PART 1: General Overview

The transformers used in industry and in commercial buildings are generally less than about 1500 kVA in rating, although some may be up to 2500 kVA. However size and space limitations keep them to typically the 1000 kVA level. For interior use in buildings they are all naturally cooled apart from, in some cases, some rudimentary additional fan-cooling systems which may be installed some time after installation as an adjunct, perhaps to try to increase the maximum short–time rating of older transformers. Table 1 gives details of the range of distribution substation transformer ratings as used by Energy Australia. Note that the substations listed are not necessarily restricted to indoor types.

Because of the potential danger from fire in enclosed spaces, such as substations in buildings, the type of insulation of transformers in such installations is often somewhat different to that used in outdoor applications. Such outdoor transformers use oil-impregnated paper as the basic dielectric.
<table>
<thead>
<tr>
<th>Transformer type</th>
<th>Current rating (A/phase @415V)</th>
<th>Power rating (3-φ) in kVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pole mount</td>
<td>140-700A (5-25 @11kV)</td>
<td>100-500 kVA</td>
</tr>
<tr>
<td>Pad mount</td>
<td>1000A (40A @11kV)</td>
<td>750 kVA</td>
</tr>
<tr>
<td>Outdoor enclosure</td>
<td>1x1000kVA unit</td>
<td>1500A</td>
</tr>
<tr>
<td></td>
<td>2x1000kVA units</td>
<td>2000A</td>
</tr>
<tr>
<td></td>
<td>(60-75A@11kV)</td>
<td></td>
</tr>
<tr>
<td>Building substation</td>
<td>1x1000kVA unit</td>
<td>1400</td>
</tr>
<tr>
<td></td>
<td>2x1000kVA units</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td>2x1500kVA unit</td>
<td>3000</td>
</tr>
<tr>
<td></td>
<td>3x1500kVA units</td>
<td>5500</td>
</tr>
<tr>
<td></td>
<td>(50-200A@11kV)</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Range of standard substation transformers.

In the standard oil-impregnated paper transformer (Figure 1) the primary insulation is high quality very dry Kraft paper wound around the transformer winding conductors. This paper is then impregnated with a dry liquid dielectric to exclude any air bubbles, to keep moisture out of the paper and to provide good thermal circulation for heat dissipation. For outdoor applications the main liquid insulation in transformers is petroleum-based mineral oil, with the windings being encased in a tank of such oil. The problem is that such oil is highly flammable and, if used in
a building in an enclosed location, could represent a serious fire hazard. If mineral oil insulated transformers are used in buildings then the room must be fitted with automatic fire extinguishers and there must be a bund structure at the base of the transformer to contain all of the oil should it be discharged from the transformer. **Moisture** is a major problem with oil transformers and they need to have precautions against ingress of moisture, such as silica gel dryers.

Liquid insulated transformers are generally limited to the **Class A** materials temperature rise limits of about 60-70°C. Higher temperature rises can cause more rapid deterioration of the cellulose (paper) insulation on the windings and also deterioration of the oil itself. The lack of forced cooling and the relatively low insulation temperature limits put some constraints on the thermal ratings of such transformers for use in buildings.

Because of the potential for deterioration of the transformer insulation with temperature and possible contaminants it needs to be tested at regular intervals to determine the insulation efficacy and whether any deterioration has occurred. This is generally done in mineral oil transformers by dissolved gas analysis to monitor both oil and paper insulation and by dielectric dissipation factor (DDF) testing. These diagnostics will be covered in more detail later in the course.

The expense of fire precautions and the potential risk of fire in buildings has generated a current trend to use what are
effectively non-flammable transformers. There are two basic types of non-flammable transformers in use:

- the **liquid insulated type**, using synthetic oil and
- the **dry type** which uses solid resin insulation or varnished insulation to replace the oil.

1 **Synthetic liquid insulation materials**

1.1 **Askarel**

The initial move away from mineral oil (in the 1930s) was to the use of askarel liquid insulation. Askarel, which is essentially a polychlorinated biphenyl (PCB), is an artificial insulating oil which is almost non-flammable. It was used for many years in a large number of electrical applications, but although it is a very insulant it has some toxic effects, particularly if heated or burnt. **It is now banned from use in most countries.** It is quite likely, however, that there are still some PCB insulated transformers or capacitors in service.

1.2 **Silicone Oil**

Silicone insulating fluid, which is tetrachloro-benzyl toluene with about 40% trichlorobenzene, is essentially non-flammable and has no toxicity problems. It is the most favoured synthetic transformer insulating oil. It has a higher viscosity than mineral oil and askarel, and so its convective heat dissipation coefficient is not so good but its other
electrical properties are very similar to those of mineral oil, although it is quite a bit more expensive and for this reason its use is not widespread.

![Oil insulated distribution transformer](image)

**Figure 1:** Oil insulated distribution transformer
ONAN cooled type (Oil Natural Air Natural)

## 2 Dry Type insulation

Because of the cost of silicone oil and the need to provide expensive bund structures to hold the oil in case of a leak, there has been a very substantial move to dry-type transformers for use in buildings and in some industry sites (such as mines) in recent years. Dry types have no fluid
impregnation, as the name implies. Most also have a much higher temperature rating, being typically about class C (150°C). Such high temperature rating transformers may use higher temperature-withstand synthetic-paper insulation such as Nomex, rather than natural cellulose paper, on the winding conductors. This type of material is self-extinguishing if subjected to a flame from a fire.

There are two different generic forms of dry-type transformers:

- the open winding type (Fig 2a) and
- the epoxy cast-resin type (Fig 2b).

### 2.1 Open Winding type

This type is the true dry-type transformer and uses the simple structure of the (paper-insulated or nomex-insulated) winding in open air and in construction simply has many layers of insulating varnish coating applied to the windings. (see Fig 2a). There is a potential problem with moisture absorption and penetration into the varnish and insulation if these transformers are left un-energized for long periods of time. The paper on the copper windings will absorb moisture readily if the varnish layer is not absolutely impermeable. The moisture ingress will increase dielectric losses in the insulation (dielectric dissipation factor) and will also reduce the insulation strength. They are form-wound windings comprising copper or aluminium rectangular strip as can be seen from the structure.
2.2 Cast-resin type

These have the windings in a cast solid epoxy resin structure as shown in Fig. 2b. They are much less susceptible to moisture ingress and absorption. The application of the casting must be done very carefully however to ensure that the expansion coefficients of both the resin and the metal windings and core are the same (Al is better than Cu in this regard). Any differential expansion or contraction will cause cracking of the casting. In most modern cast resin types the LV windings will be of Al or Cu sheet. The windings are often sheet layers on the LV side. They are more costly than the open structure dry-type transformer and are often more expensive than silicone oil transformers.

Fig.2: Dry-type transformers (a) open winding (b) cast resin
2.3 **Gas insulated transformers**

The other form of non-flammable transformers that are being used increasingly in buildings and in high-density areas are SF$_6$ insulated transformers (Figure 3). They are very expensive but very reliable. SF$_6$ is a non-toxic gas with very good electrical insulation properties and with good thermal transfer properties. SF$_6$ transformers typically operate at about 2 atmospheres of gas pressure where the dielectric strength is similar to oil. The greenhouse problems of SF$_6$ may eventually force the pure SF$_6$ dielectric currently used to be replaced by an SF$_6$-N$_2$ mixture. The dielectric strength of a mixture of 20%SF$_6$ with 80%N$_2$ is about 80% that of pure SF$_6$.

![Fig.3: SF$_6$ gas insulated transformer](image)
2.4 Biodegradeable (vegetable) oil transformers

Disposal of standard mineral oil is a major problem to the electrical industry because of its very slow biodegradeability. Thus in recent years the use of natural vegetable (ester) oils such as olive oil, soya oil, rape seed oil etc has become relatively common. Such natural ester oils have a lower flammability than mineral oil, but a much more rapid biodegradeability. Their electrical characteristics are not greatly different to mineral oil and they appear to have one major electrical insulation advantage over mineral oil in that they are able to absorb much higher levels of moisture than mineral oil without loss of insulation level. This is important because the major problem with the insulation is the moisture absorbed in the paper. If the oil type used is able to extract more of the moisture from the paper then the degradation of the paper will be much slower.

3 Comparison of characteristics of different transformer types

3.1 Cost

Fig 4a shows a cost comparison of the various transformer types. The SF$_6$ and the cast resin are the most expensive and the mineral oil is the least expensive type. The cast resin type also has higher losses because of its more difficult thermal dissipation problems with thermal conduction being the only means possible for internal heat flow.
In its most general application the cost of the transformer must include capital cost of installation and the cost of total losses amortized over the predicted life of the transformer. This aspect will be discussed later.

### 3.2 Losses

Fig.4b shows a comparison of total losses (including the variable copper and the fixed iron losses) in cast-resin and silicone-insulated transformers at various loadings. At a high load factor (80%) there is essentially no difference in total loss: at 50% loading the silicone oil transformer has lower losses (because of its inherently lower no-load losses). [Load factor is the ratio of average load to full rated load of the transformer]. The generation, measurement and determination of losses will be covered later in the course.
**Comparison of losses of cast-resin and silicone-liquid-filled transformers**

<table>
<thead>
<tr>
<th>Rating (kVA)</th>
<th>Cast-resin</th>
<th>Silicone-filled</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>no load</td>
<td>load</td>
</tr>
<tr>
<td></td>
<td>loss (W)</td>
<td>loss</td>
</tr>
<tr>
<td></td>
<td>80% LF</td>
<td>50% LF</td>
</tr>
<tr>
<td>315</td>
<td>900</td>
<td>4000</td>
</tr>
<tr>
<td>500</td>
<td>1250</td>
<td>6000</td>
</tr>
<tr>
<td>800</td>
<td>1800</td>
<td>8700</td>
</tr>
<tr>
<td>1000</td>
<td>2200</td>
<td>10800</td>
</tr>
<tr>
<td></td>
<td>470</td>
<td>4600</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>6800</td>
</tr>
<tr>
<td></td>
<td>1130</td>
<td>9700</td>
</tr>
<tr>
<td></td>
<td>1380</td>
<td>11800</td>
</tr>
</tbody>
</table>

**Figure 4b: Comparative losses of cast-resin dry type and silicone-oil transformers**

<table>
<thead>
<tr>
<th>Losses in kilowatts at operating temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>No load</td>
</tr>
<tr>
<td>Oil</td>
</tr>
<tr>
<td>Akerel</td>
</tr>
<tr>
<td>Silicone</td>
</tr>
<tr>
<td>Dry-type, 150°C</td>
</tr>
<tr>
<td>Load 0.8</td>
</tr>
<tr>
<td>Total 4.0</td>
</tr>
<tr>
<td>Epoxy dry-type</td>
</tr>
<tr>
<td>Load 0.7</td>
</tr>
<tr>
<td>Total 3.9</td>
</tr>
</tbody>
</table>

**Figure 4c: Comparison of losses of different transformers types [For 1000kVA, 11kV/415V]**

Fig.4c shows similar a comparison of losses with the other types of transformers. The liquid insulated units are seen to be generally better than the dry-type units particularly at high load factors.
Use of amorphous core transformers is starting to gain ground for small distribution units and they have much lower core losses than standard silicon-steel core transformers.

3.3 Reduction of Insulation Life

During operation, the loading of the transformers is of particular importance as it determines the total losses and these, in turn, determine the operating temperature of, and hence any deterioration of, the transformer insulation. If the insulation temperature rises to too high a level for its class, then the transformer lifetime may be reduced. The increased temperature causes increased chemical reactions in the insulation and these lead to the deterioration by changing the insulation composition. As a general rule of thumb the 10°C rule is often used, whereby an increase of continuous operating temperature by 10°C causes a reduction of insulation life time by about 50%.

The loss of life versus temperature of operation details are given in typical loading guides for transformers which are published as Standards in most countries. In Australia they are in the Australian Standards AS 2374.7-1997 (oil-filled transformers) and AS 3953-1996 (Dry-type transformers). Both of these will soon be replaced by IEC-based standards.

See Fig. 5 for some typical data that can be used to determine insulation deterioration (or lifetime reduction) if loading details and temperature rises are known.
Figure 5: Rate of deterioration of transformer insulation with change in operating temperature.

[The overall average operating temperature can be determined from a mean load factor $K$, which is derived from cyclic loading details of the transformers.]

### 3.4 Transformer Impedance & Short Circuits

As the transformer impedance will be a major part of the impedance of any short circuit path, the effect of the transformer impedance on prospective fault current in a power system is very substantial and thus accurate transformer impedance data is needed to allow such
calculations to be performed to determine protection requirements. In some cases where accuracy is not paramount, general impedance data such as that shown in Fig 6 can be used for fault current determinations involving transformers. As can be seen, an average value of 5% or .05 per unit for transformer impedance (Z) is a good and often used approximation. Usually, the leakage inductance component is the major contribution to the impedance, particularly for high voltage transformers with their larger winding structure spacings.

For precise fault calculations the impedance must be known accurately from data given on the nameplate and the resistance and leakage inductance components must be known. The nameplate will generally give only total Z.

![Figure 6: (a) Typical impedance and corresponding typical fault levels for various ratings (b) Effect of impedance on fault levels of 11kV/415V transformers](image)
3.5 **Tappings on windings**

Distribution transformers used in buildings do not normally have on-load tap changing (OLTC) facilities to adjust voltage level. However they do have permanent taps which can be altered to allow about a +/-10% variation in voltage output level, usually in about 1% steps.

The taps must be manually changed while the transformer is de-energised and isolated. The tapping points are normally on the high voltage windings only.

Figure 7 shows a large distribution transformer with on-load tapchanger. The tapchanger is at left of the three windings.

![Figure 7: Transformer with on-load tap changing [rating about 5000kVA]](image)
3.6 Connections

In general, building distribution transformers are star-connected on the low voltage side to eliminate circulating triplen harmonics ($3^{\text{rd}}$, $9^{\text{th}}$, $15^{\text{th}}$ etc.) in a delta-connected three-phase winding. The high voltage side is almost always delta connected.

There are many possible variations of winding connections of transformers. These variations can affect the magnitude of the voltages but more particularly they change the phase shift between the primary and secondary windings. There are about 20 different connections possible if the use of zig-zag earths on transformers with delta windings is included, but the most common winding connections for standard distribution transformers are:

- **DY11**
- **DY1**
- **DY5**
- **DY7**

DY11 is the most commonly used connection for distribution transformers: it gives a 30° phase shift between primary and secondary. See Fig. 8 for the corresponding vector diagrams and an explanation of phase shift symbols and phase shift values.
Figure 8: Different connections of windings in transformers and associated vector diagrams.
3.7 **Cable terminations**

Cable terminations to distribution transformers are generally achieved by means of a cable box on the transformer at the high voltage and low voltage sides for both types of transformer with paper insulated cable.

Figure 9 shows examples of medium voltage (11 kV) cable terminations. Note the use of skirts in some cases to increase creepage path lengths for cases where the termination is exposed to air and possible contaminants.

The LV cable box is usually air insulated, but the high voltage cable box is compound-filled with petroleum grease or some similar viscous insulant. Good sealing of the cable box is necessary to keep the moisture out.

The modern preference for use of XLPE cable makes terminations in the cable box a little simpler in that moulded heat-shrink terminations are able to be used: these
can be relatively easily applied for both high and low voltages. Paper insulated joints and terminations at high voltage are much more difficult to produce and require considerable expertise to achieve good results (that is, a joint without insulation problems).

Fig 10a
Electric field stress control in a cable termination -
A: geometric method
B: high permittivity

Fig 10b
Component parts of a heat shrink cable termination
3.8 Parallel Operation of transformers

When transformers are used in parallel it is necessary to ensure that they satisfy the following requirements:

- Have the same voltage ratios
- The same tapping points in use (that is the same voltage)
- Have the same vector diagram (same phase shift between primary and secondary)
- The same impedance angle (this is preferable but not imperative).

If these conditions are not designed for, problems will occur. For example:

1. There will be unequal loading of the transformers if the impedance angles vary. This can lead to overloading of one transformer and a lighter loading of the other. The same principles that apply to the sharing of load in parallel-connected feeders also apply to transformers.

2. If the voltage ratio or the tapping points are not the same there will be circulating currents set up in the two transformers which will lead to possible overheating of the transformers and possible change in operation points on the magnetization curves.

3. If the vector diagrams are different then the line and phase voltages will be intermixed and insulation stress will be stressed.
1 Construction

The basic power transformer comprises paper-insulated copper windings wound around a laminated magnetic steel core. For 50 – 60 Hz operation the core is laminated grain-oriented silicon-steel (or more rarely an amorphous magnetic metal core to reduce eddy current loss). For high frequency operation, where eddy current losses in the core become too high, even if it is laminated or amorphous, transformers use a ferrite core which has very high electrical resistance and will thus have no eddy current loss. For instrument transformers (current and voltage transformers [CTs and VTs]) where the core losses contribute to the measurement uncertainty, high permeability, low loss, materials such as Mu-metal are used in the core for higher accuracy in metering applications.

Usually the two windings (primary and secondary) are wound on the same limb of the core to reduce leakage flux. The high voltage winding is normally the outer winding, as shown in Figure 1, because of the higher electric field associated with it. Note that there are two standard core configuration forms in general use. These are:

- The Core Form
- The Shell Form
Figures 1 and 2 show the two typical core arrangements for both single and three phase units. Note the different magnetic circuits which result from the two configurations of cores. The Core Form is the most prevalent type in use in Australia and in most other countries. The shell form was manufactured primarily in the USA.

![Figure 1: Core and winding structure of a single phase transformer: (a) Core type, (b) Shell type](image1)

![Figure 2: Core construction of 3-phase transformer (a) Core type (b) Shell type or 5 limb core](image2)

The windings are normally composed of paper-insulated copper strip or enameled wire. The insulation on the copper is either lapped paper (with oil impregnation in oil-filled transformers) or enamel or possibly Nomex tape (synthetic paper) in the case of dry-type transformers.
In some oil-type distribution and most dry type transformers the LV winding may be in sheet form (usually aluminium) with layers of insulating sheet material such as polypropylene between the layers. In cast resin dry-types the aluminium thermal expansion coefficient is much closer to that of the epoxy resin. There is some difference with copper and that can lead to differential expansion stresses.

The windings of main power transformers are all form-wound as opposed to being random-wound structures. There are two general winding configurations in use:

- Concentric layer winding: these windings are helical layers wound axially along the core and the HV and LV windings are laid concentrically.

- Sandwich windings: these windings are of the pancake or disc type with radial rather than axial extension on the core. The HV and LV pancake winding discs are then sandwiched together as shown in Figure 3.

![Figure 3: Types of transformer winding](image)

(a) Concentric, (b) Sandwich – made up of disc sections.
2 Equivalent Circuits of Transformers

Figure 4a shows an ideal transformer with perfect flux coupling (no leakage outside the magnetic circuit) between the primary and secondary windings. The equivalent circuit for this is shown in Figure 4b. Only the winding resistance is needed in the equivalent circuit. The transformer (the mutual coupling section) is taken as ideal, with no losses and no saturation effects and infinite permeability. Thus there is no magnetisation current needed and no distortion. With perfect coupling and no magnetisation current the mutual inductance of the windings shown will be infinite as expected with a core material of infinite permeability and no leakage flux.

However, in a practical transformer, the coupling of flux is not perfect and there will be some flux leakage, as shown in Figure 5a. There will be leakage at both HV and LV windings and this leakage flux will appear as a leakage self-inductance (mostly in air) in each winding. This represents the main internal impedance in a high voltage transformer.
The equivalent circuit must now include this leakage inductance, as shown in Figure 5b.

![Figure 5a: Leakage Flux](image)

Primary Flux = $\Phi + \Phi_{1P}$, Secondary Flux = $\Phi + \Phi_{1S}$, Common flux = $\Phi$

$\Phi_{1P}$ and $\Phi_{1S}$ are leakage fluxes, typically $\Phi_1 \sim 1-6\%$ of $\Phi$

![Figure 5b: Equivalent circuit with leakage inductance](image)

For high voltage transformers the inductive reactances $X_p$ and $X_s$ are generally much higher than the winding resistances $R_p$ and $R_s$ and the leakage reactance thus represents the main short circuit impedance of the transformer. The total impedance is generally about $Z = 3 -$
8 % (usually called the impedance voltage rather than the impedance). Note that the percentage is based on the rated or base impedance of the transformer, $Z_B$:

$$Z_B = \frac{V_{\text{Rated}}}{I_{\text{Rated}}}$$

where $V_{\text{rated}}$ and $I_{\text{rated}}$ are the nameplate voltage and current for the transformer. Note that for $Z = 5\%$,

$$Z = 0.05Z_B = 0.05\frac{V_R}{I_R}$$

and for a terminal short circuit $I_F = \frac{V_R}{Z} = \frac{V_R}{0.05Z_B} = 20I_R$ or 20 per unit of the transformer rated current.

3 Excitation Requirements

(a) Magnetising current $I_m$

Because the core is not infinitely permeable it requires some finite level of ampere turns (magnetic potential - $N_1I_m$) in the windings to establish the flux in the core, even with no load connected. Because the core is not of zero reluctance (ie has finite permeability), there will be some finite inductance of the core and the winding used to magnetise the core. This magnetising inductance ($L_m$) will be defined by:

$$\Phi = L_mI_m$$
where $\Phi$ is the core flux and $I_m$ is the magnetising current.

Note that by using the magnetising inductance in the equivalent circuit we are taking the mutual coupling section of the transformer to be an ideal transformer, as below where $X_m$ is the magnetizing reactance, $X_m = \omega L_m$.

![Equivalent Circuit with Ideal Transformer](image)

**b) Core power loss and $I_c$**

Core losses are quite significant in large power transformers and they must be included in the equivalent circuit representation. (In instrument transformers these core losses will be the major source of error in the measurement of current and voltage). The loss is included by insertion of a notional core loss resistance $R_c$ connected in shunt as shown in Figure 6a.

The value of the notional resistance is determined by use of the equivalent core loss current $I_c$, such that

$$I_c = V_p / R_c$$

$$P_c = I_c^2 R_c = V_p^2 / R_c$$
where $V_p$ is the primary voltage and $P_c$ is the core loss.

Thus:  
$$R_c = \frac{V_p^2}{P_c}$$

(c) Total exciting current $I_o$

This is  
$$I_o = I_c + jI_m$$

Thus the full equivalent circuit is as shown in Figure 6a.

![Figure 6a: Full equivalent circuit](image)

We can exclude the ideal transformer part of the equivalent circuit by rescaling the voltages and impedances on the secondary side using the usual turns ratio squared ($a^2$) calculation. Note that $a$ is that ratio of primary turns to secondary turns.

We then have Figure 6b below where all quantities are referred to the primary side, or we can have Figure 6c below where all quantities are referred to the secondary side.
Normally the primary and secondary quantities are all lumped together to give the most general equivalent circuit as shown in Figure 6d below where:

\[ R = R_p + a^2R_s \quad ; \quad X = X_p + a^2X_s \quad \text{and} \quad Z = R + jX \]
Note that $I_m$ will lag $V_1$ by $90^\circ$ and that $I_c$ will be in phase with $V_1$ (barring small differences caused by $R$ and $X$). The magnetic flux $\Phi$ in the core will be in phase with $I_m$ and will lag $V_1$ by $90^\circ$.

Thus, the phasor diagram of the final equivalent circuit is as shown below in Figure 7 (using $V_2$ as the phase reference).

![Figure 7](image)

**Figure 7**

*Phasor diagram of the transformer equivalent circuit*

Note that when the secondary is short-circuited the effective transformer impedance $Z$ determines the fault current. This is the normal method of determination of the transformer impedance $Z$ (*the Short Circuit Test*). The secondary is shorted and the primary volts are raised until rated current $I_2$ flows in the secondary circuit. Then:

$$V_{l(test)} = Z \times I_2$$

Because $I_2$ is the rated current value, [1 per unit or 100% in percentage terms],
\[ Z\% = V_{1\text{ (test)}}(\%) \]

The transformer nameplate will give a percentage value for \( Z \), which is termed the **Impedance Voltage** rather than the impedance because of the above relationship.

Note that
\[ |Z| = \sqrt{\left( R^2 + X^2 \right)} \]
and the leakage reactance \( X \) is thus able to be determined from the equation:
\[ X = \sqrt{\left( Z^2 - R^2 \right)} \]

\( R \) is the total winding resistance referred to one side of the transformer and is able to be measured with a resistance meter (measuring both primary and secondary resistance and then combining them using the turns ratio).

Note however that \( R \) will be very temperature dependent and thus it should be measured at or near normal operating temperature of the transformer if it is to be used in determining internal thermal generation or for voltage regulation. The governing equation is:
\[ R = R_{20}(1 + \alpha[T - 20]) \]  where \( \alpha \) is 0.004 for copper.

The difference between \( R \) at 20 C and at normal operating temperature may be as much as 28% for a 70 degree rise in temperature \([T-20]\) above ambient. This will mean a 28% increase in heat loss in the windings.
**Problem Example:**

Consider a 4000/400V 10kVA transformer which has the following characteristics:

- Primary winding resistance: $R_p = 13\,\Omega$
- Secondary winding resistance: $R_s = 0.15\,\Omega$
- Total leakage reactance referred to primary: $X_p = 45\,\Omega$
- Magnetising reactance referred to primary: $X_m = 6k\,\Omega$
- Core loss resistance referred to primary: $R_c = 12k\,\Omega$

Determine:

1. total $R$ and $Z$ for transformer, referred to the primary.
2. $R$ and $Z$ referred to the secondary and also all impedances referred to the secondary.
3. the input current when:
   - a) the secondary is open circuit
   - b) $I_2 = 25A$ at 0.8 lagging PF
4. $I_m$, $I_c$, $I_o$ and the total core loss and the winding (load) loss in case (b).
5. the total transformer power loss at full load and the full load efficiency at unity PF.

**Solution:**

\[
\text{Ratio} = a = \frac{N_1}{N_2} = \frac{4000}{400} = 10
\]

Thus \[R_{\text{eq}} = 13 + 0.15 \times 10^2 = 28\,\Omega\]
\[ Z_{1eq} = 28 + j45 \ \Omega \]
\[ R_{2eq} = R_{1eq} \times \frac{1}{a^2} = \frac{28}{100} = 0.28\Omega \]
\[ X_{2eq} = 45 \times \frac{1}{100} = 0.45\Omega \]
\[ X_{m2} = \frac{6000}{100} = 60\Omega \]
\[ R_{c2} = \frac{12000}{100} = 120\Omega \]
\[ I_c = \frac{4000}{12000} = 0.33A \text{ (in phase with } V_1) \]
\[ I_m = \frac{4000}{6000} = 0.67A \text{ (lag } V_1 \text{ by } 90^\circ) \]

Hence: \[ I_o = 0.33 - j0.67 = 0.745 \angle -63.5^\circ \ \text{ A} \]

When \( I_2 = 25A \), \( I_2 = 25 \angle -36.9^\circ \)

Thus, referred to primary: \( I_{21} = 2.5 \angle -36.9^\circ = 2.0 - j1.5 \ \text{ A} \)

Hence: \[ I_1 = I_{21} + I_o \]
\[ = (2.0 - j1.5) + (0.33 - j0.67) \]
\[ = 2.33 - j2.167 = 3.18 \angle -43^\circ \ \text{ A} \]

Core loss = \( R_c I_c^2 = 12000 \times 0.33^2 = 1333 \ \text{ W} \)
Copper loss \( = R_{\text{eq}} I_1^2 = 28 \times 3.18^2 = 283 \text{ W (at load)} \)

Total loss \( = 1616 \text{ W} \)

Efficiency \( = \frac{10000}{10000 + 1616} = 86.1\% \)

At 50% of full load, the efficiency is:

\[ \eta = \frac{5000}{5000 + [1333 + 71]} = 78.1\% \]

4 Transformer losses

Losses in transformers are composed of two separate components:

a) Load (copper) loss in the resistance of the windings
b) Core (iron) loss in the core material (Hysteresis and Eddy current loss)

The copper loss \( (I^2R) \) is load-dependent and scales as the square of load current \( I_L \). The loss will also be temperature-dependent through the resistance variation with temperature of the winding.

The core loss is constant whenever the transformer is energised. Core loss is thus independent of the load.
[There is also another loss component, which is caused by eddy current loss in the steel tank and in any other metal which is coupled by the AC magnetic field of the transformer. However this loss component is often neglected but it can be significant and is important to take into account in the efficiency determination]

**Total copper loss** is thus: (neglecting stray losses)

\[ P_{\text{Cu}} = I_1^2 R_1 + I_2^2 R_2 \]

\[ = I_1^2 R_{1\text{eq}} \text{ watts} \]

**Core loss** is:

(i) Hysteresis loss \[ H = k_h \times f \times B_m^n \text{ W/m}^3 \]

where \( f \) is frequency, \( B_m \) is peak flux density, \( k_h \) is a constant of the material and of the core configuration. \( k_h \) and \( n \) are empirical values based on measured data. The exponent \( n \) is material dependent and is in the range:

\[ 1.5 < n < 2.5 \] (often use \( n = 2 \))

(ii) Eddy current loss \[ E = k_e \times f^2 \times B_m^2 E \text{ W/m}^3 \]

where \( k_e \) is a constant of the material and of the configuration. It is also temperature dependent as it includes the material resistivity.
Total Core Loss:

\[ P_{\text{total}} = H + E \]

\[ = (k_h + k_e f) f B_m^2 \quad (\text{for } n = 2) \text{ W/m}^3 \]

Note the effect of frequency: there is a significant effect even between 50 and 60 Hz and this can be an important difference.

<table>
<thead>
<tr>
<th></th>
<th>50Hz</th>
<th>60Hz</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hysteresis</td>
<td>1.0</td>
<td>1.2</td>
<td>20% increase</td>
</tr>
<tr>
<td>Eddy Current</td>
<td>1.0</td>
<td>1.44</td>
<td>44% increase</td>
</tr>
</tbody>
</table>

5 Transformer Efficiency

5.1 Power efficiency

When supplying a load, the transformer power efficiency is given by:

Efficiency \( \eta \) = \( \frac{\text{Power Out}}{\text{Power In}} = \frac{\text{Power Out}}{\text{Power Out} + \text{Losses}} \)

\[ = 1 - \frac{\text{Losses}}{\text{Power Input}} \]

For a load with voltage \( V_2 \), current \( I_2 \) and power factor \( \cos \phi \),

\[ \eta = \frac{V_2 I_2 \cos \phi}{V_2 I_2 \cos \phi + I_2^2 R_{\text{eq}} + P_{\text{core}}} \]
Transformers are very efficient items of power equipment, with efficiencies normally in the range of 95 – 99%, but the efficiency is obviously dependent on the load and on the load power factor.

It can be shown easily that maximum power efficiency of the transformer occurs when the load is such that

\[ P_{\text{core}} = I_2^2 R_{2\text{eq}} \]

That is, when \( \text{core loss} = \text{load loss} \)

For typical distribution transformers at full load, \( \text{load loss} \approx 3 – 4 \times \text{core loss} \)

Thus, the load for maximum power efficiency is about 50 – 60% of rated load. [the transformer in the previous problem example was not a typical transformer as the maximum efficiency occurred at 2.15 per unit load!]

5.2 Transformer Energy Efficiency

\( \eta \) is the instantaneous power efficiency of the transformer. However, because the load will vary (usually) in a cyclic manner, a more useful quantity to give efficiency of operation is the energy efficiency. This takes into account the duty cycle of the transformer operation and will take account of the core loss during no-load and light load situations.
For example, for a daily load duty cycle of the following:

- 8 hours at full load, 0.8 lagging
- 6 hours at 0.6 per unit, 0.8 lagging
- 6 hours at 0.4 per unit, unity PF
- 4 hours at no load (but energised)

The energy efficiency is given by the following equation:

\[
\eta = \frac{\text{24hr energy supply}}{\text{24hr energy supply} + \text{24hr energy loss}}
\]

Thus:

\[
\eta = \frac{V_2 I_2 [8 \times 0.8 + 6 \times 0.6 \times 0.8 + 6 \times 0.4 \times 1.0 + 0]}{V_2 I_2 [8 \times 0.8 + 6 \times 0.6 \times 0.8 + 6 \times 0.4] + 24P_c + \text{total } E_{Cu}}
\]

6 **Transformer Tests**

There is a need to monitor transformer load to make the most effective use of the transformer. It is also necessary to know the core and load losses. These will normally be given on the nameplate, but the hysteresis losses and eddy current losses will not be separated and this may cause some problems if there are harmonics to contend with. Thus some tests may need to be done.

6.1 **Open Circuit Test**  [for core loss determination]

This test requires normal operating flux in the core and hence needs rated voltage to be applied. There is no load connected so there is no load loss contribution in the
measured power, which is thus only the (constant) core loss \( P_o \).

The test (with circuitry outlined in Figure 8 below) requires measurement of supply voltage (rated value) \( V_1 \), exciting current \( I_0 \) and exciting real power \( P_0 \). It should be noted that \( I_0 \) is not sinusoidal because of the non-linearity of the B-H magnetising curve of the core material. This needs to be considered in choosing the ammeter and the wattmeter types.

\[ P_0 = \text{total core loss} \]

\[ I_m = I_0 \sin \phi_0 \quad I_c = I_0 \cos \phi_0 \]

\[ R_c = \frac{V_1}{I_c} = \frac{V_1^2}{P_0} \quad X_m = \frac{V_1}{I_m} = \frac{V_1}{I_0 \sin \phi_0} \]
Figure 9a

Distortion of the magnetizing current waveform
Upper trace: magnetizing current waveform
Lower trace: exciting voltage waveform

Figure 9a above shows the non-sinusoidal magnetizing current when excited with a sinusoidal voltage. This is caused by the non-linear magnetization curve of the steel core materials as shown in Figure 9b.

Figure 9b
Magnetisation curve for typical steel
6.2 Short Circuit test [for load loss determination]

In this case, the $I_2$ (and $I_1$) is the rated current, but the applied voltage $V_1$ is the impedance voltage level, only about 5%. Thus the core flux density $\phi$, is only about 5% and thus core loss is negligible, but full rated currents flow in the windings so that the measured power $P_{sc}$ is the copper loss in the winding resistances only. The test configuration is shown in Figure 10.

![Figure 10](image)

Open circuit test configuration

The test requires measurement of $P_{sc}$, $V_1$, $I_1$ and $I_2$. The test results give the copper loss and also $Z_{eq}$ and total winding resistance $R_{eq}$ and thus leakage reactance $X_{eq}$. The temperature dependence of the winding resistances must be taken into account in the results of this test.

$$\cos \phi_{sc} = \frac{P_{sc}}{V_1 I_1}$$

$$Z_{1eq} = \frac{V_1}{I_1} \cos \phi_{sc} + j \frac{V_1}{I_1} \sin \phi_{sc}$$

$$= (R_1 + R_2') + j (X_1 + X_2')$$

$$P_{sc} = I_1^2 (R_1 + R_2') = \text{total copper loss}$$
7 Effects of Harmonics on Transformer Operation

The increasing level of harmonic content in the general power supply waveform is causing some potential problems for all electrical equipment items with magnetic core materials. This includes in particular the transformer. In addition, there is also an increase in the number of non-linear loads that are being used, particularly from the increasing use of power electronic controllers. Figure 11 shows the harmonic content of a typical PC.

![Harmonic profile of a typical PC](image)

**Figure 11**
Harmonic spectrum of a typical PC with switch-mode supply

A major additional source of harmonic content in the near future is going to be in the use of large numbers of compact fluorescent lamps when incandescent lamps are eventually phased out and banned from use.
Such non-linear loads are a problem because the losses which are generated in the transformer are frequency dependent and, on a relative basis, the heating by the harmonic components scales with frequency.

If there is harmonic content in the supply voltage, the **core losses scale with the square of frequency**. If the harmonic content of the load current is high, such as may occur with power electronic devices, there is a frequency dependent increase in the copper loss due to eddy currents (skin effect) and the transformer may need to be de-rated so that it does not overheat with a high harmonic load.

In the following, the considerations of increased losses in transformers due to harmonics are those due only to current in the load and thus the increase is in the load loss due to eddy current generation by harmonic currents in the primary and secondary windings. The harmonic currents may also cause some harmonic distortion of the exciting voltage by virtue of the effect of the distorted current on the voltage drop in the leakage reactance of the equivalent circuit. This voltage harmonic distortion (from an assumed pure sinusoid) could then also lead to increased losses in the core material in addition to the windings. However it is found that the **effect on the core loss of load current harmonics is not generally significant** and thus it is usually neglected and only the load loss increase is considered when de-rating calculations are performed. This approach thus assumes a pure sinusoidal supply voltage.
There are two approaches to estimating the de-rating required for the transformer:

- the CBEMA (Computer and Business Equipment Manufacturer’s Association) **Crest Factor Method**
- the IEEE **K-Factor Method**

### 7.1 CBEMA Crest Factor

The Crest Factor is defined as the ratio of the peak value of the current (amps) of the distorted waveform to the true RMS value (amps) of the distorted waveform.

\[
\text{Crest Factor} = \text{C.F.} = \frac{\text{Peak current (amps)}}{\text{True RMS current (amps)}}
\]

The de-rating factor is then determined by the ratio of 1.414 (\(\sqrt{2}\)) to the calculated crest factor.

\[
\text{De-rating Factor} = \frac{1.414}{\text{C.F.}}
\]

Thus, for a pure sine wave, the C.F. is 1.414 and the de-rating factor is then unity (1.0). For a crest factor of 2.0, the de-rating factor will then be 0.707. Thus in the latter case a 100kVA transformer would need to be de-rated to about 70kVA to avoid overheating.

While the above approach is a simple method it has some faults:
(i) the peak value of current is not necessarily truly representative of the harmonic content. Two different waveforms with the same level of total harmonic distortion (THD) may have quite different values of peak current.

(ii) the measurement of the current data needed to calculate the crest factor requires an oscilloscope and a true RMS current meter. In particular the need for an oscilloscope is unwieldy for testing.

For these reasons the CBEMA crest factor method is not widely used and the more quantitatively accurate K-factor method is preferred.

### 7.2 The K-Factor Method

The **total harmonic distortion (THD)** of a current waveform is defined as:

\[
\text{THD} = \sqrt{\sum_{n=2}^{\infty} \left( \frac{I_n}{I_1} \right)^2}
\]

where \( n \) is the harmonic number and \( n=1 \) is the fundamental (50 Hz) component.

The **K–factor** is defined as:
\[ K = \sum_{n=1}^{\infty} \frac{I_n^2}{n^2} \]

where \( I_n \) is the nth harmonic current in amps

### 7.2.1 Application of the K-Factor

Because \( I_{n(\text{pu})} = \frac{I_n}{I_{\text{RMS}}} \)

where \( I_{n(\text{pu})} \) is the per unit value of the nth harmonic current and \( I_{\text{RMS}} \) is the true RMS current, we can express the K-factor as:

\[ K = \frac{\sum_{n=1}^{\infty} I_{n(\text{pu})}^2}{\sum_{n=1}^{\infty} I_{n(\text{pu})}^2 \cdot n^2} \]

Because the eddy current losses scale as the square of frequency, the K-factor provides a useful indicator of the increased heating due to the harmonic content. It further gives a quantitative means of calculating the de-rating factor for transformers. Figure 12 gives a typical de-rating curve for a transformer when supplying a highly non-linear (high K value) load.

Typically, K may vary up to 20 or more for badly distorted current waveforms.
7.2.2 Calculation method for transformer de-rating factor

The total losses ($P_{LL}$) are defined as:

$$P_{LL} = I^2 R + P_{EC}$$

where:

$I^2 R$ = total winding loss at pure 50Hz operation.

$P_{EC}$ = eddy current loss in the windings

We also define $P_{EC(R)}$ to be the eddy current loss at rated current ($I_R$) at 50 Hz.
Thus

\[ P_{EC} = P_{EC(R)} \sum_{n=1}^{\infty} \left( \frac{I_n}{I_R} \right)^2 \cdot n^2 \text{ watts} \]

Thus

\[ P_{EC(pu)} = \frac{P_{EC}}{P_{EC(R)}} = \sum_{n=1}^{\infty} \left( \frac{I_n}{I_R} \right)^2 \cdot n^2 \]

\[ P_{EC(pu)} = P_{EC(R)pu} \sum_{n=1}^{\infty} I_{n(pu)}^2 \cdot n^2 \]

We also have:

\[ P_{LL(R)pu} = 1 + P_{ECpu} \]

And for rated load

\[ P_{LL(R)pu} = 1 + P_{EC(R)pu} \]

Using

\[ I = \sqrt{\sum_{n=1}^{\infty} (I_n)^2} \]

\[ I_{pu} = \sqrt{\sum_{n=1}^{\infty} I_{n(pu)}^2} \]

\[ P_{LL(pu)} = \sum_{n=1}^{\infty} I_{n(pu)}^2 + P_{EC(R)pu} \sum_{n=1}^{\infty} I_{n(pu)}^2 \cdot n^2 \]

The maximum permissible current is given by:

\[ I_{\text{max}(pu)} = \sqrt{\frac{P_{LL(R)pu}}{1 + K \cdot P_{EC(R)pu}}} = \sqrt{\frac{1 + P_{EC(R)pu}}{1 + K \cdot P_{EC(R)pu}}} \]
Example:

100kW of personal computers are supplied from a transformer rated at 150kVA. Given that the harmonic current levels caused by the computers are as shown below, and that $P_{EC(R)} = 10\%$, calculate the K-factor and the required de-rating factor of the transformer.

<table>
<thead>
<tr>
<th>Harmonic no.</th>
<th>% of fundamental</th>
<th>Harmonic no.</th>
<th>% of fundamental</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>17</td>
<td>1.8</td>
</tr>
<tr>
<td>2</td>
<td>0.2</td>
<td>19</td>
<td>1.1</td>
</tr>
<tr>
<td>3</td>
<td>66</td>
<td>21</td>
<td>0.6</td>
</tr>
<tr>
<td>4</td>
<td>0.4</td>
<td>23</td>
<td>0.8</td>
</tr>
<tr>
<td>5</td>
<td>38</td>
<td>25</td>
<td>0.4</td>
</tr>
<tr>
<td>6</td>
<td>0.4</td>
<td>27</td>
<td>0.2</td>
</tr>
<tr>
<td>7</td>
<td>13</td>
<td>29</td>
<td>0.2</td>
</tr>
<tr>
<td>8</td>
<td>0.3</td>
<td>31</td>
<td>0.2</td>
</tr>
<tr>
<td>9</td>
<td>4.5</td>
<td>33</td>
<td>0.2</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>5.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>1.9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

[In this case $I_1 = \text{rated current} = 1.0 \text{ pu} \]
We can neglect even harmonics in this case and just use odd harmonics. In calculating the harmonic contribution to the K-factor value, we stop when the contribution of a high harmonic becomes negligible. In this case this occurs after the 25th harmonic.

We construct the table as follows:

<table>
<thead>
<tr>
<th>n</th>
<th>Current (pu)</th>
<th>Freq. (Hz)</th>
<th>$I_{n(\text{pu})}^2$</th>
<th>$n^2$</th>
<th>$I_{n(\text{pu})}^2 \times n^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.00</td>
<td>50</td>
<td>1.0000</td>
<td>1</td>
<td>1.0000</td>
</tr>
<tr>
<td>3</td>
<td>0.66</td>
<td>150</td>
<td>0.4356</td>
<td>9</td>
<td>3.9204</td>
</tr>
<tr>
<td>5</td>
<td>0.38</td>
<td>250</td>
<td>0.1444</td>
<td>25</td>
<td>3.6100</td>
</tr>
<tr>
<td>7</td>
<td>0.13</td>
<td>350</td>
<td>0.0169</td>
<td>49</td>
<td>0.8281</td>
</tr>
<tr>
<td>9</td>
<td>0.045</td>
<td>450</td>
<td>0.0020</td>
<td>81</td>
<td>0.1640</td>
</tr>
<tr>
<td>11</td>
<td>0.053</td>
<td>550</td>
<td>0.0028</td>
<td>121</td>
<td>0.3399</td>
</tr>
<tr>
<td>13</td>
<td>0.025</td>
<td>650</td>
<td>0.0006</td>
<td>169</td>
<td>0.1056</td>
</tr>
<tr>
<td>15</td>
<td>0.019</td>
<td>750</td>
<td>0.0004</td>
<td>225</td>
<td>0.0081</td>
</tr>
<tr>
<td>17</td>
<td>0.018</td>
<td>850</td>
<td>0.0003</td>
<td>289</td>
<td>0.0936</td>
</tr>
<tr>
<td>19</td>
<td>0.011</td>
<td>950</td>
<td>0.0001</td>
<td>361</td>
<td>0.0437</td>
</tr>
<tr>
<td>21</td>
<td>0.006</td>
<td>1050</td>
<td>3.6E-5</td>
<td>441</td>
<td>0.0159</td>
</tr>
<tr>
<td>23</td>
<td>0.008</td>
<td>1150</td>
<td>6.4E-5</td>
<td>529</td>
<td>0.0339</td>
</tr>
<tr>
<td>25</td>
<td>0.004</td>
<td>1250</td>
<td>1.6E-5</td>
<td>625</td>
<td>0.0100</td>
</tr>
</tbody>
</table>

Totals:  

$$\sum_{n=1}^{\infty} I_{n(\text{pu})}^2 = \sum_{n=1}^{\infty} I_{n(\text{pu})}^2 \times n^2 = 1.6031 \quad 10.1732$$
Thus:

\[
K = \frac{\sum_{n=1}^{\infty} I_n^{2} (pu) \cdot n^2}{\sum_{n=1}^{\infty} I_n^{2} (pu)} = \frac{10.1732}{1.6031} = 6.35
\]

For the de-rating calculation:

\[
I_{\text{max}(pu)} = \sqrt{\frac{1 + P_{EC(R)pu}}{1 + K \cdot P_{EC(R)pu}}}
\]

The value of \( P_{EC(R)pu} \) will normally be available from the manufacturer. We take a typical value of 0.1 in this example:

Thus

\[
I_{\text{max}(pu)} = \sqrt{\frac{1 + 0.1}{1 + 6.35 \times 0.1}} \text{ pu}
\]

\[
= 0.82 \text{ pu}
\]

Thus, the de-rated permissible loading of the 150 kVA transformer is:

\[
0.82 \times 150 = 125 \text{ kVA}
\]
Performing the same calculation as above for the same $P_{EC(R)} = 0.1$, but for different values of $K$, we find the following de-rating factors:

<table>
<thead>
<tr>
<th>K</th>
<th>$I_{\text{max(pu)}}$</th>
<th>kVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.96</td>
<td>144</td>
</tr>
<tr>
<td>10</td>
<td>0.74</td>
<td>111</td>
</tr>
<tr>
<td>20</td>
<td>0.61</td>
<td>91</td>
</tr>
<tr>
<td>30</td>
<td>0.52</td>
<td>78</td>
</tr>
</tbody>
</table>

7.3 **Comparison of the Crest factor values and the IEEE values for the same loads**

The table below shows the variance of the two methods for a wide range of building loads with various harmonic levels. A negative value means the CBEMA value is lower and positive that the IEEE value is lower. Reference value is the IEEE value.

$$\left[ \frac{\text{CBEMA kVA} - \text{IEEE kVA}}{\text{IEEE kVA}} \times 100 \right]$$
<table>
<thead>
<tr>
<th>#</th>
<th>Building Type</th>
<th>% Variance</th>
<th>Average Crest Factor</th>
<th>% Variance</th>
<th>Average Crest Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Office Building</td>
<td>-8.93%</td>
<td>1.95</td>
<td>49. Office Building</td>
<td>-0.67%</td>
</tr>
<tr>
<td>2</td>
<td>Office Building</td>
<td>17.45%</td>
<td>2.84</td>
<td>50. Office Building</td>
<td>-0.41%</td>
</tr>
<tr>
<td>3</td>
<td>Office Building</td>
<td>5.36%</td>
<td>2.18</td>
<td>51. Office Building</td>
<td>3.24%</td>
</tr>
<tr>
<td>4</td>
<td>Office Building</td>
<td>8.16%</td>
<td>2.27</td>
<td>52. Office Building</td>
<td>-1.52%</td>
</tr>
<tr>
<td>5</td>
<td>Office Building</td>
<td>11.62%</td>
<td>2.23</td>
<td>53. Office Building</td>
<td>-0.70%</td>
</tr>
<tr>
<td>6</td>
<td>Office Building</td>
<td>6.70%</td>
<td>2.2</td>
<td>54. Office Building</td>
<td>9.05%</td>
</tr>
<tr>
<td>7</td>
<td>Office Building</td>
<td>6.30%</td>
<td>1.96</td>
<td>55. Office Building</td>
<td>-2.50%</td>
</tr>
<tr>
<td>8</td>
<td>Office Building</td>
<td>-5.82%</td>
<td>1.59</td>
<td>56. Office Building</td>
<td>2.94%</td>
</tr>
<tr>
<td>9</td>
<td>Office Building</td>
<td>6.44%</td>
<td>1.65</td>
<td>57. Office Building</td>
<td>3.39%</td>
</tr>
<tr>
<td>10</td>
<td>Office Building</td>
<td>-12.93%</td>
<td>1.98</td>
<td>58. Office Building</td>
<td>4.4%</td>
</tr>
<tr>
<td>11</td>
<td>Office Building</td>
<td>-2.39%</td>
<td>1.59</td>
<td>59. Office Building</td>
<td>10.94%</td>
</tr>
<tr>
<td>12</td>
<td>Office Building</td>
<td>6.59%</td>
<td>2.45</td>
<td>60. Office Building</td>
<td>-3.07%</td>
</tr>
<tr>
<td>13</td>
<td>Office Building</td>
<td>12.72%</td>
<td>1.4</td>
<td>61. Office Building</td>
<td>11.94%</td>
</tr>
<tr>
<td>14</td>
<td>Office Building</td>
<td>4.19%</td>
<td>2.187</td>
<td>62. Office Building</td>
<td>5.87%</td>
</tr>
<tr>
<td>15</td>
<td>Office Building</td>
<td>14.13%</td>
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</tr>
<tr>
<td>39</td>
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<td>11.94%</td>
<td>2.48</td>
<td>87. Government Facility</td>
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<td>90. Audio Visual Facility</td>
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<td>2.09</td>
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</tr>
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</table>

Comparison of CBEMA and IEEE methods for transformer derating.
8 K-Factor Transformers

K-factor transformers are designed to be able to be used for loads with harmonic distortion without the necessity of de-rating. If a K-factor transformer is to be used in an application it is necessary to know the load characteristics and the harmonic content over the whole load cycle and then to calculate the K-factor and specify a transformer with the required K-factor value. For most general applications a K-factor rating of 15 or less is adequate.

Because they must be designed to reduce the level of eddy current generation in the windings, or to allow better dissipation of losses, K-factor transformers are:

- more expensive (about two times)
- heavier (about 15-20 % more)
- larger

when compared to standard power transformer designs of the same kVA rating.

They may have a shield between the two windings to limit harmonic induction: the basic conductor section size making up the transposed windings (particularly the low voltage) are made smaller to limit eddy currents (skin effect) while the overall conductors may be made larger to reduce ohmic heating by the power frequency current. Neutral conductors may be made larger to limit the heating effects of triplen harmonics.
The core is often made of better quality magnetic steel with lower hysteresis loss and perhaps thinner laminations to reduce core eddy current losses. The overall core size may be made larger to reduce operating flux density and hence eddy current and hysteresis losses. However the core losses are only a minor part in this aspect if the supply is free of harmonics and the only harmonics are in the load current.

Cooling is also enhanced in K-factor transformer design.

Overall the fundamental property of K-factor transformers is that they have lower losses than standard transformers of the same rating for the same level of harmonic distortion.

In general, only the transformer winding loss is used in the K-factor calculation. The core loss is not important in this determination as at full load the load loss is the much higher level. However some designs do have lower core loss as discussed above.

Dry-type transformers are more susceptible to harmonic effects because of their lower heat dissipation coefficients. This lower heat dissipation results from the lack of oil. Oil provides a much more efficient convection loss method (whether natural or forced) compared to the mainly conduction loss mechanism which dominates the thermal dissipation process in dry-type units.

K-factor transformers will also have a lower impedance than the equivalent rating standard transformer design.