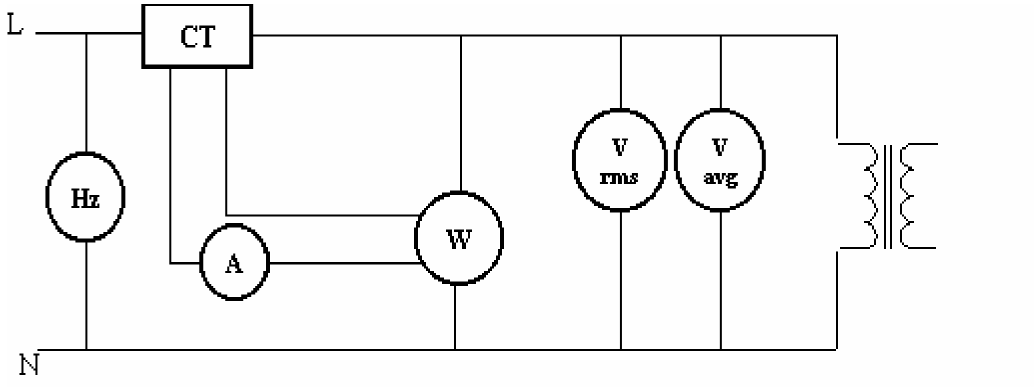
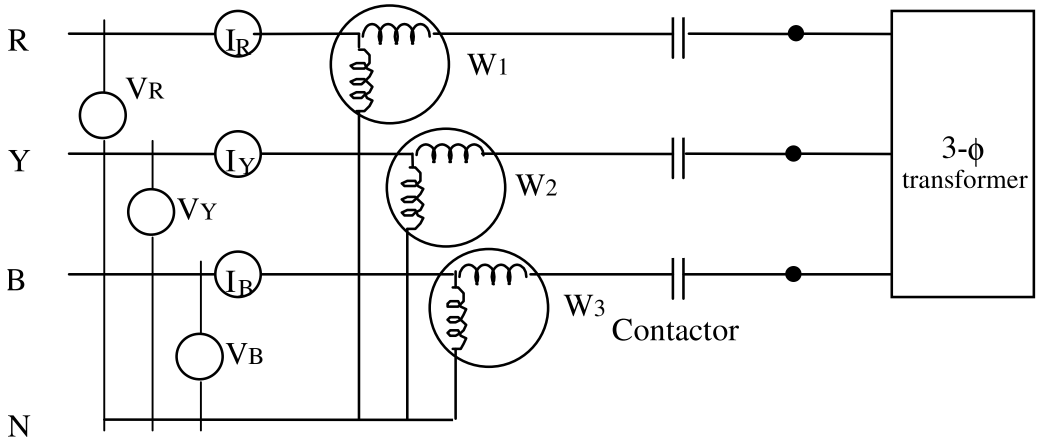


Figure 4-1: No load test set up for single phase transformers



Total power = W1+W2+W3

Figure 4-2: No load test set up for 3 phase transformers

The following figure 4.3 shows connection diagram of a typical 3 phase 4 wire energy metering for measuring energy input to the transformer. All electrical parameters can be monitored using this system.

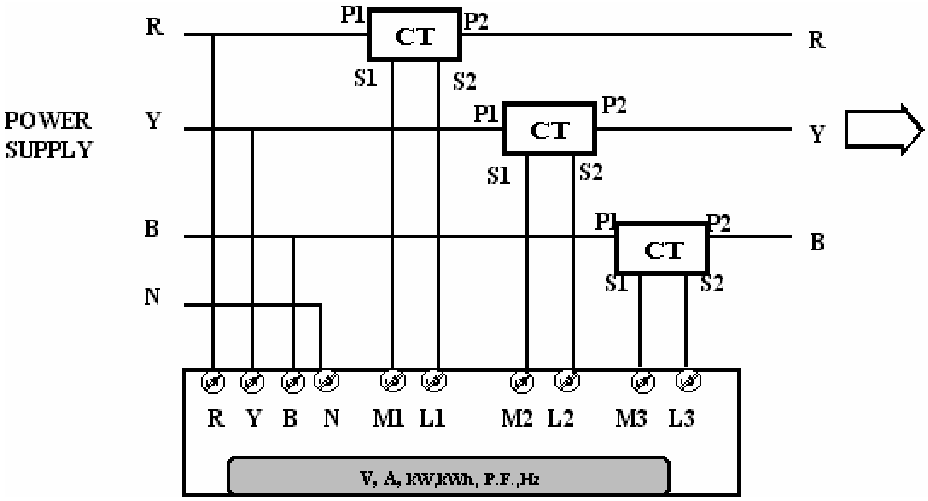


Figure 4-3: Connection diagram using 3-phase 4 wire energy meter

The no load energy consumption, E_{nl} can be measured in the 3 phase – 4 wire meter connected as in figure-4.3. Time taken, t, between initial and final readings are noted. Average no load power is estimated from average energy consumption and time taken.

Average no load power consumption, W_{nl} ' = $\left(\frac{Average\ energy\ consumption}{Time}\right)$

$$= \left(\frac{E_{nl}}{t}\right) \times 3600\ Watts$$

Where E_{nl} = Energy consumption in at no load during 't' seconds

4.2.2 Load loss Test

This test is done by energizing on the H.V. side at a suitable low voltage, while shorting the L.V. side (secondary). The applied voltage is adjusted to pass the needed current in the primary/secondary. In order to simulate conditions nearest to full load, it is customary to pass 100%, 50% or at least 25% of full load current.

A simplified test using a single phase source for 3 phase transformers is explained below. The test configuration in given in figure 4.4.

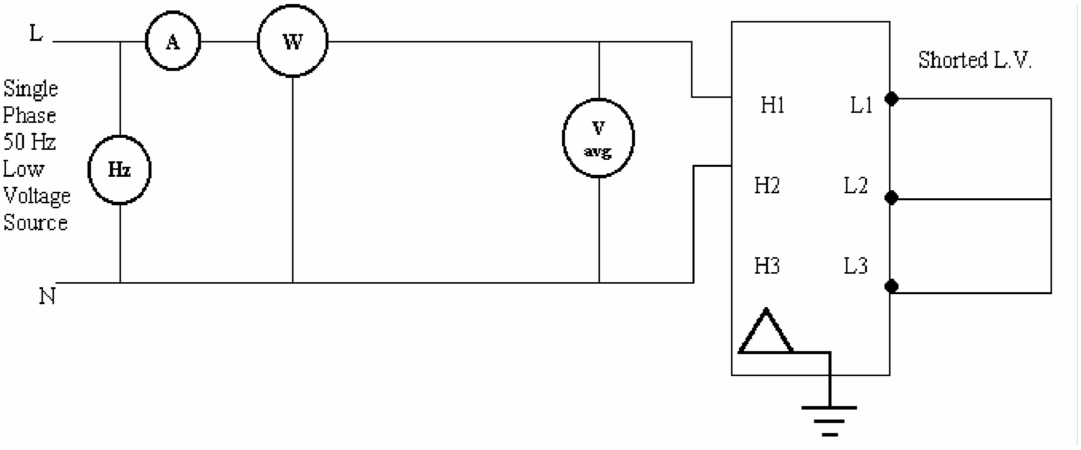


Figure 4-4: Load loss test using low voltage supply

To avoid CT's and PT's, this method can be used at current levels of 2 to 5 A and measurement of load losses is done at this condition. This measured load loss is then extrapolated to actual load currents to obtain load losses at the operating current.

H.V. side full load current, I_1 = $\left(\frac{Full\ load\ kVA \times 1000}{\sqrt{3} \times H.V.line\ voltage}\right)$

Based on the nameplate impedance value of Z%, the estimated line to line voltage for passing 5 A on the H.V. side is calculated as given below.

Line to line voltage, $V_{l\text{-}SC}$ = $\left(\frac{Line\ voltage\ kV \times 1000 \times Z \times 5}{0.866 \times I_1 \times 100}\right)$

For example, for a 11 kV/433 V, 1000 kVA transformer with 5% impedance, the voltage to be applied on H.V. side during load test is estimated below.

H.V. side full load current, $I_1 = \left(\dfrac{Full\ load\ kVA \times 1000}{\sqrt{3} \times H.V.line\ voltage} \right)$

$$= \left(\frac{1000 \times 1000}{\sqrt{3} \times 11000} \right)$$

= 52.5 A

Line to line voltage to be applied on H.V side for getting 5 A on H.V. side,

$$V_{l\text{-}SC} = \left(\frac{Line\ voltage\ kV \times 1000 \times Z \times 5}{0.866 \times I_1 \times 100} \right)$$

$$= \left(\frac{11 \times 1000 \times 5 \times 5}{0.866 \times 52.5 \times 100} \right)$$

= 60.5 volts

The test is repeated thrice, taking terminals H_R and H_Y by applying voltage E_{RY} and then H_Y and H_B with E_{YB} and then H_R and H_B applying voltage E_{RB}. The power readings with corrections are P_{RY}, P_{YB} and P_{RB} respectively. Current drawn on H.V. side I_{s1} is also noted.

Since the current drawn on H.V. side is only about 5A in this test, CT's can be avoided and hence phase angle error is not applicable.

Measured load loss, $W_{sc} = \left(\dfrac{P_{RY} + P_{YB} + P_{RB}}{3} \right) \times 1.5$

Since the test voltage is low iron losses are negligible. The measured power input represents the resistive losses in the windings and stray losses.

4.2.3 Operating load measurements

This measurement is to be carried out after a sustained load level for 3 to 4 hours. The Frequency, Voltage, Current and Power should be measured at L.T side using calibrated 0.5 class meters of suitable range. Note that p.f. at actual load conditions may vary from 0.7 to 1.0 and power meters should be calibrated in this range. The power measured at the L.T side will give the output power of the transformer.

4.3 Voltage

Two types of voltmeters are used in the measurements.

1. Average reading type voltmeters with scale calibrated assuming the normal form factor of 1.11 for sine wave. The usual digital voltmeters are of this variety.
2. R.M.S. reading voltmeter, preferably digital true r.m.s meters are the second type.

Digital electronic instrument with usual a.c range calibrated for sine wave is used for Average reading voltage measurement.

For true r.m.s reading a digital electronic meter of true r.m.s type with a 600v/750v range is recommended of 0.5 class accuracy.

4.3.1 Waveform errors

Ideally, the no load loss is to be measured at the rated maximum flux density and sinusoidal flux variation, at rated frequency. This means that during no load test, an adjustable voltage supply would be required to vary the applied voltage to get the rated flux density.

$$\text{Applied voltage} = \frac{\text{Rated voltage}}{\text{Rated frequency}} \times \text{actual frequency}$$

To account for the distortion in waveforms, which is usually seen in waveforms, which may be present during measurements, the values of average and r.m.s voltages are to be measured across the transformer phase windings. The r.m.s. voltage U may slightly higher than average voltage U'.

The measured core losses need to be corrected to sinusoidal excitation, by using the following expression.

No load losses corrected for sinusoidal excitation, $W_{nl} = \dfrac{W_{nl-m}}{(C_h + kC_e)}$

Where k = form factor correction = $\left(\dfrac{U}{U'}\right)^2$

C_h = Ratio of hysteresis loss to total iron losses
C_e = Ratio of eddy current losses to total iron losses

For usual flux densities, the following data can be used.

For oriented steel, $C_h = C_e = 0.5$
For non-oriented steel , $C_h = 0.7$, $C_e = 0.3$
For amorphous core materials, $W_{nl} = W_{nl\text{-}m}$

4.4 Frequency

A digital frequency-measuring instrument for 50 Hz range with 600v range and having a resolution of 0.1 Hz is preferred.

4.5 Winding temperature

The transformer should be de-energised with continued cooling for at least 8 hours. Alternatively, if the winding temperature does not vary by more than 1ºC over a period of 30 minutes, the transformer can be assumed to have reached a cold stage. For oil cooled transformers, the temperature can be measured either at the top of the oil surface or in an oil filled thermo-well if it is provided.

For dry type transformers, the temperature sensor should be kept in close contact with coil surface. The sensor should be covered and protected from direct draft. When a stable temperature is reached in the indicator, within 1ºC, this temperature is taken as temperature of the windings, $\mathbf{T_m}$**,** at the time of measuring the winding resistance.

For oil temperature measurements calibrated mercury in glass thermometer can be used with a resolution of 1ºC .in general, electronic instruments with suitable probes are preferred. They include probes using thermo couple resistance or Thermisters with the resolution of 1ºC.

For surface temperature measurements the probe of the instrument should be mounted and covered suitably. Due care should be taken to isolate the instrument for reliable reading and safety

4.6 Cold winding resistance

The winding resistance can be measured using a Kelvin bridge for low resistances or a wheat-stone bridge for resistances above 10 Ω.

It is preferable to use modern direct reading digital resistance measuring instruments with a resolution of 10 micro Ω or better for L.V. windings.

If resistance is measured across line terminals, the per phase resistance can be calculated as follows:

1. If winding is connected in delta, $R_{ph} = 1.5 \times R_{ll}$
2. If winding is connected in Star, $R_{ph} = 0.5 \times R_{ll}$

The value of the resistance for primary and secondary windings as measured should be corrected to a standard temperature of 75 ºC by using the following expression.

$$R_{ph} = R_{ph-m} \times \left(\frac{T+F}{T_m+F} \right)$$

Where

R_{ph} = Resistance at temperature T, Ω
R_{ph-m} = Resistance measured at measured winding temperature T_m, Ω
T = Winding temperature, ºC at which resistance is to be referred
T_m = Temperature of winding at the time of resistance measurement, ºC
F = Temperature coefficient.
= 235 for copper
= 225 for Aluminium
= 230 for alloyed Aluminium

Thus, for copper windings, $R_r = R_m \times \left(\frac{T_r+235}{T_m+235} \right)$

For low resistance measurements an electronic, four terminal digital instruments is preferred with a minimum accuracy of 10 micro ohms.

Note: The micro ohmmeters generally inject 1.0 ampere current to the winding while measuring resistance. For transformers rated above 100 kVA, this current may not be sufficient to give appreciable voltages for the instrument to measure. Hence a DC current generator capable of supplying about 5 Amp may be required.

4.6.1 Settling time for readings

Due to circuit time constant, for the current driving circuit used, final reading will take some time for reaching a stable value. This time should be measured and noted. This time is useful for taking a valid reading when taking hot winding resistance. If hot resistance is measured after de-energising the transformer, a valid reading can only be considered after the lapse of settling time as measured above.

Polarity of D.C. current with respect to winding terminals should be consistently same. The above comment is applicable to all resistance measurements including those taken by bridge method or using a direct indicating digital meter.

5 COMPUTATION OF RESULTS

5.1 Sequence of Tests

Any convenient sequence can be followed, but preferably after a sufficiently long OFF period, the test for cold winding resistance should be taken first to minimise minor temperature rise errors.

This should be followed by no load loss test and then followed by short circuit test, if needed.

Indirect or direct measurement of operating winding temperature can be planned and taken after a proper stabilization period under any chosen load condition. Measurement of actual operating parameters also needs to be done during normal load condition.

5.2 Chronological order of measurements and calculations

1. Obtain nameplate specifications of the transformer.
2. Switch off the transformer for at least 8 hours with continued cooling to attain steady state. Alternatively, measure winding temperature at every 15 minutes and if temperature drop is not more than 1ºC, the transformer can be considered to have attained steady state.
3. Measure resistances of primary and secondary windings. If resistance is measured across line terminals, the per phase resistance can be calculated as follows:

   If winding is connected in delta, $R_{ph} = 1.5 \times R_{ll}$
   If winding is connected in Star, $R_{ph} = 0.5 \times R_{ll}$

4. Conduct no load test, by energizing on the L.V. side. For this, first connect instruments as in figure 4.3 for single phase transformers or as in figure 4.1 for three phase transformers.

   - Measure frequency (f), r.m.s voltage (U), average voltage (U'), current (I_{nl}), energy consumption (E_{nl}) during a period (t) seconds. No load power input (W_{nl}) is calculated from E_{nl} and 't' as follows.

Average no load power consumption, $W_{nl\text{-}m}$ = $\left(\dfrac{Average\ energy\ consumption}{Time} \right)$

$$= \left(\frac{E_{nl}}{t} \right) \times 3600\, Watts$$

Alternatively, if watt meters are used, the wattmeter reading is taken as Average no load power consumption, $W_{nl\text{-}m}$

- The measured core losses need to be corrected to sinusoidal excitation, by using the following expression.

  No load losses corrected for sinusoidal excitation, $W_{nl} = \dfrac{W_{nl-m}}{(C_h + kC_e)}$

  Where k = form factor correction = $\left(\dfrac{U}{U'} \right)^2$

  C_h = Ratio of hysteresis loss to total iron losses
  C_e = Ratio of eddy current losses to total iron losses

For usual flux densities, the following data can be used.
For oriented steel, $C_h = C_e = 0.5$
For non-oriented steel, $C_h = 0.7$, $C_e = 0.3$
For amorphous core materials, $W_{nl} = W_{nl\text{-}m}$

- This value of form factor corrected core loss is then corrected to normal operating voltage and frequency, to be measured when the transformer is on load.

  The core losses are roughly proportional to square of actual voltage and frequency, as explained below.

  $$k_v = \left(\frac{U_l}{U_r}\right) \qquad k_f = \left(\frac{f_{nl}}{f_r}\right)$$

  Corrected value of no load loss to site voltage and frequency

  $$P_{core} = \left(Wnl \times \left[\left(C_k \times k_u^{1.6} \times k_f\right) + \left(C_e \times k_u^{2} \times k_f^{2}\right)\right]\right)$$

  Where,
  U_{nl} = Measured voltage during no load test, volts
  U_r = Actual site voltage, volts
  f_{nl} = Measured frequency during no load test, Hz
  f_r = Actual site frequency, Hz

5. Conduct short circuit test. Refer figure 4.4 for connection diagram. Short circuit the L.V. terminals and apply a reduced voltage on each phase on H.V. side, so that about 5 A current is maintained on H.V. side.

   Line to line voltage to be applied on H.V side for getting 5 A on H.V. sides

   $$V_{l\text{-}SC} = \left(\frac{Line\ voltage\ kV \times 1000 \times Z \times 5}{0.866 \times I_1 \times 100}\right)$$

   Since the current drawn on HV side is only about 5A in this test, CT's can be avoided.

   The test is repeated thrice, taking terminals H_R and H_Y by applying voltage E_{RY} , H_Y and H_B with E_{YB} and then H_R and H_B applying voltage E_{RB}. The power readings are P_{sc}-$_{RY}$, P_{sc}-$_{YB}$ and P_{sc}-$_{RB}$ respectively. Currents drawn on H.V. side $I_{s1\text{-}ph}$ is also noted. For STAR primary, only the corresponding L.V. side is shorted. I.e. L1&L2, L2 & L3 and L1& L3 sequencially.

   Measured load loss, $W_{sc} = \left(\frac{P_{RY} + P_{YB} + P_{RB}}{3}\right) \times 1.5$

   Alternatively, use of energy meter reading and time taken between readings can also be used to calculate P_{sc}-$_{RB}$ etc. in place of direct power measurements. This is similar to the calculation procedure explained in point no.4 above for no load test.

6. Calculate total copper losses in windings based on short circuit current, I_{s1} and measured cold phase winding resistances.

$$P_{cu} = \left(3 \times I_{s1.ph}{}^{2} \times R_{m1.ph} + 3 \times \left[I_{s1.ph} \times \left(\frac{V_1}{V_2}\right)\right]^2\right) \times R_{m2.ph}$$

Where $I_{s1\text{-}ph}$ = Measured current on H.V. side during load loss test for STAR primary
= 0.577 times measured current for delta primary
V_1 = Rated H.V. side line to line voltage
V_2 = Rated L.V. side line to line voltage
$R_{m1\text{-}ph}$ = Cold winding resistance per phase on H.V. side
$R_{m2\text{-}ph}$ = Cold winding resistance per phase on L.V. side

7. Calculate stray loss

   Stray loss, $P_{s\text{-}m} = W_{sc} - P_{cu}$

8. Convert the copper losses and stray losses to base kVA and reference temperature.

   Copper losses can be converted to base kVA level and reference temperature as follows.

   $$P_{cu\text{-}base} = P_{cu} \times \left(\frac{I_1}{I_{s1}}\right)^2 \times \left(\frac{T_R + 235}{T_m + 235}\right) \text{---(1)}$$

   Where T_m = Measured cold winding temperature of windings.
   I_1 = Rated primary current

   Stray losses are also converted to base kVA level and reference temperature as follows.

   $$P_s = P_{s\text{-}m} \times \left(\frac{I_1}{I_{s1}}\right)^2 \times \left(\frac{T_m + 235}{T_R + 235}\right) \text{-----(2)}$$

   Where P_s = Stray loss at base kVA and at T_m
   T_R is usually specified as 75º C.

   Total load losses at full load = (1) + (2)
   = $P_{cu\text{-}base} + P_s$

9. Operate the transformer on actual load conditions for at least 2 hours. Measure actual load parameters of frequency (f_L), site voltage (U_L), current (I_L) and power consumption (P_L).

10. Measure operating winding resistance and estimate winding temperature as explained in section 4.6.

    $$T_L = \frac{R}{R_m} \times (235 + T_m) - 235$$

11. Extrapolate the load losses at the actual load and operating temperature.

    Copper losses at actual load,

    $$\mathbf{P_{cu\text{-}L} = P_{cu} \times} \left(\frac{I_{L1}}{I_{s1}}\right)^2 \times \left(\frac{T_L + 235}{T_m + 235}\right)$$

    Where T_L = Measured temperature of windings under actual load.
    I_L = Primary current at actual load

I_{L1} can also be estimated from secondary current at actual load, I_2 by using transformer voltage ratio.

$I_{L1} = I_{L2} \times \left(\frac{V_2}{V_1} \right)$

I_{L2} = Secondary current at actual load

Stray losses at actual load,

$$P_{sL} = P_{s\text{-}m} \times \left(\frac{I_{L1}}{I_{s1}} \right)^2 \times \left(\frac{T_m + 235}{T_L + 235} \right) \text{-----(2)}$$

Where P_{sL} = Stray loss at actual load

12. Estimation of transformer efficiency

    The above steps calculates total losses in a transformer at base kVA as well as at the actual load.

$$\text{Efficiency at full load, } \eta_{FL} = \left[\frac{Rated\ output}{(Rated\ output + Total\ losses\ at\ \ full\ load)} \right] \times 100\%$$

$$= \frac{P \times 1000}{(P \times 1000 + P_{core} + P_{cu} + P_s)} \text{ x } 100$$

Efficiency at actual load, η_L =

$$\left[\frac{Ouput\ \ power\ at\ actual\ load}{(Output\ \ power\ at\ actual\ load + Total\ losses\ at\ actual\ load)} \right] \times 100\%$$

$$= \frac{P_L \times 1000}{(P_L \times 1000 + P_{core} + P_{cu} + P_s)} \text{ x } 100\ \%$$

Table 5.1 shows the calculations for estimating transformer efficiency at full load with MS Excel™ programmable equations.

Table 5-1: *Transformer efficiency estimation at full load*

Sl.No.	A	B	C
2	**Description**	**Units**	**Value**
3	**Transformer Specifications**		
4	Output	kVA	
5	High voltage	Volts	
6	Low voltage	Volts	
7	Full load current-secondary	Amp	
8	Full load current primary	Amp	
9	Efficiency	%	
10	Reference temperature	℃	
11	Frequency	Hz	
12			
13	**No load test**		
14	R.M.S. Voltage, V_{rms}	Volts	
15	Average voltage, V_{avg}	Volts	
16	Frequency, f	Hz	
17	No load Current, I_{nl}	A	
18	No load power input, P_{nl}	Watts	
19	Winding resistance of secondary (L.V.) side R_{ph-2}	Ohms	
20	Winding resistance of primary (H.V.) side, R_{ph-1}	Ohms	
21	Ambient temperature	℃	
22			
23	**Short circuit test**		
24	Applied reduced voltage on H.V, V_{sc} (Average of three currents measured)	Volts	
25	H.V. side phase current, (Average of three currents measured) I_{s1}	A	
26	Power measured (average of three power measured), W_{sc-m}	Watts	
27	Total power input at short circuit, W_{sc}	Watts	**C26*1.5**
28			
29	**Calculation of results**		
30	Form factor, k	p.u.	**(C14/C15)^2**
31	Corrected no load loss	Watts	**C18/(0.5+(C30/1.11)^2*0.5)**
32	Core loss at rated voltage and freq.	Watts	**(C31)*(C14/C6)^2*(C16/C11)^2**
33			
34	Total Copper loss estimated at test current	Watts	**3*(C25^2*C20)+3*((C25*SQRT(3)*(C5/C6))^2*(C19))**
35	Stray losses at test current	Watts	**C27-C34**
36			
37	Total Copper loss at full load current	Watts	**C34*(C8/(C25*SQRT(3)))^2*(235+C10)/(235+30)**
38	Stray losses at full load current	Watts	**C35*(C8/(SQRT(3)*C25))^2*(235+30)/(235+C10)**
39			
40	Total losses at full load	Watts	**C37+C38+C32**
41			
42	**Efficiency at full load**	**%**	**(C4*1000)/(C4*1000+C40)**

Table 5.2 shows the calculations for estimating transformer efficiency at actual load with MS Excel™ programmable equations.

Table 5-2: Transformer efficiency estimation at actual load

Sl.No	A	B	C
2	**Description**	**Units**	**Value**
3	**Transformer Specifications**		
4	Output	kVA	
5	High voltage	Volts	
6	Low voltage	Volts	
7	Full load current-secondary	Amp	
8	Full load current primary	Amp	
9	Efficiency	%	
10	Reference temperature	C	
11	Frequency	Hz	
12			
13	**No load test**		
14	R.M.S. Voltage, V_{rms}	Volts	
15	Average voltage, V_{avg}	Volts	
16	Frequency, f	Hz	
17	No load Current, I_{nl}	A	
18	No load power input, P_{nl}	Watts	
19	Winding resistance of secondary (L.V.) side R_{ph-2}	Ohms	
20	Winding resistance of primary (H.V.) side, R_{ph-1}	Ohms	
21	Ambient temperature	C	
22			
23	**Short circuit test**		
24	Applied reduced voltage on H.V, V_{sc} (Average of three currents measured)	Volts	
25	H.V. side phase current, (Average of three currents measured) I_{s1}	A	
26	Power measured (average of three power measured), W_{sc-m}	Watts	
27	Total power input at short circuit, W_{sc}	Watts	C26*1.5
28			
29	Actual load		
30	Measured load current, I_L	A	
31	Voltage, V_L	Volts	
32	Power, P_L	kW	
33	Winding temperature, T	C	
34			
35	Calculation of results		
36	Form factor, k	p.u.	(C14/C15)^2
37	Corrected no load loss	Watts	C18/(0.5+(C36/1.11)^2*0.5)
38	Core loss at rated voltage and freq.	Watts	(C37)*(C14/C6)^2*(C16/C11)^2
39	Core loss at actual voltage and freq.	Watts	(C37)*(C31/C6)^2*(C16/C11)^2

40			
41	Total Copper loss estimated at test current	Watts	3*(C25^2*C20)+3*((C25*SQRT(3)*(C5/C6))^2*(C19))
42	Stray losses at test current	Watts	C27-C41
43			
44	Total Copper loss at full load current	Watts	(C41*(C8/(C25*SQRT(3)))^2*(235+C10)/(235+30))
45	Stray losses at full load current	Watts	C42*(C8/(SQRT(3)*C25))^2*(235+30)/(235+C10)
46			
47	Total Copper loss at actual load current	Watts	C44*(C30/C7)^2*(235+C33)/(235+C10)
48	Stray losses at actual load current	Watts	C45*(C30/C7)^2*(235+C21)/(235+C10)
49			
50	Total losses at actual load	Watts	C47+C48+C39
51			
52	Efficiency at actual load	%	(C32*1000-C50)/(C32*1000)

6 FORMAT OF TEST RESULTS

6.1 Data Collection & Analysis

The format of Transformer specification data is given in table 6.1. The data collection format and calculations are also summarized in the table given below, in MS Excel spread sheet format.

Table 6-1:: Format for data collection & Test results

Name of Industry:

Test Date:

Time:

Details of instruments used

Sl.No	Description	Measured parameter	Description of accuracy
1	Power Analyser	Voltage, current, p.f, power input, frequency	0.5% 0.5% 1.0% 0.01Hz
2	Digital micro ohm meter	Winding resistance	1 micro ohms
3	Thermometer	Ambient temperature	1 C

Transformer Specifications			
1	Output	800	kVA
2	H.V voltage	6600	Volts
3	L.V voltage	400	Volts
4	H.V. Full load current	70	Amp
5	L.V. Full load current	1154	Amp
6	Efficiency	-	%
7	Reference temperature	75	C

No load test			
8	R.M.S. Voltage	429	Volts
9	Average voltage	403	Volts
10	Frequency	50	Hz
11	No load Current	9.96	Amp
12	No load power input	1960	Watts
13	Winding resistance of secondary (L.V.) side	0.00111	Ohms
14	Winding resistance of primary (H.V.) side	1.03	Ohms

Short Circuit Test			
15	Applied reduced voltage on H.V	36.6	Volts
16	H.V. side phase current	2.78	Amp
17	Power input	44.3	Watts

Results			
19	Core loss at rated voltage and freq.	2207.88	Watts
20	Copper loss at full load	11100.69	Watts
21	Stray losses at full load	3893.24	Watts
22	Total losses at full load	17201.82	Watts
23	**Efficiency at full load**	97.9	%
24	Uncertainty	0.03	%

Test conducted by:
(Energy Auditing Firm)

Test witnessed by:
(Energy Manager)

7 UNCERTAINTY ANALYSIS

7.1 Introduction

Uncertainty denotes the range of error, i.e. the region in which one guesses the error to be. The purpose of uncertainty analysis is to use information in order to quantify the amount of confidence in the result. The uncertainty analysis tells us how confident one should be in the results obtained from a test.

Guide to the Expression of Uncertainty in Measurement (or GUM as it is now often called) was published in 1993 (corrected and reprinted in 1995) by ISO. The focus of the ISO *Guide* or GUM is the establishment of "general rules for evaluating and expressing uncertainty in measurement that can be followed at various levels of accuracy ".

The following methodology is a simplified version of estimating combined uncertainty at field conditions, based on GUM.

7.2 Methodology

Uncertainty is expressed as X +/- y where X is the calculated result and y is the estimated standard deviation. As instrument accuracies are increased, y decreases thus increasing the confidence in the results.

A calculated result, r, which is a function of measured variables X_1, X_2, X_3,….., X_n can be expressed as follows:

$r = f(X_1, X_2, X_3,\ldots.., X_n)$

The uncertainty for the calculated result, r, is expressed as

$$\partial_r = \left[\left(\frac{\partial r}{\partial X_1}\times\delta x_1\right)^2+\left(\frac{\partial r}{\partial X_2}\times\delta x_2\right)^2+\left(\frac{\partial r}{\partial X_3}\times\delta x_3\right)^2+\ldots\ldots\right]^{0.5} \quad \text{----(1)}$$

Where:

∂_r = Uncertainty in the result

δxi = Uncertainties in the measured variable X_i

$\frac{\partial r}{\partial X_i}$ = Absolute sensitivity coefficient

In order to simplify the uncertainty analysis, so that it can be done on simple spreadsheet applications, each term on RHS of the equation-(1) can be approximated by:

$$\frac{\partial r}{\partial X_1} \text{ x } \partial X_1 = r(X_1+\partial X_1) - r(X_1) \quad \text{----(2)}$$

The basic spreadsheet is set up as follows, assuming that the result r is a function of the four parameters X_1, X_2, X_3 & X_4. Enter the values of X_1, X_2, X_3 & X_4 and the formula for calculating **r** in column A of the spreadsheet. Copy column A across the following columns once for every variable in **r** (see table 7.1). It is convenient to place the values of the uncertainties $\partial(X_1)$, $\partial(X_2)$ and so on in row 1 as shown.

Table 7-1: Uncertainty evaluation sheet-1

	A	B	C	D	E
1		∂X_1	∂X_2	∂X_3	∂X_4
2					
3	X_1	X_1	X_1	X_1	X_1
4	X_2	X_2	X_2	X_2	X_2
5	X_3	X_3	X_3	X_3	X_3
6	X_4	X_4	X_4	X_4	X_4
7					
8	$y=f(X_1, X_2, X_3, X_4)$	$y=f(X_1, X_2, X_3, X_4)$	$y=f(X_1, X_2, X_3, X_4)$	$y=f(X_1, X_2, X_3, X_4)$	$y=f(X_1, X_2, X_3, X_4)$

Add ∂X_1 to X_1 in cell B3 and ∂X_2 to X_2 in cell C4 *etc.*, as in Table 7.2. On recalculating the spreadsheet, the cell B8 becomes $f(X_1+\partial X_1, X_2, X_3, X_4)$.

Table 7-2: Uncertainty evaluation sheet-2

	A	B	C	D	E
1		∂X_1	∂X_2	∂X_3	∂X_4
2					
3	X_1	$X_1+\partial X_1$	X_1	X_1	X_1
4	X_2	X_2	$X_2+\partial X_2$	X_2	X_2
5	X_3	X_3	X_3	$X_3+\partial X_3$	X_3
6	X_4	X_4	X_4	X_4	$X_4+\partial X_4$
7					
8	$r=f(X_1, X_2, X_3, X_4)$	$r=f(X_1', X_2, X_3, X_4)$	$r=f(X_1, X_2', X_3, X_4)$	$r=f(X_1, X_2, X_3', X_4)$	$r=f(X_1, X_2, X_3, X_4')$

In row 9 enter row 8 minus A8 (for example, cell B9 becomes B8-A8). This gives the values of $\partial (r, X_1)$ as shown in table 7.3.

$\partial (r, X_1)=f(X_1+\partial X_1), X_2, X_3\ldots) - f(X_1, X_2, X_3..)$ *etc.*

To obtain the standard uncertainty on *y*, these individual contributions are squared, added together and then the square root taken, by entering $\partial (r, X_1)^2$ in row 10 (Figure 7.3) and putting the square root of their sum in A10. That is, cell A10 is set to the formula, SQRT(SUM(B10+C10+D10+E10)) which gives the standard uncertainty on r, $\partial (r)$

Table 7-3: Uncertainty evaluation sheet-3

	A	B	C	D	E
1		∂X_1	∂X_2	∂X_3	∂X_4
2					
3	X_1	$X_1+\partial X_1$	X_1	X_1	X_1
4	X_2	X_2	$X_2+\partial X_2$	X_2	X_2
5	X_3	X_3	X_3	$X_3+\partial X_3$	X_3
6	X_4	X_4	X_4	X_4	$X_4+\partial X_4$
7					
8	$r=f(X_1, X_2, X_3, X_4)$	$r=f(X_1', X_2, X_3, X_4)$	$r=f(X_1, X_2', X_3, X_4)$	$r=f(X_1, X_2, X_3', X_4)$	$r=f(X_1, X_2, X_3, X_4')$
9		$\partial (r,X_1)$	$\partial (r,X_2)$	$\partial (r,X_3)$	$\partial (r,X_4)$
10	$\partial (r)$	$\partial (r,X_1)^2$	$\partial (r,X_2)^2$	$\partial (,X_3)^2$	$\partial (r,X_4)^2$

7.3 Uncertainty evaluation of transformer efficiency testing:

Based on above discussions, the methodology for estimating uncertainty in transformer efficiency testing is explained below.

Specification of the transformer is given in table 7.4.

Table 7-4: Test Transformer specifications

Transformer Specifications	Units	Value
Output	kVA	800
High voltage	Volts	6600
Low voltage	Volts	400
Full load current-secondary	Amp	1154
Full load current primary	Amp	70
Efficiency	%	6.78
Reference temperature	C	75
Frequency	Hz	50

An instrument accuracy table can be prepared based on instrument specified accuracies and calibration certificates.

The following points may be noted:

1. For instruments, which are calibrated for the entire working range, a calibration curve should be plotted to obtain errors at the measurement point. If accuracy is specified only at the full scale value, then full scale error is to be taken as uncertainty in the parameter.

2. For example, for a voltmeter of 0.5 % error and 600 Volts full scale value, error, assume that error at the measured value of 400 volts is 0.5%. The absolute error at this point shall be 0.005 x 400 = 2 Volts. Thus, uncertainty in voltage measurement is ±2 Volts.

3. If calibration curve is not available, the absolute error will be based on full scale value. I.e. 600 x 0.5% = 3 Volts. Thus, uncertainty in voltage measurement is ±3 Volts.

4. If CTs of 0.5 class is used with ammeter for measuring current, this error also needs to be considered. If the ammeter error is 0.5%, then the total error in the measurement of current is used for measuring current is $\sqrt{[(0.5)^2 + (0.5)^2]} = 0.7\%$.

5. Similarly, If the power meter is also connected through the same CT, the combined uncertainty in power measurement will be 0.7% as in current measurement.

6. When CT's of larger ratio is used for small currents, the error in power measurements is very large, especially at low p.f. For example, a portable power analyzer connected with a 1000/5 A CT used for measuring a load current of 5 A and o.3 p.f, the error in power measurement was 5%, compared to an error of 0.5% at 0.8 p.f for the same current.

7. In Table 7.5, each uncertainty term is added to the corresponding measured value, one parameter at a time.

Table 7-5: Uncertainty Evaluation

			δV_{rms}	δV_{avg}	δf	δI_{nl}	δW_{nl}	δR_{ph-2}	δR_{ph-1}	δV_{sc}	δI_{s1}	δW_{sc}
*If % accuracy is known at **operating point**, enter % value in this row*	Units	**% acc.**	0.50%	0.50%		1.00%	5.00%	0.50%	0.50%	0.5%	1.0%	5.0%
*If % accuracy is known at **full scale** only, calculate full scale error and enter actual value in this row*		**value**	2.15	2.02	0.01	0.10	98.0	0.000006	0.0052	0.183	0.0278	3.32250
No load test												
R.M.S. Voltage, V_{rms}	Volts	**429.0**	**431.1**	429.0	429.0	429.0	429.0	429.0	429.0	429.0	429.0	429.0
Average voltage, V_{avg}	Volts	**403**	403.00	**405.02**	403.00	403.00	403.00	403.00	403.00	403.00	403.00	403.00
Frequency, f	Hz	**50**	50.00	50.00	**50.01**	50.00	50.00	50.00	50.00	50.00	50.00	50.00
No load Current, I_{nl}	A	**9.96**	9.96	9.96	9.96	**10.1**	9.96	9.96	9.96	9.96	9.96	9.96
No load power input, P_{nl}	Watts	**1960**	1960	1960	1960	1960	**2058.0**	1960	1960	1960	1960	1960
Winding resistance of secondary (L.V.) side R_{ph-2}	Ohms	**0.00111**	0.00111	0.00111	0.00111	0.00111	0.00111	**0.001116**	0.00111	0.00111	0.00111	0.00111
Winding resistance of primary (H.V.) side, R_{ph-1}	Ohms	**1.0300**	1.0300	1.0300	1.0300	1.0300	1.0300	1.0300	**1.0352**	1.0300	1.0300	1.0300
Ambient temperature		**30.0**										
Short circuit test												
Applied reduced voltage on H.V, V_{sc} (Average of three currents measured)	Volts	**36.60**	36.60	36.60	36.60	36.60	36.60	36.60	36.60	**36.78**	36.60	36.60
H.V. side phase current, (Average of three currents measured) I_{s1}	A	**2.78**	2.78	2.78	2.78	2.78	2.78	2.78	2.78	2.78	**2.81**	2.78
Power measured (average of three power measured), W_{sc-m}	Watts	**44.30**	44.30	44.30	44.30	44.30	44.30	44.30	44.30	44.30	44.30	**44.30**
Total power input at short circuit, W_{sc}	Watts	**66.45**	66.45	66.45	66.45	66.45	66.45	66.45	66.45	66.45	66.45	66.45
Calculation of results												
Form factor, k	p.u.	**1.1332**	1.1446	1.1219	1.1332	1.1332	1.1332	1.1332	1.1332	1.1332	1.1332	1.1332
Corrected no load loss	Watts	**1919.47**	1899.93	1939.02	1919.47	1919.47	2015.45	1919.47	1919.47	1919.47	1919.47	1919.47
Core loss at rated voltage and freq.	Watts	**2207.88**	2207.32	2230.37	2208.77	2207.88	2318.28	2207.88	2207.88	2207.88	2207.88	2207.88
Total Copper loss estimated at test current	Watts	**44.90**	44.90	44.90	44.90	44.90	44.90	45.01	45.02	44.90	45.80	44.90
Stray losses at test current	Watts	**21.55**	21.55	21.55	21.55	21.55	21.55	21.44	21.43	21.55	20.65	21.55
Total Copper loss at full load current	Watts	**11100.69**	11100.69	11100.69	11100.69	11100.69	11100.69	11126.68	11130.21	11100.69	11100.69	11100.69
Stray losses at full load current	Watts	**3893.24**	3893.24	3893.24	3893.24	3893.24	3893.24	3874.25	3871.67	3893.24	3656.69	3893.24
Total losses at full load	Watts	**17201.82**	17201.25	17224.30	17202.70	17201.82	17312.21	17208.81	17209.76	17201.82	16965.27	17201.82
Efficiency at full load	%	**97.90%**	97.90%	97.89%	97.89%	97.90%	97.88%	97.89%	97.89%	97.90%	97.92%	97.90%

Table 7-5: Uncertainty Evaluation cont'd..

Delta			-0.000001	0.000027	0.000001	0.000000	0.000132	0.000008	0.000010	0.000000	-0.000283	0.000000
Delta Square			0.000000	0.000000	0.000000	0.000000	0.00000	0.00000	0.00000	0.000000	0.00000	0.000000
Sum of 'delta squares'		0.00000010										
Delta		0.000314189										
% uncertainty	**%**	**0.03%**										

Comments: The most significant measurements are no load input power, current and power input at short circuit. Rest of the measurements does not really impact the accuracy of the results.

8 GUIDELINES FOR ENERGY CONSERVATION OPPORTUNITIES

The following points have to be considered.

1. Power factor correction for reducing copper losses.
2. System operating voltages to be observed for maintaining near rated voltages and unbalanced to be minimized.
3. Augmented cooling and relative benefits to be seen where applicable.
4. Possibility of switching off paralleled transformers at any low loads.
5. Working out existing realistic losses and cost thereof. This follows study of annual r.m.s. loading and operating losses at operating temperature, covering harmonic loading. This is a prerequisite for finding replacement alternatives.
6. Replacement by a low loss transformer with economic justification, considering present and future harmonic loading and load pattern.
7. When replacement is not justified, collection of invited/standard low loss design data for optimum cost/rating of transformer for future replacement or for new installation.

ANNEXURE 1: EFFECT OF HARMONICS

A1.1 Effect of current harmonics on load losses

A1.2 Introduction

The load losses consist of normal I^2R losses in the conductor and the stray losses due to eddy currents in thick conductors due to varying induced voltage within the cross section of the conductor due to self linkages and due to currents in near by current carrying conductors. These induced voltages circulate eddy current in the local loop. In oil cooled transformers, the heavy current output conductors have proximity to structural parts wherein eddy losses can take place. Similarly, some stray flux can in general cause eddy losses in structural parts. The distribution of stray losses in the two last named categories can be estimated by design experience. It can not be directly measured.

Thus load losses = I^2R_{DC} + I^2R_{extra} Eddy in windings + I^2R_{extra} eddy in structure near out going conductors + I^2R_{extra} Eddy in Tank Structure

The last three are clubbed together and distribution is assumed 90% and 10%.
In general, the eddy losses are materially increased since they vary as per square of frequency.

Effects of the triplens (3^{rd}, 9^{th} etc.) is to cause circulating currents which circulate in delta winding causing added losses.

They also add up in neutral connection and conductor causing extra heating and losses.
In general, harmonic order h = p (pulse number) x K ± 1 where K = 1 to n.

Accordingly six pulse converters give 5,7,11,13,…….
Twelve pulse converters give 11,13,………

The application problems are of two types.

a) How to specify the transformer for a general mix of active loads.
b) How to estimate extra losses when current harmonics are known for an existing transformer.

A1.4 U.S. Practices – K- Factor

The K-Factor rating assigned to a transformer and marked on the transformer case in accordance with the listing of Underwriters Laboratories, is an index of the transformer's ability to supply harmonic content in its load current while remaining within its operating temperature limits.

For specification in general, the U.S. practice is to estimate the K – Factor which gives ready reference ratio K for eddy losses which driving non linear loads as compared to linear loads.

$$K = \sum_{1}^{h} I_h^2 H^2$$

K = 1 for Resistance heating motors, distribution transformers etc.
K = 4 for welders Induction heaters, Fluorescent lights
K = 13 For Telecommunication equipment.
K = 20 For main frame computers, variable speed drives and desktop computers.

A sample K- factor calculation is given for a given set of harmonic measurements, based on the above relationships.

Table A1-0-1: Sample calculation-K factor

Harmonic No.	**RMS Current**	**I_n/I_1**	**$(I_n/I_1)^2$**	**(I_n/I)**	**$(I_n/I)^2$**	**$(I_n/I)^2 x n^2$**
1	1	1	1	0.6761	0.4571	0.4571
3	0.82	0.82	0.6724	0.5544	0.3073	2.7663
5	0.58	0.58	0.3364	0.3921	0.1538	3.8444
7	0.38	0.38	0.1444	0.2569	0.0660	3.2344
9	0.18	0.18	0.0324	0.1217	0.0148	1.2000
11	0.045	0.045	0.0020	0.0304	0.0009	0.1120
*Total r.m.s	1.479					
Sum				2.1876		11.6138

*r.m.s. current = square root of (2.1876)

K factor = 11.618

A K13 rated transformer is recommended for this load.

A1.5. European Practices- ‘Factor K’

The European practice as defined in BS 7821 Part 4 and HD 538.3.S1 defines a derating factor for a given transformer by a ‘Factor-K’.

$$K = \left[1 + \frac{e}{1+e}\left(\frac{I_1}{I}\right)^{2} \times \sum_{n+2}^{N} n^{q} \times \left(\frac{I_n}{I_1}\right)^{2}\right]^{0.5}$$

e = Eddy current loss at fundamental frequency divided by loss due to a D.C. current equal to the r.m.s. value of the sinusoidal current.

I = R.M.S. value of the sinusoidal current including all harmonics

$$= \sum_{n=1}^{n=N} (I_n)^2)^{0.5}$$

$$= I_1 \text{ fundamental} \times \left[\sum_{n=1}^{n=N} (I_n/I_1)^2\right]^{0.5}$$

I_n = magnitude of nth harmonic current.

q = Exponential constant dependent on type of winding and frequency
= 1.7 for round /rectangular section
= 1.5 for foil type low voltage winding.

Typical calculation (taking *q* as 1.7 and assuming that eddy current loss at fundamental is 10% of resistive loss i.e. e= 0.1) is given below.

Table A1-0-2: Sample calculation factor K

Harmonic No.	RMS Current	I_n/I_1	$(I_n/I_1)^2$	n^q	$n^q (I_n/I)^2$
1	1	1	1	1	1
3	0.82	0.82	0.6724	6.473	4.3525
5	0.58	0.58	0.3364	15.426	5.1893
7	0.38	0.38	0.1444	27.332	3.9467
9	0.18	0.18	0.0324	41.900	1.3576
11	0.045	0.045	0.0020	58.934	0.1193
Sum			2.1876		Σ=15.9653

Total r.m.s current, I = √(2.1876) = 1.479
$(I_n/I)^2$ = 0.457
$\Sigma \times (I_n/I)^2$ = 7.296
e/(1+e) = 0.091
K2 = (1 + 0.091 x 7.296) = 1.6639
K = 1.29

Transformer derating factor **= 1**/K = 1/1.29 x 100 = 77.52%

A1.4 Extra losses due to Harmonics – Estimation

As per IEC 61378-1 the R.M.S. current I_L with harmonics is given by $I^2_L = \sum_1^h I_h^2$

Where I_L is the r.m.s value of total current and I_h is the r.m.s value of the harmonic of order h.

If P_{WE} is the total eddy current loss in the winding, then

$$P_{WE} = \sum^{n} I_{Weh} = P_{WE1} \text{ (at fundamental) } \times \sum_1^n (I_h / I_1)^2 \times h^2$$

The other losses for oil cooled transformers and absent in dry type are P_{CE} in conductor (operating at a few kilo amperes) dependent losses and P_{SE} in structures are affected similarly but vary as $h^{0.8}$ instead of h^2.

$$\text{Thus } P_{CE} + P_{SE} = (P_{CE1} + P_{SE1}) \times \left[\sum_1^n (I_h/I_1)^2 \times h^{0.8} \right]$$

Thus for normal loads
$P_{T1} = P_{DC1} + P_{EXTRA1} = P_{DC1} + P_{WE1} + (P_{CE1} + P_{SE1})$ The last two are absent in dry type

For harmonic currents

$$P_T = P_{DC1} \times (I_L/I_1)^2 + P_{WE1} \times \left(\sum_1^n (I_h/I_1)^2 \times h^2\right) + (P_{CE1} + P_{SE1}) \left[\sum_1^n (I_h/I_1)^2 \times h^{0.8}\right]$$

The last two are absent in dry type transformers.

ANNEXURE-2: REFERENCES

1. IS 2026- 1977– Specifications for Power Transformers
2. IEEE Standard C57.12.90 – 1993: IEEE Standard Test Code for Dry Type Distribution Transformers
3. Energy Saving In Industrial Distribution Transformers- **W.T.J. Hulshorst, J.F. Groeman, KEMA**
4. Discussion on Transformer testing in the factory- William R. Herron III, ABB Power T&D Company Inc.
5. Harmonics, Transformers & K factors – Copper development Association – Publication 144