1. **OVERVIEW**

In its first part this paper will address the fundamental aspects in transformer design and the main influencing factors such as specification requirements, manufacturing capability and materials technology. It is compiled such that the reader may gain an insight into a designer's work and thus permit a better focus for those who purchase, use and maintain large power transformers.

In order to cover reactive plant more comprehensively, a section is also devoted to gapped-core reactors. The gapped core reactor technology is practically the only one nowadays employed for high voltage (66 kV and above) shunt reactors. For series connected high voltage reactors the method of iron shielding under oil is also employed and many of the matters discussed here will also apply to those. Air-core reactors, which are used for voltages of 33 kV and below, are not further discussed here.

The paper then treats significant issues associated with testing of both power transformers and shunt reactors.

2. **TRANSFORMER PHYSICS**

In its broader concept, a transformer can be described as a device which transforms electrical energy from one circuit to another by means of a common magnetic field. This definition does not yet include the core which provides a refinement, namely the efficient coupling between the windings.

The design of transformers covers the art of the most efficient allocation of resources of production in achieving the completed transformer. Importantly as will become more evident later, the core can be made smaller at the expense of the windings and vice versa. Also both can be made more weight efficient at the expense of labour. Finally of course all this can be influenced by the degree of quality control, which translates into safety factors and rework.

In the language of quality assurance, what then are the inputs into a design? There is the customers specification, the national and other standards, lots of economic data such as cost of labour and materials and of course the laws of physics.

The first law of importance is that the voltage transformation ratio equals that of the turns
This law has but a limit in that it is not quite correct as soon as current is drawn from the secondary winding(s) owing to the lack of coupling between the windings, or say simply owing to the impedance of the transformer. More fundamentally, the Ampere-turns of all the windings in circuit must equal, ie.

\[ \frac{V_1}{V_2} = \frac{N_1}{N_2} \]

This is the current transformer part of the relationship.

We now have a relationship which governs voltage and current and thus power. \[ V_1 * I_1 = V_2 * I_2 + \text{losses} \]. These losses, both resistive and reactive, come from the portion of volts which were lost in the transformation as indicated above.

Then of course there must be an equation which links the core effort to that of the windings. This is that the amount of flux is proportional to both voltage and frequency. Apart from Ohm's law, the rest amounts to an art by the designer to get it right.

3. **ECONOMIC EVALUATION**

Two methods for evaluating losses are commonly used giving the same ultimate result. They are firstly an annual cost method which contains the annual depreciation plus the ongoing cost of lost sales of kWh in a particular year.

The other is the capitalised cost method which is the method used by most utilities. It comprises firstly the capital cost of the investment (ie. mostly power stations). Based on a replacement cost of say 1.74 Billion $ for a Station having 2 x 660 MW machines and using 70% availability, this might be

\[ \frac{1.74 \times 10^9}{2 \times 660 \times 10^3 \times 0.7} = 1885 \text{ $/kW} \]

To that has to be added the cost of running the system of approximately 2c/kWh. (Labour and cost of coal etc.). Capitalising this over the life of the plant and discounting future costs at a factor of say 7%, this makes \(0.02 \times 24 \times 365 / 0.07 = 2503\text{$/kW} \) and a grand total of 4388$/kW.

The formula to be optimised takes the form:

\[ \text{Evaluated Cost} = \$C + \$A \times \text{Load Loss} + \$B \times \text{No Load Loss} \]

where \( A = \text{Cost per kW of Load Loss (depends on the average load factor over 20 years)} \)
$B = \text{Cost per kW of No Load Loss (4388$/kW for a transformer which is always energised).}$

$C = \text{Initial cost}$

For reactors of course, the cost applicable is the cost of no-load losses multiplied by the ratio of usage. Compared with overseas trends the evaluation of losses in Australia has always been significantly lower owing to the lower cost of thermal power and the particularly cheap coal. Presently the above cost of 4388$/kW compares with 5000 Pounds in the UK.

Figure 1 - Types of Core-Form transformers
Figure 2 - Types of Shell-Form transformers
4. TRANSFORMER CONSTRUCTION TYPES

4.1 Shell-Form Transformers

Windings are constructed in flat pancake type coils with a rectangular inner opening. The coils are then assembled between huge insulation washers with small blocks separating them, glued on. Coils can be series or parallel connected and the HV and LV windings can alternate.

These winding assemblies are then placed vertically into the tank base and the core laminations assembled around these windings such that all layers of core plates pass also through the winding opening.

4.2 Core-Form Transformers

Windings are constructed in cylindrical coils usually one for each winding ie. LV, HV and taps. These are then fitted concentrically over one another and also over the core.

The core is constructed with a circular cross sectional area as best as is possible given that it consists of plates. This is particularly necessary for the legs, over which windings are fitted, but may be varied on the yokes and those legs if any which contain no windings.

5. CONSTRUCTION MATERIALS

The basic materials used in manufacture have been improved upon over the many years and this process goes on and on. These are:

5.1 Electrical Steel - Cores

The major breakthrough here in the last 40 years was the introduction of Cold Rolled Grained Oriented Steel. This produced lower losses and enabled the cores to be operated at higher flux densities and thereby reduced overall costs. The insulation coating on steel is called Carlite by one manufacturer and being a phosphorous-glass type coating capable of withstanding the core annealing temperature of 800 °C. It was at first very patchy with concerns for continuity of insulation across the core. An ASTM test with a test stand of some complexity was necessary then to be able to reject faulty laminations.

Today the insulation is continuous without question, lamination thicknesses have further reduced and a high performance steel is used enabling extra flux density. Most significantly, the fundamentals of magnetism are better understood in that the steel forms into magnetic domains which are several centimetres long. These domains are being broken up in one of two ways, either by laser scribing or by mechanical means, thereby further restricting losses.
Copper or Aluminium - Windings

These materials have changed little over the years but increasing use is being made of work hardened copper to give added strength for resisting short circuit forces. One of the more and more significant types of winding is the one using Continuously Transposed Cable (CTC). This has the benefit of being able to break up the required cross sectional area into many parallel conductors and thus reduce eddy losses. The individual wires are (PVA) enamel coated and the whole conductor bundle wrapped with insulation paper. Originally this paper was normal manilla paper, however after some adverse experience of bulging and reducing the cooling ducts, a heat-shrink paper (Glupac) is now used. Another form where required for very high short circuit performance is to coat the enamelled wires with thermal setting epoxy, making the whole winding set rock-hard after the hot air dry-out.

Copper varies in price over the years, being subject to supply and demand, and if the optimum transformer is to be achieved, the price has to be noted on a regular basis.

Electrical Paper - Conductor and Lead Insulation

These papers are used for insulating the conductor in the windings and various tappings and high voltage leads. They may be of pure Kraft or a mixture of Kraft and Manilla. The latter increases the mechanical strength but is not as good electrically. Conductor insulation papers are commonly either 40 or 60 microns thick. They can withstand about the same electrically, thus mechanical strength and efficiency can be economised dependent on the electrical strength requirements.

Pressboard

The pressboard is made of pure Kraft or a combination of Kraft and Cotton. These materials have almost reached the ultimate in purity and are used (a) between windings; (b) insulation blocks to earth; (c) inside winding as chocks duct strips. These materials are subject to the major electrical stress and are therefore extremely critical components. For cylinders, duct strips and chocks the density is approximately 1.3 which is extremely dense and manufacturers expect that no further shrinkage will take place during the lifetime of the transformer. For other components, specially shaped funnels for lead-outs and collars, a less dense material is used for its better moulding capacity. The very curved components must be moulded directly from the paper slurry after it has been deposited on the conveyor belts during the manufacture.

Oil

Mineral oil in transformers is used to impregnate all insulation materials, it provides the dielectric strength between windings and windings to earth and also conducts the heat away from windings. It is currently receiving enormous attention because the requirements of electrical and chemical performance and its longevity at high temperatures do somewhat conflict.
It is a hydrocarbon and one of the products obtained from crude oil. Dependent on the origin of the crude oil, it can be either naphthenic or paraffinic in its composition. The molecular structure of naphthenes, of which there are many sub-types, is a closed ring. For paraffins it is a chain capable of mechanically linking up with its neighbour. It is not normally used in transformers because of this and its tendency to solidify into wax.

The most defining molecules of “transformer-oil” are the aromatics. They can be present in transformer oil from between 3 and 10% and also comprise of thousands of different types of molecules. Simply, one can divide them into mono-aromatics and poly-aromatics. The quantity of aromatics is reduced in the refining process with a particular view to eliminating the poly-aromatics.

Grossly simplified, the oil’s performance in electrical apparatus can be stated thus:

- the less aromatics, the better the electrical qualities
- the more aromatics, the higher the longevity at high temperatures

Methods such as adding one or the other inhibitor to oil (essentially substituting for aromatics) or a passivator all help in maintaining the thermal and mechanical properties of oil whilst ensuring high electrical properties as is the case with highly refined oil.

5.6 Mild Steel/Stainless Steel - Tanks/Yoke Clamps

Most tanks are constructed from mild steel as are the yoke clamps which support the core. Certain areas of very large transformers and reactors, however, need a non-magnetic, high resistance material such as stainless steel. This is to avoid excessive losses and local high temperatures occurring due to leakage fields and tank circulating currents. Examples of where this becomes necessary is between bushings carrying over 1000 Amperes. Where more than 5000 Amperes are involved, often the whole turret needs to be out of stainless steel.

Tanks can also be constructed from aluminium, refer the now scrapped transformers at Vales Point A and particularly the generator transformers at Liddell Power Station. From the engineering point of view this is a fabulous concept because the stray field (which will be further covered later) has a perfect conductor material to nullify its effect of causing losses and heat.

Sometimes components are required to limit the effect of the stray flux. These can be thought of as two basically different types. Firstly the shunts manufactured from core lamination material and applied to either shield the (steel) tank wall or the yoke clamps. These would be collecting the flux and guiding it without causing either heat or losses into areas where it can close its loop unimpeded. This is particularly the core.

Secondly the flux rejectors, made from conducting material, mostly aluminium but sometimes copper. The physics of flux rejectors is that flux enters the shield, causes current to flow in the shield and at right angle to the flux, which in turn produces a voltage, a back electromagnetic force, in turn opposing the flux such that it cannot penetrate and cause excessive heat in mild steel components behind. The problem with
5.7 Wood or Laminated Wood - Lead Supports/Pressure Rings

Laminated Wood is built up from beech which grows in Western Europe. It can be used for lead supports and packing between cores and inner windings of transformers. Where moderately high electrical stresses occur, laminated wood can be used. It is also used extensively for clamping rings because it has good mechanical strength in several directions. However, for any dielectric strength it must be impregnated with oil. Typical applications are the winding pressure rings, lead and particularly tapping lead support clamping structures.

5.8 Other Items Normally Purchased as Completed Components

These items particularly comprise tapchangers, bushings, pumps and coolers. For reactors these are particularly tie-rods and very large Belleville washer type clamping gear.

6. CORES

Transformer core design involves a number of considerations which are discussed below.

6.1 Iron Loss and Magnetising Current

Cold rolled oriented steel has a feature that the specific loss in watts/kg is lowest in the direction of rolling. With the flux at right angles to the direction of rolling, the loss can increase by a factor of 4 or more. There is a good incentive therefore, to reduce the amount of core steel where the flux travels across the grain. This has been achieved by the almost universal use of mitred cores, see below.

Fig. 3 - Three-phase core laminations
In core form transformers the windings are circular and therefore a cross section of the core form core will have a reasonably circular shape. It cannot be made completely round and is therefore made up of a number of discrete steps. The greater the number of steps the greater the area of core steel which can be accommodated within a given core circle.

It is desirable to get as much core steel within a given circle but this has to be matched against the cost of providing more and more core steps. The inevitable compromise will be to balance this design advantage against the cost of making the core.

Core steel is nominally 0.23 to 0.28 mm thick and is available in rolls up to 1 m wide, each weighing up to 3 tonnes. It has to be slit to the required width, and guillotined into the various shapes. Investment by transformer manufacturers into automatic, computer controlled core cutting machinery typically exceeds $1M and savings are not only labour, but also lower losses because of the extremely good accuracy which can be achieved. This is particularly so for magnetising current. At the time when both manually and automatically cut cores were still manufactured it was not uncommon that a machine cut core resulted in only half the magnetising current of a core cut with conventional guillotines.

Nowadays much attention is focused on the laminations not having burrs as this causes short circuits between laminations and also reduces the stacking factor.

Different types of mitred joints are in use. Consider the simplest joint such that all laminations butt lap at the same position. They all have the same length and are laid perfectly on top of one another. The whole core yoke could be lifted off the legs in one go. There would be no strength in the core but this could be overcome in some other way. More importantly the flux would have no alternative but to jump across the air gap. Thereby causing high losses and very high excitation currents.

As an improvement the two position overlap or the 2-step lap construction is widespread. Here the flux will cross to the continuing other lamination rather than jump across the gap. Whilst this causes nominally a doubling of the flux density at the point of crossover, core performance is substantially improved. And of course with modern core-cutting machines even better performance is now possible, refer to the 7-step lap core plate lay plan with progressively staggered joints.

6.2  Mechanical Considerations

A magnetic core made up of several thousand laminations has to be made such that is mechanically stable and will withstand short circuit forces. Early cores had holes punched in the laminations and insulated bolts were passed through the core and tightened with special nuts. The disadvantage of this is that this reduces the core area locally, resulting in higher flux densities and creating extra losses. Also as the flux curves around the holes, its direction is again against the grain direction, thus causing even more losses and hot spots.
Manufacturers at first only eliminated the leg bolts but today holes are no longer punched into the laminations for bolting anywhere. Instead glass fibre bands hold the laminations or steel bands with glass fibre buckles.

6.3 Core Temperatures

The core losses generated within the core result in a temperature gradient above the oil. Owing to the insulation of the laminations, the heat transfer against the lamination direction is greatly lower than that in the direction of the laminations. The hottest point is usually at the top of the centre leg and cooling ducts may be required within the core. However, the constant reduction in losses has made this now unnecessary except in the largest transformers.

During conditions of over-excitation, some flux will be forced out of the core in places and enter the yoke clamps and tank wall. This condition is particularly dangerous on large transformers and during periods of overload because all these conditions combine to substantially raise the temperature of mild steel components. This is a matter of serious concern during operating conditions at low power factor and during overloads. This
requires detailed computer studies.

6.4 Transformer Sound Level

When a core lamination is subjected to alternating magnetisation, the physical dimensions of the lamination changes. This is the reason of the typical hum associated with an energised transformer. It is called magnetostriction and increases with flux density. As a result one of the most effective ways for a designer to reduce the sound level is to lower the working flux density. Whilst this is also rather expensive, one mitigating feature is lower core losses.

Care is required as to what is meant by sound level. In accordance with IEC Standard practice, the Australian practice of measuring sound pressure and expressing it thus has been abandoned in the latest issue of the standard and the result will now be expressed as sound power. The resulting decibel figures are quite different and can easily be confused!

7. WINDINGS

Windings can be categorised according to the type of work required on the winding machine. There are Disc windings, either normal or interleaved; Layer windings which are used mainly for Tertiary and Tapping windings; and Helical windings where high current requires disc windings with only one turn so to speak. There are also windings using Transposed Cable. This cable comprises two stacks of rectangular, enamel coated conductors which are transposed every 100 mm by bringing the top conductor from one stack to the other and compensating for this with the bottom conductor of the other stack.

7.1 Load Loss

The load loss comprise firstly the d.c. resistance losses ($I^2R$), secondly the a.c. eddy current losses in the windings and thirdly stray losses in other metallic components.

The first one is simple enough to calculate. The second item depends on the leakage field distribution. Since it was first defined in 1910 until the advent of digital computers, this field was assumed to be straight. Today it requires a program which can calculate the field. Since it is also responsible for all electromagnetic forces in the transformer, it received double the attention in the last 40 years. The most difficult item to evaluate is the Stray Loss which particularly occurs in Yoke clamps, Limb stiffeners, the Main tank, Leads but also in the core due to a radial leakage field component.

High leakage fields can be created by high axial ampere turns per unit length. These will give a complex pattern of circulating currents in the vicinity of metallic components such as tank walls.

Particular attention must be paid to gasketted joints as excessive circulating currents may flow between the main tank and the cover via the bolts. These currents of 100 amperes and more can generate sufficient heat to reduce the life of a gasket. An alternative
solution is to eliminate the bolts altogether and weld the tank to the lid. Whilst this even
tends to increase the currents, they are distributed over the whole of the tank side and
cause less hot spots, quite apart from the fact that non-gasketted areas can take higher
temperatures.

7.2 Thermal Performance

Most transformers of 30 MVA and above are of the forced directed (OD) type with oil
pumped into the tank and also directed through the windings. This type of cooling has
the following advantages:

(a) Temperature difference between top and bottom oil is only a few 0°C.

(b) The average oil temperature adjacent to the windings is nearly the same as
the average oil temperature of the radiator bank. When oil pumps were
first used, oil was pumped around the transformer tank while the windings
were virtually without forced cooling. Thus the temperature rise of the oil
near the windings could be much higher than that in the radiator bank.
Some of the best designers prefer this even today, however, they
compensate with winding designs which have very low temperature
gradients.

(c) Better cooling since the temperature gradient equals watts/sq.mm *
(A*T+K), where:

\[
\begin{align*}
A & = \text{constant depending on conductor insulation} \\
T & = \text{paper thickness on the conductor and} \\
K & = \text{constant dependant on the oil velocity across the winding} \\
& \text{surface. The lower the flow rate the higher the value of K}
\end{align*}
\]

This is typically demonstrated by the following result on a 60 MVA 132/33 kV
transformer. In comparing the results, one must remember that the heat generated at 60
MVA is nearly three times that at 35 MVA.

<table>
<thead>
<tr>
<th>Test</th>
<th>ONAN</th>
<th>ODAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>MVA</td>
<td>35</td>
<td>60</td>
</tr>
<tr>
<td>Winding Gradient (Gr)</td>
<td>⁰C</td>
<td>11.7</td>
</tr>
<tr>
<td>Average Oil Rise (AOR)</td>
<td>⁰C</td>
<td>38.9</td>
</tr>
<tr>
<td>Top Oil Rise (TOR)</td>
<td>⁰C</td>
<td>46.0</td>
</tr>
<tr>
<td>Hot Spot Rise</td>
<td>⁰C</td>
<td>58.9</td>
</tr>
</tbody>
</table>
The forced directed rating of 60 MVA, employing both fans and pumps of course also shows benefits arising out of the fans. These are that the absolute value of the Average (and Top) Oil Rise will be reduced.

Back on oil flow itself, the calculation of the required oil velocity must depend on the amount of heat loss in each of the windings. Failing this the outlet temperature at the individual windings will be different and pending direct temperature measurements with the use of fibre optics, an indeterminable hot spot arises which will limit the transformer's life.

With disc windings the oil flow should be directed at the radial surfaces as they amount to some 80% of the total available area. This is mostly achieved with the use of specially formed washers built into the windings. They direct the oil in zig-zag fashion across the discs as shown below.

![Diagram showing non-directed and directed oil flow through disk windings](image)

**Figure 5 - Oil flow through disk windings**

The method of getting oil into the windings at strategic points for uniform flow and at the same time have an effective insulation structure requires consideration. The complexity is
obvious as the requirements seem mutually exclusive. However, the use of a computer offers much improved means to the design engineer. For each separate part of the oil circuit, the hydraulic calculations are simple enough. However there are many series and parallel paths and today's computer programs cover all these combinations.

8. INSULATION

The voltage tests carried out in a manufacturer's works must, as near as possible be sufficient to guarantee a satisfactory life for the transformer in service.

The three main materials used in power transformers and oil filled reactors as mentioned in the section on Materials are paper, pressboard and oil. The dielectric strength can now be considered as follows:

![Cross-section through transformer windings](image)

Figure 6 - Cross-section through transformer windings

8.1 Major Insulation

This is the insulation strength between windings and from windings to earth. Between windings the insulation takes the form of pressboard cylinders separated by small oil
ducts. The higher the voltage the larger the clearance and the more barriers and oil ducts will be required. The reason for small oil ducts is that the strength of an oil gap becomes stronger as its size gets smaller. Because the dielectric constants of pressboard and oil are nearly 2 to 1, the oil has to carry twice the stress of the electrically much stronger pressboard.

In a cylindrical arrangement the voltage across one particular duct of the multi-duct configuration as a fraction of the whole voltage is

\[
\frac{V_d}{V_{tot}} = \frac{1}{\varepsilon_d} \prod \ln\left(\frac{R_o}{R_i}\right)
\]

where:

\(\varepsilon_d\) = the dielectric constants of oil and paper as appropriate
\(R_o \& R_i\) = outside and inside duct radii under consideration

The ends of the windings can present areas of high electrical stress, particularly around the corners. Specially shaped electro static rings, which alter the electrical field in that local area, relieve these stresses. Moulded angle rings can be fitted around the ends of windings in such a manner as to causing minimum obstruction to the oil path.

8.2 Internal Insulation

This has to be designed to withstand the:

(a) Induced and Partial Discharge Voltage Test  
(b) Lightning Impulse Voltage Test; and the  
(c) Switching Impulse Voltage Test.

The Induced Voltage Test is a matter of applying a voltage which is a multiple of the normal operating voltage. It results in a linear voltage distribution between turns and is proportioned according to the number of turns between parts.

The Lightning Impulse Voltage Test is a rather different matter and voltage distribution can be quite non-linear. The wave shape of the voltage is shown below. Because of the very fast rise time of this voltage wave, the initial voltage distribution is governed by the capacitance of the windings between sections and to ground.

The initial voltage at any part is calculated as follows:

\[
E_x = E \cdot \frac{\sinh(\alpha L_x)}{\sinh \alpha}
\]

Where:

\(L_x\) = per unit distance from neutral end
\(\alpha\) = \(\sqrt{C_g/C_s}\)
\(C_g\) = capacitance to ground
\(C_s\) = series capacitance of the winding
From the figure below, it can be seen how the initial voltage distribution changes for varying values of:

- $\alpha = 1$ - 55% voltage across 50% of winding
- $\alpha = 10$ - 55% voltage across 8% of winding
- $\alpha = 20$ - 55% voltage across 3% of winding

![Voltage Distribution Graph](image)

**Figure 7** - Lightning Impulse voltage wave shape and voltage distribution

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![Continuous Disk Winding and Interleaved Winding Diagram](image)

**Figure 8** - Types of disk winding
On high voltage windings it is quite impossible to accept a high value of $\alpha$ and therefore special measures must be taken. One possible method is to use interleaved windings, which have a dramatic effect on the series capacitance.

The Switching Impulse Test is only required on 330 kV and 500 kV transformers. The reason for this lies in the insulation co-ordination where for economic reasons the test/service voltage factor is progressively reduced with increasing voltage.

The voltage wave has a much longer front (250µs) and also a longer tail. One immediate difference is that voltage distribution no longer depends on the capacitive coupling of the windings and as a result a much more linear voltage distribution results. A peculiar aspect of the test is that the tail time is limited by the fact that the iron core saturates from the prolonged application of d.c. and the voltage wave collapses.

9. Transformer Reactance

The calculation of the leakage reactance is basically as follows:

$$\% X = K\times MVA \times D(a/b+c/l), \text{ where}$$

$$\frac{(V)2}{L}$$

- $K$ = constant
- $MVA$ = Power on which impedance is based
- $D$ = mean Diameter of Winding
- $a$ = radial dimension of LV
- $b$ = radial distance between windings
- $c$ = radial dimension of HV
- $L$ = effective length of Winding

![Diagram of transformer leakage reactance](image)

Figure 9 - Leakage reactance of a transformer

It is noteworthy that the impedance comprises two seemingly independent components, one electro-magnetic and the other comprising physical dimensions. Some of the parameters are fixed such as the MVA and the dimension $b$, which is largely dictated by the insulation level. Other can be chosen, to begin with the core diameter and flux density as this will determine the volts per turn:

$$B \propto \frac{V_{\text{turn}}}{\text{Area of Core}}$$

From the volts per turn ($V_{\text{turn}}$) the number of turns are calculated for each winding. With some thought about the required load loss performance which determines the conductor size, finally the reactance quantities $a$, $c$, $D$ and $L$ can be derived.
It is then a matter of juggling with all these parameters to arrive at the lowest evaluated cost. Generally, if a higher than normal reactance is required, the $V_{turn}$ would be reduced as this is a squared term below the line. This then means more turns and hence more copper and load loss.

Whilst a higher reactance reduces the short circuit forces in the transformer, the cost of the higher load losses far exceeds any performance gains under no load which may result. With the exception of Auto-transformers it can thus be said that a lower reactance than customary will result in economic benefits. It is therefore important to consider circuit breaker ratings and costs when specifying transformer impedance.

10. Mechanical Forces

During a short circuit a transformer is subject to large mechanical forces generated by the leakage field and the currents in the winding conductor. For a current flowing in a magnetic field the force per unit length is proportional to $B \times I$:

\[ F = B \times I \]

*Here, $B$ = flux density, $I$ = current.*

![Figure 10 - Direction of radial forces](image)

Now, the leakage field $B$ (not to be confused with the main field in the core) produced by any given winding is proportional to the short circuit current. Therefore, the force is proportional to the square of the current.

During a short circuit a force is applied to the outside winding which experiences bursting. On normal transformers this causes a hoop stress, to be taken up by the tensile strength of the conductors in the winding. The inner winding is subjected to an equal inward force which tends to crush the winding by buckling of the conductors between radial supports. These forces, which on large transformers exceed 1000 tonnes, can be contained if necessary by the use of work hardened copper.

If one assumes the leakage field to be parallel to the coil axis, then life is very simple. No axial forces exist (and of course eddy losses are also easily calculated). However since the advent of digital computers the real field can be easily calculated at least in the two-dimensional plane. As can be seen from the sketch below, axial forces exist which are primarily directed towards the middle of the coil stack.
The magnitude of forces is much increased when the coil stacks are not perfectly balanced. Windings are not always perfectly matched owing to slight differences in the thickness of spacer material. On smaller transformers, taps are taken out of the body of the winding, which raises the axial forces considerably.

In Australia, actual short circuit tests can only be carried out on distribution transformers. It is therefore particularly important that the transformer designers can accurately calculate the forces involved and the stresses and modes of possible failure. For the same reason, it is necessary for any large utility to have the expertise to independently calculate the forces and bring the calculations of the various manufacturers to a common denominator.

![Typical core-forms cross section with stray field distribution](image)

**Figure 11(a)** - Typical core-forms cross section with stray field distribution

![Resolution of forces in horizontal and vertical directions](image)

**Figure 11(b)** - Resolution of forces in horizontal and vertical directions

11. Voltage Tappings

In order to cater for voltage variations the majority of transformers require an On-load tapchanger. The tapping range and the effect on the impedance variation over the range will determine where the tapping winding is best placed. Voltage and current considerations lead almost invariably to the tapping winding being electrically part of the HV winding. Four possible cases are show below.
The lower end of the tapping range is on normal step down transformers required to boost the output voltage, particularly on overload. The impedance should therefore also be at its lowest on that end. For those transformers, arrangements (d) is therefore commonly preferred over b).

![Graph showing impedance voltage variation across tapping range]

**Figure 12 - Impedance voltage variation across tapping range**

### 12. Processing

One of the great improvements which are being made is vapour phase drying. Consider the conventional method of drying transformer insulation. The transformer is first being heated to some 105 °C, for about one week or more, measurements of the loss tangent or dispersion of moisture etc. being made regularly. When the heating no longer produces benefits in moisture extraction, the transformer is evacuated. Water is collected in condensers and measured. The above measurements are continued. The temperature...
falls not only because of the radiated heat (there is no convection inside the evacuated tank) but for the latent heat required in boiling the moisture off. Again the best part of one week is required. Further such processes are often required making the dryout and coil sizing cycle consume approximately one month.

Take vapourphase drying. Kerosin vapour is introduced into the evacuated transformer (or reactor) at 130 °C. As it hits cold surfaces it condenses and releases the latent heat. All parts of the core and insulation are heated as progressively the vapours penetrate to the components which are further away from the inlet. The condensed vapours are drained off, water removed, reheated and returned into the tank. Great care is required with components which require slow heating such as large blocks, thick rings and some very finely tolerated tapchanger parts. With all this however, experience shows that oil filling can start some 48 hours after commencement of the drying cycle.

13. SHUNT REACTORS ASPECTS

13.1 Purpose and Physical Principle

The main purpose of shunt reactors is:

1. Limited voltage rises on long transmission lines at periods of light load or after load shedding;
2. Prevention of self-excitation on generator transformers on leading power factor load;
3. Reduction of over-voltages on sound phases during a line to ground fault (Petersen Coils);
4. Reduction of switching over-voltages due to initial charging of lines.

Examples of such applications in the NSW system are in the Sydney area, for use during periods of light load, in the north of the State at the remote ends of the 330 kV system (Tamworth, Lismore and Armidale) and associated with the 330 kV cable in the southern Sydney area.

If we consider the physical principle which distinguishes the reactor from a transformer, a good illustration would be to consider the no-load or excitation current of the transformer. The reason why it is held so small is that the fitters build the core with the absolute minimum possible air gap.

With increasing gaps the current increases further and further until at its maximum with none of the core left, air-core reactance is reached. Then of course the second winding is superfluous as all (reactive) power is consumed in maintaining the flux. The gapped-core type represents an ideal compromise having a major benefit of being able to control the flux path over its entire length.

One other method is to have no core steel inside the windings, ie. a single air gap but core steel all around it. This magnetically shielded core construction has been successfully applied in the past and Pacific Power has two such reactors. The total losses and the
weight of such reactors has been estimated by one manufacturer as 15% higher than that of a gapped core reactor, largely owing to the fact that the flux density permissible within the winding of a shielded reactor is very much lower than that of a gapped core reactor. For this lack of cost effectiveness it has now largely given way to the gapped core design for large shunt reactors. However, on series reactors where constant impedance is essential, the shielded type core is more appropriate.

13.2 Main Types of Gapped-Core Reactors

Several different types of such reactors are being manufactured dependent on the specification requirements. These are:

- Single-phase three-legged core
- Three-phase three-legged flat core
- Three-phase three-legged spatially arranged core
- Three-phase five-legged core

There are also special reactors with variable gaps, even more exotically, motor driven core stumps to adjust to the exact current required for short term fault current compensation but to my knowledge they have not been used in Australia. Other designs employ a tapping winding and an on-load tap changer. Others again control saturation by means of dc injection.

Naturally on a three-phase system the three-legged three-phase core is the cheapest and most often used. A number of these are in service on the 132 kV and 330 kV NSW systems ranging form 30 to 165 MVA.

These reactors have one feature which may not always be acceptable and this is the reduced zero-sequence reactance at full voltage compared with the positive sequence reactance.

13.3 Low Zero-Sequence Reactance

Under symmetrical excitation the sum of momentary fluxes in the three phases is always zero. However, under earth fault conditions this is not so and the flux must find a return path outside the windings. Quite similar to a star connected transformer, if this can only be accomplished through the air or the tank then the zero sequence reactance is lower than the normal reactance (perhaps as low as 60 - 80% at rated voltage) and also non-linear with the difference increasing with increasing voltage because of the varying saturation levels of clamps and tank steel.

The requirement of a high and constant zero sequence reactance is almost unavoidable in a case when single pole re-closing is a specification requirement. Even so it is often necessary to add a further neutral reactance. For one such application an optimal ratio of $X_o/X_1 = 1.45$ was determined.
Figure Diagrammatical view of the shunt reactor types
Figure 14 - Flux paths in the various 3-phase arrangements

Just as with transformers, a high zero sequence reactance results from a low-reluctance unwound (and un-gapped) return limb, either of the three legged single phase type or the five legged three-phase type. Costs however are a disadvantage amounting to approx. 25% more than for a three-phase three-limb reactor.

13.4 Core Packet Construction

Core packet laminations could possibly be manufactured like those in a transformer resulting in a stepped cross-section area and all laminations parallel. Indeed, some reactors of limited size have been built in this way quite satisfactorily. In practice however and for application with reactors of sufficient size for modern power system capacities, the laminations must be arranged radially and inevitably they are cut from steel segments of continuously varying lengths.

Figure 15 - Core construction of gapped-core type shunt reactors
The radially arranged laminations prevent fringing flux from entering flat surfaces of core steel, thereby avoiding overheating and Figure 16 shows the fringing flux in the direction which causes most problems.

(a) Parallel laminated core

(b) Radially laminated core

Figure 16 - Fringing flux problems

Manufacturers have applied ingenuity using encapsulating techniques to make strong packets. Commonly, these packets are resin impregnated. Difficulties lie in selecting suitable resin, impregnating into the gaps between laminations thereby providing adhesion, cracks during curing due to shrinkage and finally design co-ordination of flux density and flux hot spot heating as against endurance of the resin.

Given the right spacer material and a suitable clamping structure and the various types of cores can be constructed.
13.5 Design Equations of Gapped-Core Reactors

The design of the magnetic circuit is heavily influenced by the precise behaviour of the flux and flux fringing for example tends to require increased gaps. Nevertheless, some fundamental equations provide the basis. Thus for a sinusoidal AC system it can be shown that:

\[ E = \omega B A N / \sqrt{2} \]
\[ I = B G / \sqrt{2} \mu_0 N \]
\[ L = \mu_0 N^2 A / G \]
\[ P = \omega B^2 A G / 2 \mu_0 \]
\[ F = P / \mu_0 A \]

where,

- \( E \) = rms Voltage [V]
- \( I \) = rms Current [A]
- \( L \) = Inductance [H]
- \( N \) = Number of turns
- \( B \) = Magnetic peak flux density [Tesla]
- \( A \) = Effective cross section area [m²]
- \( G \) = Total effective gap length [m]
- \( \mu_0 \) = space permeability = \( 4 \pi \times 10^{-7} \)
- \( \omega \) = \( 2\pi f \) [sec⁻¹]
- \( P \) = Reactive Power [VA]
- \( F \) = Peak magnetic attraction force [N]

In the context of all magnetic circuits, it is noteworthy that core steel has almost infinite permeability (\( \mu = \infty \)) where by definition, "air gaps" have \( \mu = \mu_0 = 1 \). Therefore with a series circuit of core steel packets and air gaps, the formulae above neglect the effect of the core steel. Further it should be noted that the reactive power and hence the attraction force can be ascribed almost entirely to the gaps.

It can be seen that power varies with the square of induction and linearly with the air gap volume. Inductance reduces with increasing air gap length but as with transformers varies as the square of the winding turns.

13.6 “Air” Gap Considerations

Once the magnetic effect and the approximate length of the air gaps has been determined as per the above, the size of individual air gaps and the location must be chosen with great care. Magnetic field plots as carried out by FEM assist the designer greatly in this task and singularly for that reason the technology has been pushed to larger and more compact designs than was possible only twenty years ago.
In principle air gaps should not be too close to winding ends so as not to add to the field’s already loss rising curvature and methods of varying length of air gaps have been employed with the longest deep within the winding.

There is a further issue in that the radial distance between core and winding in transformers is governed by voltage withstand considerations, not the magnetic field. Not quite so with reactors. Sizing of the individual gap lengths governs the size of the radial flux and this will therefore have a major impact on the radial core - winding distance, at least as much as winding voltage. It further has a profound impact on the individual conductor strand size.

Figure 17 is a flux fringing field plot also showing beautifully how flux exits the packets well clear of the actual gap. The flux distribution would of course be very different if parallel laminations were employed because partial saturation effects would work against the flux exiting.

![Figure 17 - Fringing flux distribution](image)

**13.7 Reactor Winding Design**

The general problem of flux fringing is also illustrated in Fig. 18 which shows the magnetic field at the ends of a layer wound coil. It also depicts one manufacturer’s comparison of the leakage field between core and winding of a reactor and a similarly sized transformer.

It can be seen that the inner diameter of the windings will first of all need to be large enough to avoid the highest flux fringing zones. However, this variable of radial distance is still insufficient to overcome the flux problem completely. The winding conductor dimensions themselves must be kept very small and a very large number of parallel
13.8 Construction of the “Air” gaps

As seen from Fig. 19, the force acting on the gaps is a tensile force, tending to reduce the gap and it is also unidirectional and pulsating with twice the system frequency.

Clearly solid materials will be required to withstand the force and not permit the core packets to move. Moreover, even the tiniest of height difference in the manufacture of the packets or the duct material will give rise to large levels of noise from vibration. This is not just a nuisance, it will lead to the destruction of the reactor if such hammering motion remains unchecked! A prudent specification contains therefore a requirement for a
guarantee of a "natural" sound level, that is one which is achieved without external measures. This would go some way towards assurance that internal vibrations are kept in check.

![Tensile Force vs Flux Density](image)

**Figure 19 - Tensile force versus flux density**

The measurement of vibrations on the tank wall is an additional measure to ensuring that the mechanical design is capable of enduring the expected duty. Vibrations up to 100 to 200 microns of peak-peak amplitude, supported by mechanical stress calculations would be satisfactory in my view.

The solution to the containment of the high forces is to select the hardest material available (maybe porcelain). Manufacturers have their individual recipes such as adding a very small amount of soft bedding to even out the manufacturing unevenness. Obviously the structure must not be allowed to resonate with the system frequency. Fig. 20 shows such a patented method where items 7 denote the soft bedding and items 6 the hard spacer material.

![Diagram of soft bedding and hard spacer materials](image)

**Figure 20 - Use of soft bedding of hard spacer materials**

To assign practical data to the formulae in the appendix, in a 50 Hz system and assuming a core with a flux density of 1.6 Tesla,
P = 2\pi f * 10^7 * 1.6^2 / (8\pi) * 10^{-6} = 320 \text{ [MVA/m}^2\text{]} \text{ and}
F = 10^7 * 1.6^2 / (8\pi) \text{ [N/m}^2\text{]} = 104 \text{ [tonnes/m}^2\text{]}

It can be seen from the above that working with such flux densities as gapped core reactors do, a very high efficiency of material usage can be achieved compared with other types of construction. However, it is essential that the core be clamped with enough pressure so that no movement results from this force \(F\) above, i.e. that this force be the minimum clamping force. This requirement results in very strong clamping structures and special devices, i.e. large Belleville washers to maintain the pressure throughout the sinusoidal cycle.

It comes as a gift with radially laminated core packets to use the inefficient central space for extra strong tie rods to hold top and bottom yoke together and some manufacturers make use of that. Another characteristic is that no magnetic material is permissible in this area of high flux density and even non-magnetic materials are difficult to use because of the circulating currents.

13.9 Reactor Core Saturation Characteristics

Wherever core material is used, a saturation level exists resulting in changed flux patterns and having hot spots as a consequence. For this reason the saturation level of reactors should be no less than 120\% of rated voltage, preferably up to 130\% with the positive sequence reactance substantially linear up to 125\%.

The Australian Standard provides a definition of saturation as can be seen from Fig. 21.

![Figure 21 - Core Saturation](#)
The distortions resulting from very high system voltage transients are no different to those in transformers and can produce wave shapes as shown in Fig. 22 and for that reason too, saturation should not occur at/near system voltage.

![Wave shapes](Image)

**Figure 22 - Saturation Effects**

Another special aspect in reactor design, often required and specified in the Australian Standard, is that the asymmetry between phases must be limited to 2%.

### 14. TESTING OF TRANSFORMERS AND REACTORS

Testing is a very important subject because the tests should be
- sufficient to ensure reasonable service and maintenance margins and
- appropriate to the purpose the transformer or reactor is intended for.

Tests can be split into groups dependent on whether they are precise measurements of performance or whether a test level is to be passed.

Of the first group which particularly applies to transformers are:
- Turns Ratio, Vector Group and d.c. Resistance
- No Load Losses
- Load Losses
- Impedance
- Temperature Rise

The second group would comprise the voltage achievement tests:
- Applied Voltage for 1 minute
- Induced Voltage for 1 minute or less dependent on frequency
- Lightning Impulse Voltage
- Switching Impulse Voltage on transformers of 330 kV or more
- Partial Discharge
- Sound Level
Safety margins above the required level firstly depend on the quality of researched failure levels. Then they depend on the quality assurance which can be relied upon in the manufacturing process. Finally the transient portion of the voltage applications depend on the quality of the computer programs which calculate the levels and their duration on all points of interest. If the safety margins are too large, the manufacturer will become uncompetitive and go out of business. Failures on the other hand are terribly expensive. They disrupt the normal flow of work, the consume expensive replacement materials and an inproportionately large amount of engineering time. result in late delivery and so hard to avoid, failures cause bad impressions. For those reasons a design withstand level for voltage tests as much as three standard deviations below the mean failure level have been observed.

14.1 Special Aspects with Reactor Testing

Unlike transformers in order to carry out any of the conventional tests, a very large amount of power is required. In fact to carry out an excitation test at rated frequency, full 100% current is required. That is, a core loss test cannot be separately undertaken since full voltage results in full current and thus full winding losses.

The measurement of losses is a particularly difficult issue in that owing to the low power factor, a Schering bridge or similar is required. AS 1028 states that “conventional methods may be subject to considerable errors”. Often therefore, recourse to calorimetric measurements will also be required to check the electrical test results.

The induced voltage and partial discharge tests also require considerably more power than transformers even though they are carried out at higher frequency. The Australian Standard makes reference to this and permits such a test to be substituted by a switching impulse test. To the utility engineer this is not very satisfactory since partial discharge testing is a very good quality control tool and discharges are much harder to identify from lightning impulse tests. However, it is gratifying to note that at least one Australian manufacturer has the specialised reactor testing equipment and sufficient installed capacitors to test middle sized 330 kV reactors.

A measurement considered important is that of the zero sequence impedance which unlike transformers must be carried out at rated voltage.

Reactor current wave form is normally also tested and a maximum harmonic content of 3% at rated voltage would be in order.

15 FUTURE TRENDS

In future much more attention will be paid to obtaining a consistent quality in materials, workmanship and processing as those improvements flow directly back into yet even tighter designs. With FEM plots of the magnetic field, ingenious ways will be found to channel flux into the core and tank shields will be developed to prevent losses in tanks.
Noise reduction methods will be further developed both by the steel and the transformer manufacturers. The noise level “at full load” will become a consideration. Components will be engineered which can be machine produced but are cleverly designed to enhance the dielectric strength. And most of all the insulation component and oil processing will be driven to such quality, with concern for particles as well as moisture, that maintenance in the field too will assume a new dimension.

More highly refined oil will be required as this will also produce the better dielectric performance, probably a inhibitor being added to overcome the worse thermal wear of the oil under such conditions.

Superconducting transformers will not be brought onto the market tomorrow, however, the concept known for decades, is challenging scientists and engineers and one day maybe our power transformers will be no larger than an office desk, with the circuit breaker etc. already built in.

16. SUMMARY

It is hoped that this paper results in a better understanding of the complexities of reactive plant which very often and conveniently is deemed a black box. In particular engineers from electricity utilities will be more aware in what is being purchased, installed, maintained and eventually rehabilitated ready for further use.

The reactor part of this paper would not have been possible but for the published literature by manufacturers, particularly those contained in the references. Thanks are expressed herewith.

Practical issues in the manufacture of transformers and reactors always remain and procurement from a renowned manufacturer together with a “Customer Design Review” by competent staff is the best safeguard against unexpected performance.

17 REFERENCES

Australian Standard 2734-1982, ‘Transformers’
Messe, G. 1985, ‘Development of UHV Shunt Reactors’, Alstom Review No. 2