3 Constructional features

Transformers used in practice are of extremely large variety depending upon the end use. In addition to the transformers used in power systems, in power transmission and distribution, a large number of special transformers are in use in applications like electronic supplies, rectification, furnaces, traction etc. Here the focus is on power transformers only. The principle of operation of these transformers also is the same but the user requirements differ. Power transformers of smaller sizes could be air cooled while the larger ones are oil cooled. These machines are highly material intensive equipments and are designed to match the applications for best operating conditions. Hence they are 'tailor made' to a job. This brings in a very large variety in their constructional features. Here more common constructional aspects alone are discussed. These can be broadly divided into

1. Core construction
2. Winding arrangements
3. Cooling aspects

3.1 Core construction

Transformer core for the power frequency application is made of highly permeable material. The high value of permeability helps to give a low reluctance for the path of the flux and the flux lines mostly confine themselves to the iron. Relative permeability μ_r well over 1000 are achieved by the present day materials. Silicon steel in the form of thin laminations is used for the core material. Over the years progressively better magnetic properties are obtained by going in for Hot rolled non-oriented to Hot rolled grain oriented steel.

Later better laminations in the form of cold Rolled Grain Oriented (CRGO), -High B (HiB) grades became available. The thickness of the laminations progressively got reduced from over 0.5mm to the present 0.25mm per lamination. These laminations are coated with a thin layer of insulating varnish, oxide or phosphate. The magnetic material is required to have a high permeability μ and a high saturation flux density, a very low remanence B_r and a small area under the B-H loop-to permit high flux density of operation with low magnetizing current and low hysteresis loss. The resistivity of the iron sheet itself is required to be high to reduce the eddy current losses. The eddy current itself is highly reduced by making the laminations very thin. If the lamination is made too thin then the production cost of steel laminations increases. The steel should not have residual mechanical stresses which reduce their magnetic properties and hence must be annealed after cutting and stacking.

In the case of very small transformers (from a few volt-amperes to a few kilo volt-amperes) hot rolled silicon steel laminations in the form of E & I, C & I or O as shown in Fig. 3 are used and the core cross section would be a square or a rectangle. The percentage of silicon in the steel is about 3.5. Above this value the steel becomes very brittle and also very hard to cut. The saturation flux density of the present day steel lamination is about 2 Tesla.

Broadly classifying, the core construction can be separated into core type and shell type. In a core type construction the winding surrounds the core. A few examples of single phase and three phase core type constructions are shown in Fig. 4. In a shell type on the other hand the iron surrounds the winding.

In the case of very small transformers the conductors are very thin and round. These can be easily wound on a former with rectangular or square cross section. Thus no special care is needed for the construction of the core. The cross section of the core also would be square or rectangular. As the rating of the transformer increases the conductor size

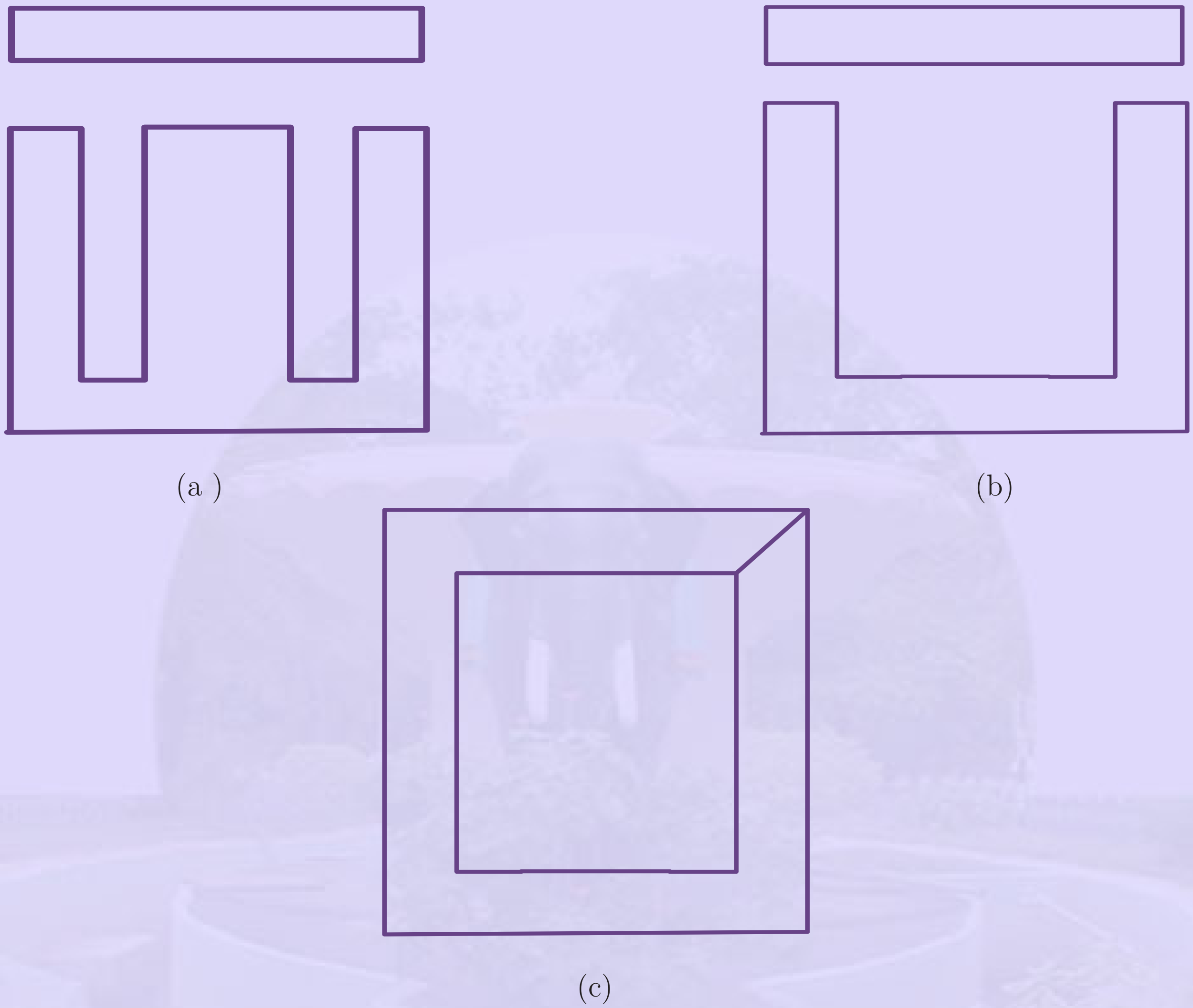
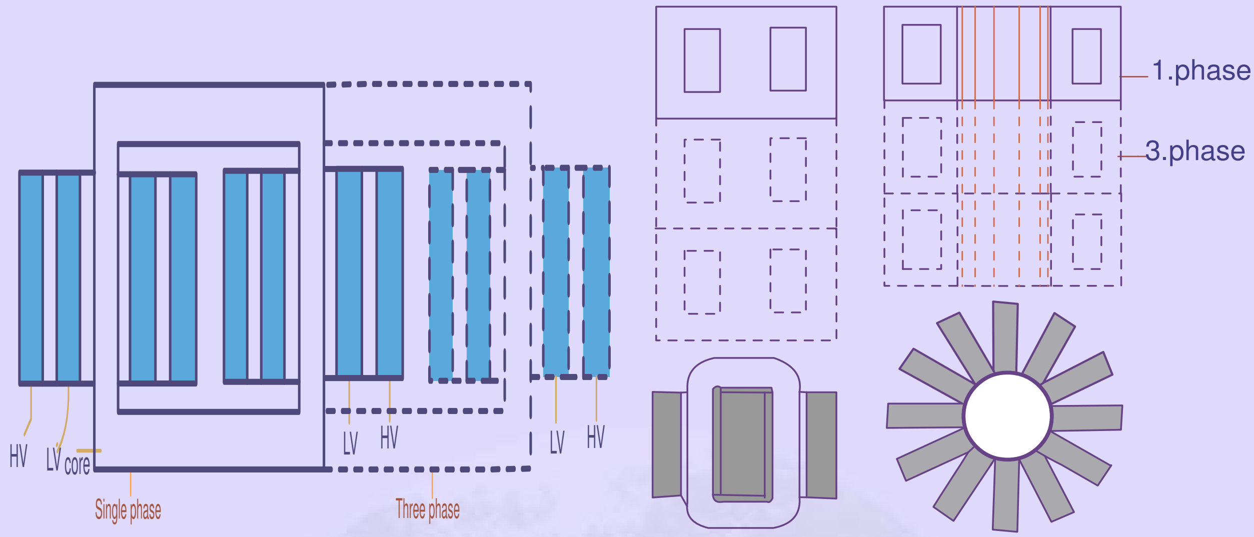


Figure 3: E and I,C and I and O Type Laminations



(a)Core type (b) Shell type

Figure 4: Core and Shell Type Construction

also increases. Flat conductors are preferred to round ones. To wind such conductor on a rectangular former is not only difficult but introduces stresses in the conductor, at the bends. From the short circuit force with stand capability point of view also this is not desirable. Also, for a given area enclosed the length of the conductor becomes more. Hence it results in more load losses. In order to avoid all these problems the coils are made cylindrical and are wound on formers on heavy duty lathes. Thus the core construction is required to be such as to fill the circular space inside the coil with steel laminations. Stepped core construction thus becomes mandatory for the core of large transformers. Fig. 5 shows a few typical stepped core constructions. When the core size increases it becomes extremely difficult to cool the same (Even though the core losses are relatively very small). Cooling ducts have to be provided in the core. The steel laminations are grain oriented exploiting the simple geometry of the transformer to reduce the excitation losses. The iron losses in the lamination, when the flux

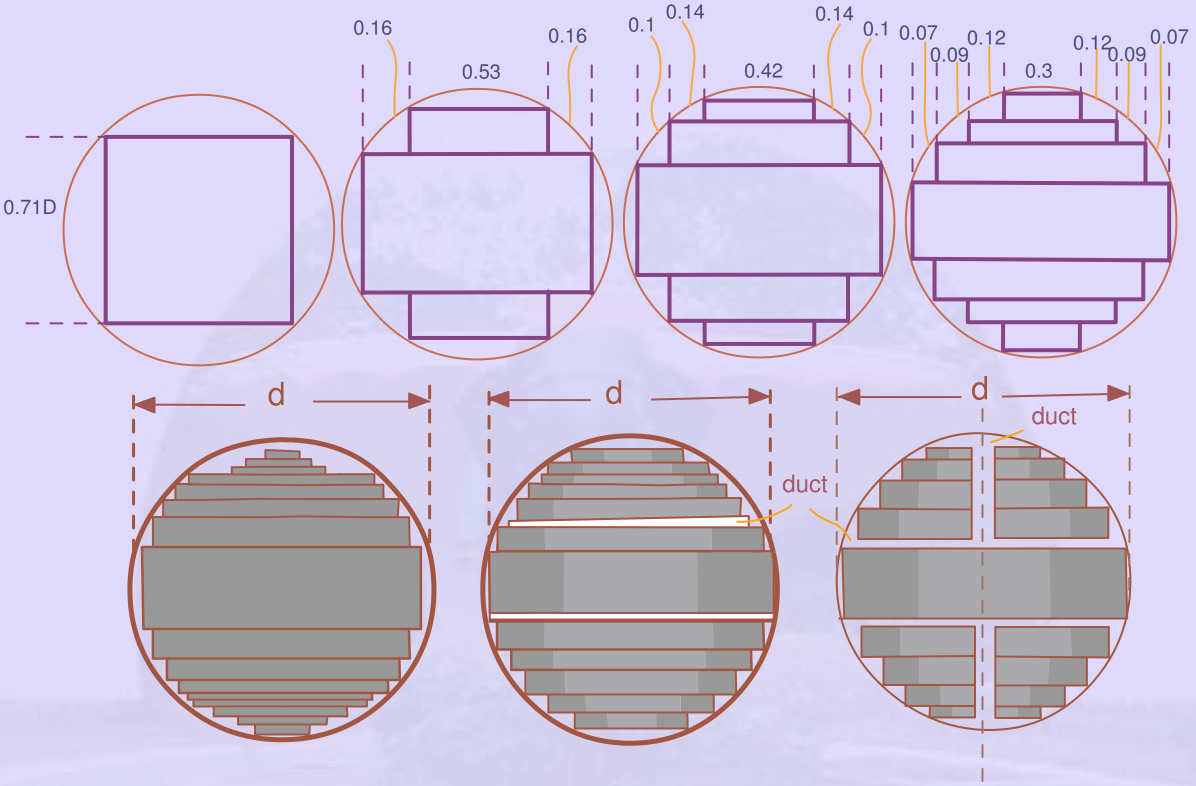


Figure 5: Stepped Core Construction

is oriented in the direction of grain orientation, is about 30% of that in the normal direction.

Another important aspect to be carefully checked and monitored is the air gaps in

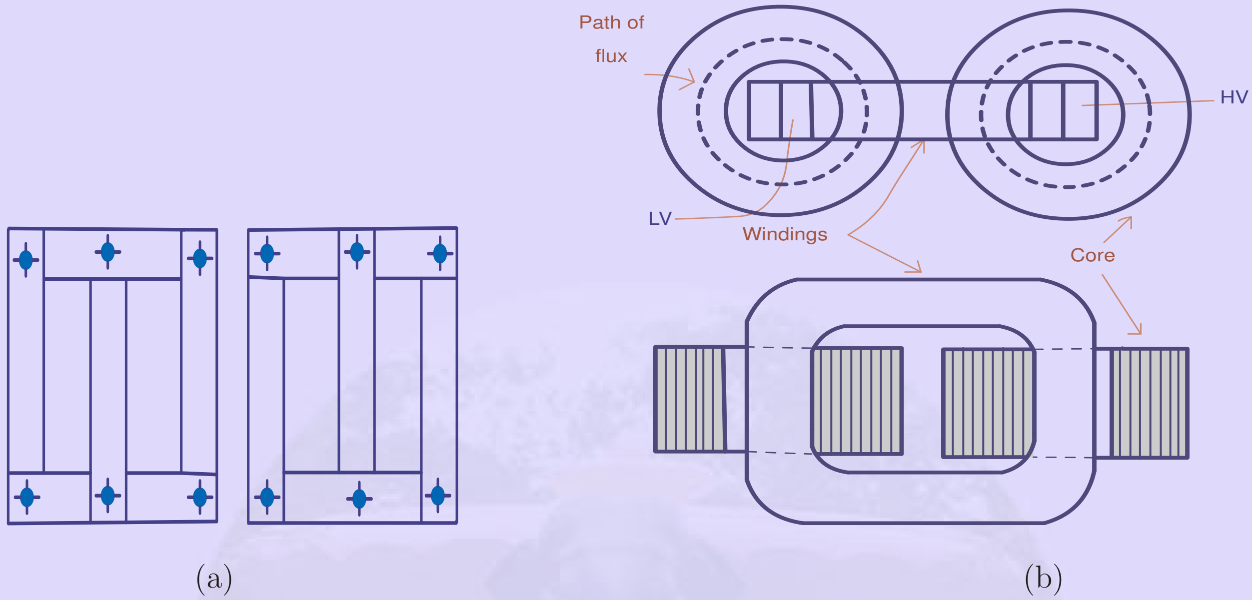


Figure 6: Typical stacked Core and wound core Construction

series in the path of the main flux. As the reluctance of air path is about 1000 times more than that of the steel, an air path of 1mm will require a mmf needed by a 1 meter path in iron.

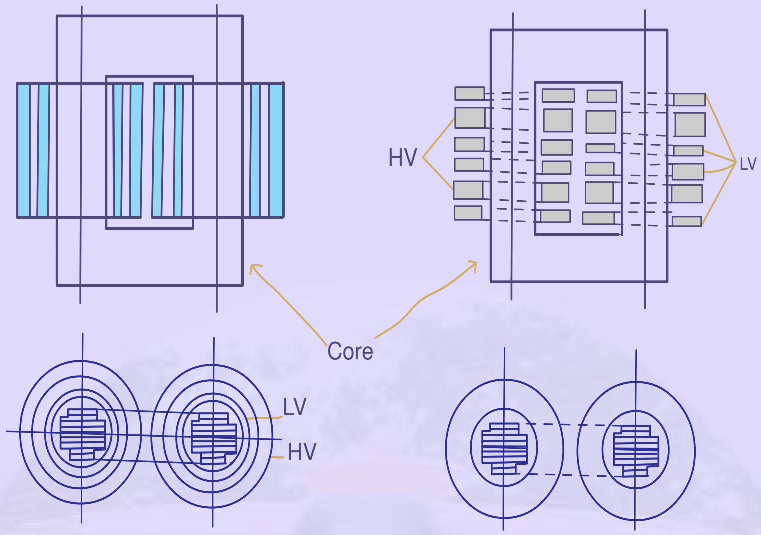
Hence butt joints between laminations must be avoided. Lap joints are used to provide alternate paths for flux lines thus reducing the reluctance of the flux paths. Some typical constructional details are shown in Fig. 6. In some power transformers the core is built up by threading a long strip of steel through the coil in the form of a toroid. This construction is normally followed in instrument transformers to reduce the magnetizing current and hence the errors.

Large cores made up of laminations must be rendered adequately stiff by the provision of stiffening plates usually called as flitch plates. Punched through holes and bolts are progressively being avoided to reduce heating and melting of the through bolts. The whole stack is wrapped up by strong epoxy tapes to give mechanical strength to the core which can stand in upright position. Channels and angles are used for the frame and they hold the bottom yoke rigidly.

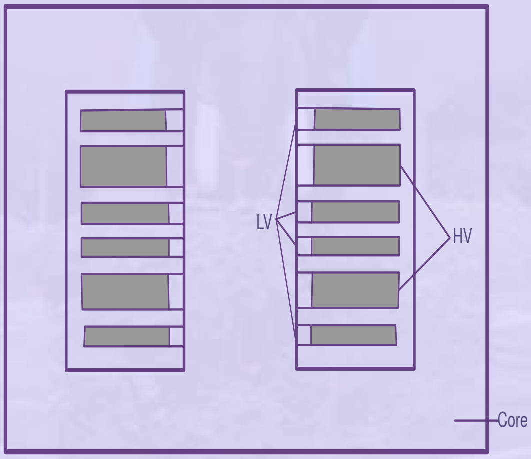
3.2 Windings

Windings form another important part of transformers. In a two winding transformer two windings would be present. The one which is connected to a voltage source and creates the flux is called as a primary winding. The second winding where the voltage is induced by induction is called a secondary. If the secondary voltage is less than that of the primary the transformer is called a step down transformer. If the secondary voltage is more then it is a step up transformer. A step down transformer can be made a step up transformer by making the low voltage winding its primary. Hence it may be more appropriate to designate the windings as High Voltage (HV) and Low Voltage (LV) windings. The winding with more number of turns will be a HV winding. The current on the HV side will be lower as V-I product is a constant and given as the VA rating of the machines. Also the HV winding needs to be insulated more to withstand the higher voltage across it. HV also needs more clearance to the core, yoke or the body. These aspects influence the type of the winding used for the HV or LV windings.

Transformer coils can be broadly classified in to concentric coils and sandwiched coils Fig. 7. The former are very common with core type transformers while the latter one



(a)Concentric coil



(b) Sandwich coil

Figure 7: Concentric and Sandwich Coils

are common with shell type transformers. In the figure the letters L and H indicate the low voltage and high voltage windings. In concentric arrangement, in view of the lower insulation and clearance requirements, the LV winding is placed close to the core which is at ground potential. The HV winding is placed around the LV winding. Also taps are provided on HV winding when voltage change is required. This is also facilitated by having the HV winding as the outer winding.

Three most common types of coils viz. helical, cross over and disc coils are shown in Fig. 8.

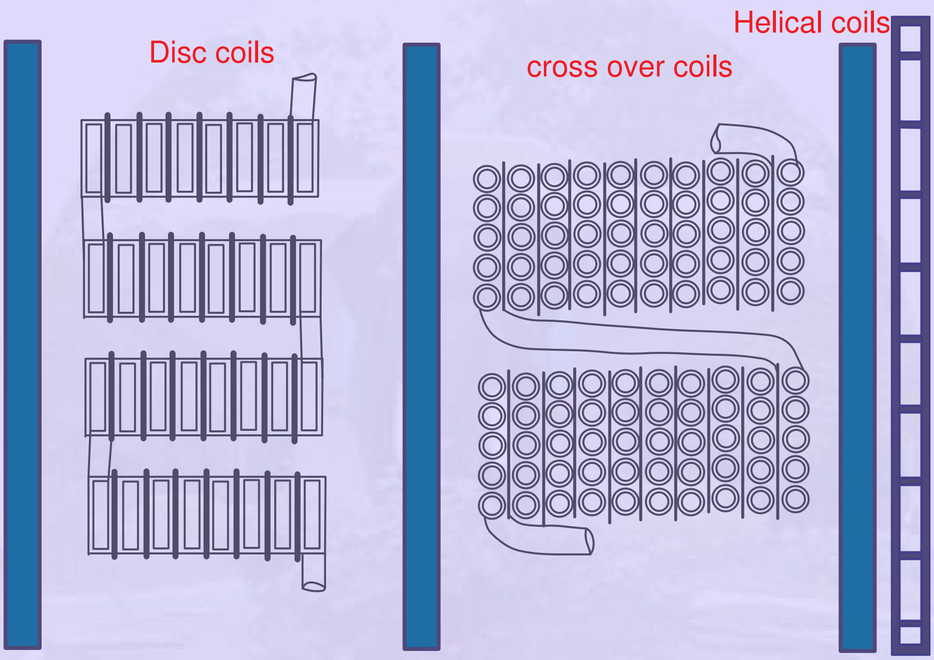


Figure 8: Disc, Crossover and Helical Coil Construction

Helical Windings One very common cylindrical coil arrangement is the helical winding. This is made up of large cross section rectangular conductor wound on its flat side. The coil progresses as a helix. This is commonly used for LV windings. The insulation requirement also is not too high. Between layers no insulation (other than conductor insulation) is needed as the voltage between layers is low. The complexity of this type of winding rapidly increases as the current to be handled becomes more. The conductor cross section becomes too large and difficult to handle. The eddy current losses in the conductor rapidly increases. Hence two or more conductors have to be wound and connected in parallel. The parallel circuits bring in problems of current sharing between the circuits. Transpositions of the parallel paths have to be adopted to reduce unequal current distribution. The modern practice is to use continuously transposed and bunched conductors.

Cross over coils The second popular winding type is the cross over coil. These are made of circular conductors not exceeding 5 to 6 sq mm in cross section. These are used for HV windings of relatively small transformers. These turns are wound in several layers. The length and thickness of each block is made in line with cooling requirements. A number of such blocks can be connected in series, leaving cooling ducts in between the blocks, as required by total voltage requirement.

Disc coils Disc coils consist of flat conductors wound in a spiral form at the same place spiralling outwards. Alternate discs are made to spiral from outside towards the center. Sectional discs or continuous discs may be used. These have excellent thermal properties and the behavior of the winding is highly predictable. Winding of a continuous disc winding needs specialized skills.

Sandwich coils Sandwich windings are more common with shell type core construction. They permit easy control over the short circuit impedance of the transformer. By bringing HV and LV coils close on the same magnetic axis the leakage is reduced and the mutual flux is increased. By increasing the number of sandwiched coils the reactance can be substantially reduced.

3.3 Insulation

The insulation used in the case of electrical conductors in a transformer is varnish or enamel in dry type of transformers. In larger transformers to improve the heat transfer characteristics the conductors are insulated using un-impregnated paper or cloth and the whole core-winding assembly is immersed in a tank containing transformer oil. The transformer oil thus has dual role. It is an insulator and also a coolant. The porous insulation around the conductor helps the oil to reach the conductor surface and extract the heat. The conductor insulation may be called the minor insulation as the voltage required to be withstood is not high. The major insulation is between the windings. Annular bakelite cylinders serve this purpose. Oil ducts are also used as part of insulation between windings. The oil used in the transformer tank should be free from moisture or other contamination to be of any use as an insulator.

3.4 Cooling of transformers

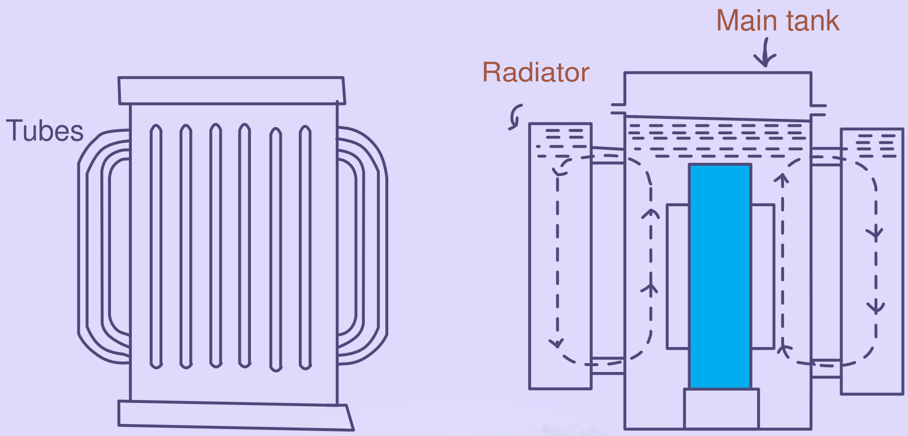
Scaling advantages make the design of larger and larger unit sizes of transformers economically attractive. This can be explained as below. Consider a transformer of certain rating designed with certain flux density and current density. If now the linear dimensions are made larger by a factor of K keeping the current and flux densities the same the core and conductor areas increase by a factor of K^2. The losses in the machine, which are proportional to the volume of the materials used, increase by a factor of K^3.The rating of the machine increases by a factor of K^4.

The surface area however increases by a factor of K^2 only. Thus the ratio of loss per surface area goes on increasing by a factor of K. The substantial increase in the output is the major attraction in going in for larger units. However cooling of the transformer becomes more and more difficult. As the rating increases better cooling techniques are needed.

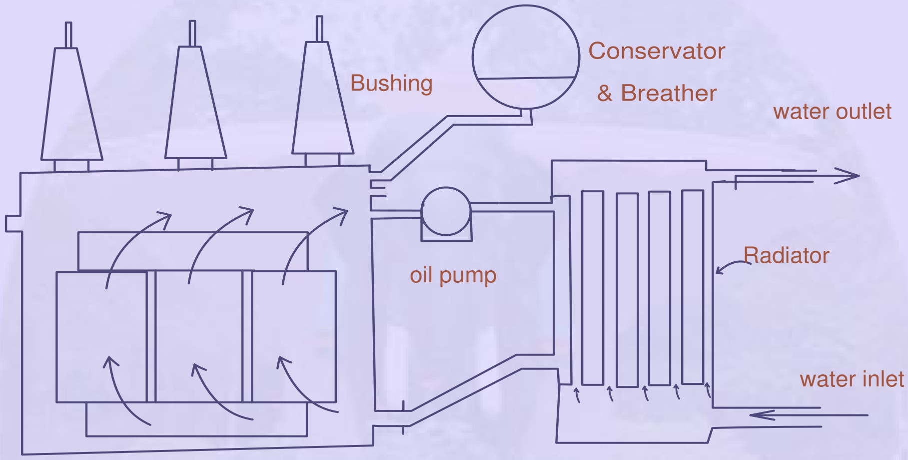
Simple air cooling of the transformers is adopted in dry type transformers. The limit for this is reached by the time the rating is a few kVA. Hence air cooling is used in low voltage machines. This method of cooling is termed as AN(Air Natural). Air Blast(AB) method improves on the above by directing the blast of air at the core and windings. This permits some improvement in the unit sizes.

Substantial improvement is obtained when the transformer is immersed in an oil tank. The oil reaches the conductor surface and extracts the heat and transports the same to the surface of the tank by convection. This is termed as ON (Oil Natural) type of cooling. This method permits the increase in the surface available for the cooling further by the use of ducts, radiators etc.

OB(Oil Blast) method is an improvement over the ON-type and it directs a blast of air on the cooling surface. In the above two cases the flow of oil is by natural convective forces. The rate of circulation of oil can be increased with the help of a pump, with the cooling at the surface remaining natural cooling to air. This is termed as OFN (Oil Forced Natural). If now a forced blast of air is also employed, the cooling method become OFB(Oil Forced Blast). A forced circulation of oil through a radiator is done with a blast of air



(a)



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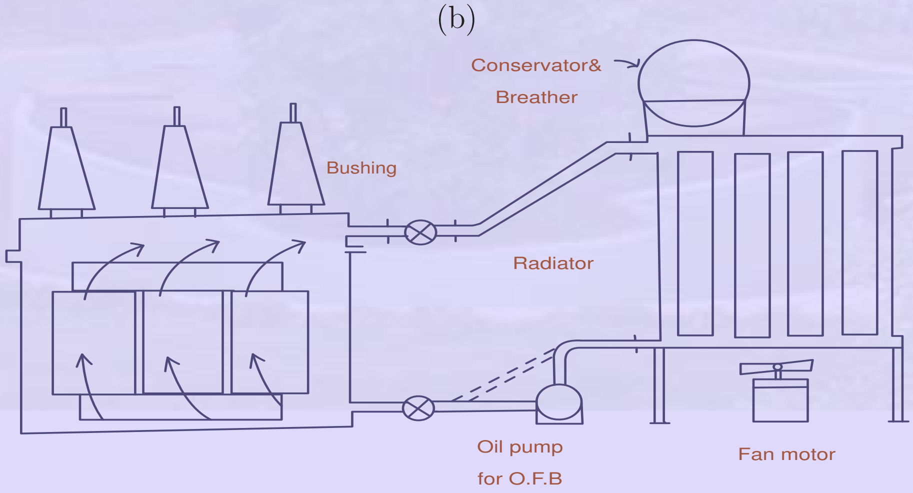

(c)

Figure 9: Some Typical Cooling Arrangements

over the radiator surface. Substantial amount of heat can be removed by employing a water cooling. Here the hot oil going into the radiator is cooled by a water circuit. Due to the high specific heat of water, heat can be evacuated effectively. Next in hierarchy comes OFW which is similar to OFB except that instead of blast of air a forced circulation of cool water in the radiator is used in this. Some cooling arrangements are shown in Fig. 9.

In many large sized transformers the cooling method is matched with the amount of heat that is required to be removed. As the load on the transformer changes the heat generated within also changes. Suitable cooling method can be pressed into service at that time. This gives rise to the concept of mixed cooling technique.

ON/OB Works as ON but with increased load additional air blast is adopted. This gives the ratings to be in the ratio of 1:1.5

ON/OB/OFB Similarly gives the ratings in the ratio of 1:1.5:2

The temperature rise permitted in the British standard specification for power transformers are tabulated below.

Type	winding		oil	core
	Class A	Class B		
	$^{\circ}C$	$^{\circ}C$	$^{\circ}C$	
AN,AB	55	75	-	As
ON,OB,OW	60	-	50	for
OFN,OFB	65	-	50	adjacent
OFW	70	-	50	winding

3.4.1 Properties of the transformer coil

Even though the basic functions of the oil used in transformers are a) heat conduction and b) electrical insulation, there are many other properties which make a particular oil eminently suitable. Organic oils of vegetative or animal origin are good insulators but tend to decompose giving rise to acidic by-products which attack the paper or cloth insulation around the conductors.

Mineral oils are suitable from the point of electrical properties but tend to form sludge. The properties that are required to be looked into before selecting an oil for transformer application are as follows:

Insulting property This is a very important property. However most of the oils naturally fulfil this. Therefore deterioration in insulating property due to moisture or contamination may be more relevant.

Viscosity It is important as it determines the rate of flow of the fluid. Highly viscous fluids need much bigger clearances for adequate heat removal.

Purity The oil must not contain impurities which are corrosive. Sulphur or its compounds as impurities cause formation of sludge and also attack metal parts.

Sludge formation Thickening of oil into a semisolid form is called a sludge. Sludge formation properties have to be considered while choosing the oil as the oil slowly forms semi-solid hydrocarbons. These impede flows and due to the acidic nature, corrode metal parts. Heat in the presence of oxygen is seen to accelerate sludge formation. If the hot oil is prevented from coming into contact with atmospheric air sludge formation can be greatly reduced.

Acidity Oxidized oil normally produces CO_2 and acids. The cellulose which is in the paper insulation contains good amount of moisture. These form corrosive vapors. A good breather can reduce the problems due to the formation of acids.

Flash point And Fire point Flash point of an oil is the temperature at which the oil ignites spontaneously. This must be as high as possible (not less than $160°C$ from the point of safety). Fire point is the temperature at which the oil flashes and continuously burns. This must be very high for the chosen oil (not less than $200°C$).

Inhibited oils and synthetic oils are therefore used in the transformers. Inhibited oils contain additives which slow down the deterioration of properties under heat and moisture and hence the degradation of oil. Synthetic transformer oil like chlorinated diphenyl has excellent properties like chemical stability, non-oxidizing, good dielectric strength, moisture repellant, reduced risk due fire and explosion.

It is therefore necessary to check the quality of the oil periodically and take corrective steps to avoid major break downs in the transformer.

There are several other structural and insulating parts in a large transformer. These are considered to be outside the scope here.