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DISTRIBUTION TRANSFORMERS AND MAINTENANCE

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Abstract

 This paper is produced by student Stylianos Kalogerakis and professor Jari Halme. The main purpose of this research is to gather in one paper information about distribution transformers and maintenance practices. Information about fist transformers ,General Transformer Design Dry-type and cast resin, protection methods are being referred and more also included in the specific research document. Also there is detailed analysis about the consisting of a distribution transformer.

Also information about some types of transformers are gathered as well as distribution transformer connections installations. Also some maintenance tests are referred as well as Over current and earth leakage protection.

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1.1 introduction

Distribution Transformers

Distribution transformers are normally considered to be those transformers which provide the transformation from 11 kV and lower voltages down to the level of the final distribution network. In the UK this was, until January 1995, 415 V three-phase and 240 V phase to neutral. Now it is nominally 400 V three-phase and 230 V between phase and neutral. Of course, these are nominal voltages to be applied at consumers' terminals and there are tolerances to take account of light loading conditions and regulation at times of peak load. Prior to January 1995, most distribution transformers were designed for a secondary open-circuit voltage on principal tapping of 433 V and it remains to be seen whether this situation will change in the long term. At the present time, however, transformer voltage ratios have not changed, although it is possible that some adjustment of transformer off-circuit tappings might have been made at some points of the distribution network. Throughout the following section, therefore, in making reference to distribution transformer low-voltage windings and systems, these will be termed 415 V or 0.415 kV. Except where specifically indicated to the contrary this should be taken as a nominal description of the winding or system voltage class and not necessarily the rated voltage of the winding or system in question. Distribution transformers are by far the most numerous and varied types of transformers used on the electricity supply network. There are around 500 000 distribution transformers on public electricity supply system operated by the Regional Electricity Companies and a similar number installed in industrial installations. They range in size from about 15 kVA, 3.3/0.415 kV to 12.5 MVA, 11/3.3 kV, although most are less than 2000 kVA, the average rating being around 800 kVA. The vast majority are free breathing oil-filled to BS 148, but they may be hermetically sealed oil-filled, dry type, or, occasionally, where there is a potential fire hazard, fire resistant fluids notably silicone fluid, synthetic ester or high molecular weight hydrocarbons which have a fire point in excess of 300° C may be specified. This section will first discuss oil-filled units in some detail and later highlight those aspects which are different for dry-type transformers. As far as the constructional features of transformers using these are concerned, there are no significant differences compared with oil-filled units apart from the need to ensure that all the materials used are compatible with the

dielectric fluid. Most insulating materials, including craft paper and pressboard, are satisfactory on this score; if there are problems it is usually with gaskets and other similar synthetic materials.

Design considerations

Distribution transformers are very likely to be made in a different factory from larger transformers. Being smaller and lighter they do not require the same specialised handling and lifting equipment as larger transformers. Impregnation under very high vacuum and vapour-phase drying equipment is notgenerally required. At the very small end of the range, manufacturing methods are closer to those used in mass production industries. There are many more manufacturers who make small transformers than those at the larger end of the scale. The industry is very competitive, margins are small and turnround times are rapid. As a result the main consideration in the design of the active part is to achieve the best use of materials and to minimise costs, and a 1000 or 2000 kVA transformer built in 1996 would, on reasonably close examination, appear quite different from one made as recently as, say, 20 years earlier.

Historical Background , Long-Distance Power

In 1886, George Westinghouse built the first long-distance alternating-current electric lighting system in Great Barrington, MA. The power source was a 25-hp steam engine driving an alternator with an output of 500 V and 12 A. In the middle of town, 4000 ft away, transformers were used to reduce the voltage to serve light bulbs located in nearby stores and offices.

The First Transformers

Westinghouse realized that electric power could only be delivered over distances by transmitting at a higher voltage and then reducing the voltage at the location of the load. He purchased U.S. patent rights to the transformer developed by Gaulard and Gibbs.

William Stanley, West-inghouse's electrical expert, designed and built the transformers to reduce the voltage from 500 to 100V on the Great Barrington system.

1.2 What Is a Distribution Transformer?

Just like the transformers in the Great Barrington system, any transformer that takes voltage from a primary distribution circuit and "steps down" or reduces it to a secondary distribution circuit or a consumer's service circuit is a distribution transformer. Although many industry standards tend to limit this definition by kVA rating (e.g., 5 to 500 kVA), distribution transformers can have lower ratings and can have ratings of 5000 kVA or even higher, so the use of kVA ratings to define transformer types is being discouraged. We can see a type of distribution transformer in picture 1.2.1.

Picture 1.2.1

1.3 Construction-Early Transformer Materials

The Gaillard-Gibbs transformer has used a coil of many turns of iron wire to create a ferromagnetic loop. The Stanley model, however, appears to have used flat sheets of iron,

stacked together and clamped with wooden blocks and steel bolts. Winding conductors were most likely made of copper from the very beginning. Several methods of insulating the conductor were used in the early days. Varnish dipping was often used and is still used for some applications today.Paper-tape wrapping of conductors has been used extensively, but this has now been almost completely replaced by other methods.

1.4 Oil Immersion

In 1887, the year after Stanley designed and built the first transformers in the U.S., Elihu Thompson patented the idea of using mineral oil as a transformer cooling and insulating medium (Myers et al.,1981). Although materials have improved dramatically, the basic concept of an oil immersed cellulosic insulating system has changed very little in well over a century.

1.5 Cores

Simplicity of design and construction is the keynote throughout in relation to distribution transformers. Simplification has been brought about in the methods of cutting and building cores, notably by the reduction in the number of individual plates required per lay by the use of single plates for the yokes (notched yokes) rather than the two half-yoke plates as would generally be used for a larger transformer. Nonetheless all joints are still mitred and low-loss high permeability materials are widely used. Cores are built without the top yoke in place and, when the yoke is fitted, this is done in a single operation rather than by laboriously slotting in individual packets of plates. Core frames have been greatly simplified so that these have become little more than plain mildsteel 'U' section channels drilled in the appropriate places, and occasionally some manufacturers may use timber for the core frames. These have the advantage that there are no problems with clearances from leads, for example, to be considered in the design of the unit but they are not so convenient in other respects, for example it is not so easy to make fixings to them for lead supports or to support an off-circuit tapchanger. Timber frames are now generally considered by most manufacturers to be less cost effective than steel channels and are now generally tending to be phased out. It is, of course, hardly necessary to state that distribution transformer cores are invariably of a totally boltless construction. Wound cores, in which the core material is threaded in short lengths through the windings to form a coil are common for smaller ratings up to several tens of kVA. While this form of construction might occasionally be used in some large transformers, it is to be regarded as the norm for most distribution transformer cores. There are a number of reasons for this:

- Joints form a greater proportion of the total iron circuit in the case of a small distribution transformer core compared to that of a large power transformer and so measures to reduce losses at the joints will show a greater benefit.

- Building a small core is so much easier than it is for a large core, so that the more sophisticated construction does not present such an obstacle in manufacture.

- Distribution transformers tend to operate at poor load factors. Although this means that the magnitude of the load loss is not too important, iron loss is present all the time and it is therefore desirable to minimise its impact.

- The competitive nature of the industry, discussed above, gives an incentive to provide low losses and noise levels, both of which are improved by using the step-lap construction. Distribution transformer cores also represent the only occasion for which

  the use of amorphous steel has been seriously considered in the UK (and quite widely adopted in other countries, notably the USA).

1.6 Core Improvements

The major improvement in core materials was the introduction of silicon steel in 1932. Over the years,the performance of electrical steels has been improved by grain orientation (1933) and continued improvement in the steel chemistry and insulating properties of surface coatings. The thinner and more effective the insulating coatings are, the more efficient a particular core material will be. The thinner the laminations of electrical steel, the lower the losses in the core due to circulating currents. Mass production of distribution transformers has made it feasible to replace stacked cores with wound cores. C-cores were first used in distribution transformers around 1940. A C-core is made from a continuous strip of steel, wrapped and formed into a rectangular shape, then annealed and bonded together. The core is then sawn in half to form two C-shaped sections that are machine-faced and reassembled around the coil. In the mid 1950s, various manufacturers developed wound cores that were die-formed into a rectangular shape and then annealed to relieve their mechanical stresses. The cores of most distribution transformers made today are made with wound cores. Typically, the individual layers are cut, with each turn slightly lapping over itself. This allows the core to be disassembled and put back together around the coil structures while allowing a minimum of energy loss in the completed core. Electrical

steel manufacturers now produce stock for wound cores that is from 0.35 to 0.18 mm thick in various grades. In the early 1980s, rapid increases in the cost of energy prompted the introduction of amorphous core steel. Amorphous metal is cooled down from the liquid state so rapidly that there is no time to organize into a crystalline structure. Thus it forms the metal equivalent of glass and is often referred to as metal glass or "met-glass."Amorphous core steel is usually 0.025 mm thick and offers another choice in the marketplace for transformer users that have very high energy costs.

1.7 Windings

Foil windings are frequently used as low-voltage windings. In this form of construction the winding turn, of copper or aluminium foil, occupies the full width of the layer. This is wound around a plain mandrel, with intermediate layers of paper insulation, to form the required total number of turns for the winding. Strips of the conductor material are welded or brazed along the edge of the foil at the start and finish to form the winding . Any slight bulge that this creates in the section of the winding is of no consequence. This arrangement represents a very cost-effective method of manufacturing low-voltage windings and also enables a transformer to be built which has a high degree of electromagnetic balance and hence good mechanical short-circuit strength. Diamond dotted press paper is frequently used as interlayer insulation for these windings which also gives them added mechanical strength. The diamond dotted pattern enables the dry-out process to be carried out more easily than would be the case if the resin bonding material were applied uniformly to the whole surface of the presspaper sheet. Foil windings are produced in this way for use in oil-filled transformers; however, the same construction using class that can be used in air-insulated transformers or as the low-voltage windings of cast resin transformers.   Distribution transformers frequently use other types of winding construction not found in larger transformers in addition to the foil windings described above. Because of the small frame sizes resulting from low kVA ratings, the volts per turn is usually very low so that for a high-voltage winding a considerable number of turns will be required. The current is, however, also low and the turn cross-section, as a result, is small. Winding wires are frequently circular in section and enamel covered. Circular cross-section wire cannot be wound into continuous disc windings so multilayer spiral windings are common. These will normally have one or more wraps of paper between layers to give the winding stability and to provide insulation for the voltage between layers. One problem with this arrangement is that when drying out the winding the only route for removal of moisture is via the winding ends so that the dry-out process must allow sufficient time under temperature and some degree of vacuum to allow the moisture to migrate axially along the length of the layers. Frequently the dry-out time for this type of winding might appear disproportionately long for a small transformer. Another alternative for high-voltage windings is the use of 'crossover' coils. Each section of the winding, or coil, is itself a small multilayer spiral winding having a relatively short axial length. A complete HV winding will then be made up of perhaps 6 or 8 coils arranged axially along the

length of the winding and connected in series. Crossover coils are easier to dry out than full length multilayer windings since they have a short axial length and, by subdividing the winding into a number of sections, the volts within each section are only a fraction of the phase volts, thus distributing this evenly along the leg. For this reason this form of construction is likely to be used for the higher voltage class of HV winding, for example at 22 or 33 kV, where a simple layer construction would not provide the necessary clearance distances.   Continuous disc windings are, of course, used for any high-voltage winding which has a large enough current to justify the use of a rectangular conductor. At 11 kV, this probably means a rating of about 750 kVA, three phase and above would have a disc wound HV winding. At 3.3 kV disc windings will probably be used for ratings of 250 kVA, three phase and above. Because of their intrinsically greater mechanical strength, disc windings would be preferred for any transformer known to have a duty for frequent starting of large motors or other such frequent current surges.   Pressure for much of the innovation introduced into distribution transformers has come from the competition within this sector of the industry. Although many of the materials and practices used have some application or spin-off for larger sized units, others can be used only because they are tolerable when currents are small and short-circuit forces, for example, are modest. One such case is in the use of winding arrangements which are square in platform . By adopting this arrangement the core limb can have a square cross-section so there is no need to cut a large range of plate widths, and the core with its three-phase set of windings is more compact so a smaller tank can be used. This is only permissible because small units with modest short-circuit forces do not need the high mechanical strength provided by the use of windings which are circular in section.

1.8 Winding Materials

Conductors for low-voltage windings were originally made from small rectangular copper bars, referred to as "strap." Higher ratings could require as many as 16 of these strap conductors in parallel to make one winding having the needed cross section. A substantial improvement was gained by using copper strip, which could be much thinner than strap but with the same width as the coil itself. In the early 1960s, instability in the copper market encouraged the use of aluminum strip conductor. The use of aluminum round wire in the primary windings followed in the early 1970s (Palmer, 1983). Today, both aluminum and copper conductors are used in distribution transformers, and the choice is largely dictated by economics. Round wire separated by paper insulation between layers has several disadvantages. The wire tends to "gutter," that is, to fall into the troughs in the layer below. Also, the contact between the wire and paper occurs only along two lines on either side of the conductor. This is a significant disad - vantage when an adhesive is used to bind the wire and paper together. To prevent these problems, manufacturers often flatten the wire into an oval or rectangular shape in the process of winding the coil. This

allows more conductor to be wound into a given size of coil and improves the mechanical and electrical integrity of the coil.

1.9 Conductor Insulation

The most common insulation today for high-voltage windings is an enamel coating on the wire, with kraft paper used between layers. Low-voltage strip can be bare with paper insulation between layers. The use of paper wrapping on strap conductor is slowly being replaced by synthetic polymer coatings or wrapping with synthetic cloth. For special applications, synthetic paper such as DuPont's Nomex®1 can be used in place of kraft paper to permit higher continuous operating temperatures within the transformer coils.

1.10 Thermally Upgraded Paper

In 1958, manufacturers introduced insulating paper that was chemically treated to resist breakdown due to thermal aging. At the same time, testing programs throughout the industry were showing that the estimates of transformer life being used at the time were extremely conservative. By the early 1960s, citing the functional-life testing results, the industry began to change the standard average winding-temperature rise for distribution transformers, first to a dual rating of 55/65 C and then to a single 65 C rating (IEEE,1995). In some parts of the world, the distribution transformer standard remains at 55 C rise for devices using non upgraded paper.

1.11 Conductor Joining

The introduction of aluminum wire, strap, and strip conductors and enamel coatings presented a number of challenges to distribution transformer manufacturers. Aluminum spontaneously forms an insulatingoxide coating when exposed to air. This oxide coating must be removed or avoided whenever an electrical connection is desired. Also, electrical-conductor grades of aluminum are

quite soft and are subject to cold flow and differential expansion problems when mechanical clamping is attempted. Some methods of splicing aluminum wires include soldering or crimping with special crimps that penetrate enamel and oxide coatings and seal out oxygen at the contact areas. Aluminum strap or strip conductors can be TIG

(tungsten inert gas)-welded. Aluminum strip can also be cold-welded or crimped to other copper or aluminum connectors. Bolted connections can be made to soft aluminum if the joint area is properly cleaned. "Belleville" spring washers and proper torquing are used to control the clamping forces and contain the metal that wants to flow out of the joint. Aluminum joining problems are sometimes mitigated by using hard alloy tabs with tin plating to make bolted joints using standard hardware.

1.12 Coolants-Mineral Oil

Mineral oil surrounding a transformer core-coil assembly enhances the dielectric strength of the windingand prevents oxidation of the core. Dielectric improvement occurs because oil has a greater electricalwithstand than air and because the dielectric constant of oil is closer to that of the insulation. As a result, the stress on the insulation is lessened when oil replaces air in a dielectric system. Oil also picks up heat while it is in contact with the conductors and carries the heat out to the tank surface by self-convection. Thus a transformer immersed in oil can have smaller electrical clearances and smaller conductors for the same voltage and kVA ratings.

1.13 Askarels

Beginning about 1932, a class of liquids called askarels or polychlorinated biphenyls (PCB) was used as a substitute for mineral oil where flammability was a major concern. Askarel-filled transformers could be placed inside or next to a building where only dry types were used previously. Although these coolants were considered nonflammable, as used in electrical equipment they could decompose when exposed to electric arcs or fires to form hydrochloric acid and toxic furans and dioxins. The compounds were further undesirable because of their persistence in the environment and their ability to accumulate in higher animals, including

humans. Testing by the U.S. Environmental Protection Agency has shown that PCBs can cause cancer in animals and cause other non cancer health effects. Studies in humans provide supportive evidence for potential carcinogenic and non carcinogenic effects of PCBs . The use of askarels in new transformers was outlawed in 1977 (Clai-borne, 1999). Work still continues to retire and properly dispose of transformers containing askarels or askarel-contaminated mineral oil.

1.14 High-Temperature Hydrocarbons

Among the coolants used to take the place of askarels in distribution transformers are high-temperature hydrocarbons (HTHC), also called high-molecular-weight hydrocarbons. These coolants are classified by the National Electric Code as "less flammable" if they have a fire point above 300 C. The disadvantages of HTHCs include increased cost and a diminished cooling capacity from the higher viscosity that accompanies the higher molecular weight.

1.15 Silicones

Another coolant that meets the National Electric Code requirements for a less-flammable liquid is a silicone, chemically known as polydimethylsiloxane. Silicones are only occasionally used because they exhibit biological persistence if spilled and are more expensive than mineral oil or HTHCs.

1.16 Halogenated Fluids

Mixtures of tetrachloroethane and mineral oil were tried as an oil substitute for a few years. This and other chlorine-based compounds are no longer used because of a lack of biodegradability, the tendency to produce toxic by-products, and possible effects on the Earth's ozone layer.

1.17 Esters

Synthetic esters are being used in Europe, where high-temperature capability and biodegradability are most important and their high cost can be justified, for example, in traction (railroad) transformers. Transformer manufacturers in the U.S. are now investigating the use of natural esters obtained from vegetable seed oils. It is possible that agricultural esters will provide the best combination of high-temperature properties, stability, biodegradability, and cost as an alternative to mineral oil in distribution transformers (Oommen and Claiborne, 1996).

1.18 Tank and Cabinet Materials

A distribution transformer is expected to operate satisfactorily for a minimum of 30 years in an outdoor environment while extremes of loading work to weaken the insulation systems inside the transformer. This high expectation demands the best in state-of-the-art design, metal processing, and coating technologies.

1.19 Tanks

Because of the relatively large numbers made, some flow-line production can be introduced into tank manufacture for the smaller units, notably the 3.3/0.415 kV pole-mounted types. This requires that tanks should be standardized, which means that the fittings provided and the location of these must also be standardized. Internal surfaces, as well as the steel core frames, are usually left unpainted. Although this goes against the principle of preventing oil coming into contact with the catalytic action of the steel, manufacturers claim that with modern oils, for the conditions of operation encountered in sealed distribution transformers this does not lead to unacceptable levels of oxidation.   Provision of a silica gel breather for most small distribution transformers would result in an unacceptably high maintenance liability. These transformers are therefore frequently hermetically sealed, with a cushion of dry air above the oil to allow for expansion and contraction. This limited amount of air in contact with the oil is then considered to present only a modest tendency towards oxidation. Sealing of the transformers prevents the moisture arising from insulation degradation from escaping, but again this amounts to far less of a threat to insulation quality than would be the case if the transformers were left to breathe freely without a silica gel breather or if a breather, having been provided, was not maintained in a dry condition.   Larger distribution transformers, say those of 1 or 2 MVA and greater, would probably benefit from having silica gel breathers fitted provided that these were well maintained, in which case tank internals should be painted to prevent contact between the oil and mild steel components. As the units become larger, the use of a conservator tank to reduce the surface area of contact between oil and air, and the fitting of a Buchholz relay, must be considered, although

the precise rating at which these measures become economically justified is a decision for the user.

1.20 Mild Steel

Almost all overhead and pad-mounted transformers have a tank and cabinet parts made from mild carbon steel. In recent years, major manufacturers have started using coatings applied by electrophoretic methods (aqueous deposition) and by powder coating. These new methods have largely replaced the traditional flow-coating and solvent-spray application methods.

1.21 Stainless Steel

Since the mid 1960s, single-phase submersibles have almost exclusively used AISI 400-series stainless steel. These grades of stainless were selected for their good welding properties and their tendency to resist pit-corrosion. Both 400-series and the more expensive 304L (low-carbon chromium-nickel) stainless steels have been used for pad mounts and pole types where severe environments justify the added cost.

Transformer users with severe coastal environments have observed that pad mounts show the worst corrosion damage where the cabinet sill and lower areas of the tank contact the pad. This is easily explained by the tendency for moisture, leaves, grass clippings, lawn chemicals, etc., to collect on the pad surface. Higher areas of a tank and cabinet are warmed and dried by the operating transformer, but the lowest areas in contact with the pad remain cool. Also, the sill and tank surfaces in contact with the pad are most likely to have the paint scratched. To address this, manufacturers sometimes offer hybrid trans-formers, where the cabinet sill, hood, or the tank base may be selectively made from stainless steel.

1.22 Composites

There have been many attempts to conquer the corrosion tendencies of transformers by replacing metal structures with reinforced plastics. One of the more successful is a one-piece composite hood for single-phase pad-mounted transformers.

1.23 Modern Processing-Adhesive Bonding

Today's distribution transformers almost universally use a kraft insulating paper that has a diamond pattern of epoxy adhesive on each side. Each finished coil is heated prior to assembly. The heating drives out any moisture that might be absorbed in the insulation. Bringing the entire coil to the elevated temperature also causes the epoxy adhesive to bond and cure, making the coil into a solid mass, which is more capable of sustaining the high thermal and mechanical stresses that the transformer might encounter under short-circuit current conditions while in service. Sometimes the application of heat is combined with clamping of the coil sides to ensure intimate contact of the epoxy-coated paper with the conductors as the epoxy cures. Another way to improve adhesive bonding in the high-voltage winding is to flatten round wire as the coil is wound. This produces two flat sides to contact adhesive on the layer paper above and below the conductor. It also improves the space factor of the conductor cross section, permitting more actual conductor to fit within the same core window. Flattened conductor is less likely to "gutter" or fall into the spaces in the previous layer, damaging the layer insulation.

1.24 Vacuum Processing

With the coil still warm from the bonding process, transformers are held at a high vacuum while oil flows into the tank. The combination of heat and vacuum assures that all moisture and all air bubbles have been removed from the coil, providing electrical integrity and a long service life. Factory processing with heat and vacuum is impossible to duplicate in the field or in most service facilities. Transformers, if opened, should be exposed to the atmosphere for minimal amounts of time, and oil levels should never be taken down below the tops of the coils. All efforts must be taken to keep air bubbles out of the insulation structure.

1.25 General Transformer Design Dry-type and cast resin transformers

Dry-type transformers, particularly those using cast resin insulation, are now widely used in locations where the fire risk associated with the use of mineral oil is considered to be unacceptable, for example in offices, shopping complexes, apartment buildings, hospitals and the like. The background to this development and the factors requiring to be considered in installing cast resin transformers with in buildings. This section describes the special features of cast resin transformers themselves. Complete encapsulation of the windings of a power transformer in cast resin is an illogical step to take, because, as explained on a number of occasions elsewhere in these pages, one of the main requirements in designing transformer windings is to provide a means of dissipating the heat generated by the flow of load current. Air is a very much poorer cooling medium than mineral oil anyway, without the additional thermal barrier created by the resin. All air-cooled transformers are therefore less efficient thermally than their oil-filled counterparts and cast resin are poorer than most. Hence they will be physically larger and more costly even without the added costs of the resin encapsulation process. In addition, the absence of a large volume of oil with its high thermal inertia means that cast resin-insulated transformers have shorter thermal time constants which limit their overload carrying capability.The incentive to develop an economic design of cast resin transformer was provided by the outlawing of polychlorinated biphenyls (PCBs) in the late 1970s on the grounds of their unacceptable environmental impact. Alternative non-flammable liquid dielectrics have all tended to have had some disadvantages, with the result that users have come to recognize the merits of eliminating the liquid dielectric entirely. Nevertheless, cast resin does not represent an automatic choice of insulation system for a power transformer. Cast resin transformers are expensive in terms of first cost. They are less energy efficient than their liquid-filled equivalents. In their early days there

were suggestions that their reliability was poor and even that their fire resistance left something to be desired. In recent times, however, their qualities of ruggedness, reliability and excellent dielectric strength have come to be recognized as outweighing their disadvantages and their use has become widespread in situations where these properties are most strongly valued.

1.26 Resin-encapsulated windings

Cores and frames of cast resin transformers are very similar, if a little larger, to those of oil-filled distribution transformers. It is in the design of the windings that cast resin transformers are unique. 415 V low-voltage windings are usually foil wound, as described above for oil-filled transformers, and are non-encapsulated, although they are frequently given a coating of the same resin material as that used for the high-voltage winding in order to provide them with an equivalent level of protection from the environment. It is the high-voltage winding which is

truly resin encapsulated. Apart from the problem of heat dissipation, the other problem arising from resin encapsulation is the creation of internal voids or minute surface cracking of the resin. Voids can arise due to less than perfect encapsulation or they can be created due to differential thermal expansion between winding conductors and the resin, which may also lead to surface cracking. Surprisingly, the resin has a greater coefficient of expansion than the conductors. The coefficient of expansion of aluminum is a closer match to that of resin than is copper, and aluminum is therefore the preferred winding material. This may be either wire or foil. If wire is used this will normally be round in section, with a thin covering of insulation. This will probably be randomly wound to the required build-up in diameter, either over a plain mandrel or one which is notched at intervals so that the turns progress from one end of the winding to the other to provide an approximately linear voltage distribution along the axial length of the winding. If the winding is wound from foil, then a number of narrow foil-wound sections will be connected in series in a similar manner to the method of connecting crossover coils described earlier. Each foil-wound section will be machine wound with two layers of melamine film between foils to provide the interterm insulation; two layers being used to avoid the possibility of any minute punctures in the film coinciding and creating turn-to-turn faults. The melamine film is exceedingly flimsy and the foil must be free from any edge defects which could cut through the film, and a very high level of cleanliness is necessary during the foil winding process to ensure that no particles are trapped between foil and film which could also lead to breakdown by puncturing the film. The winding process usually takes place within an enclosed windingmachine which is pressurized with air to above the pressure of the winding room and dry filtered air is blown across the surfaces of the foil and films at the point within the machine where these are brought together. After winding, the foil sections must be kept in a carefully controlled ambient temperature to ensure that the winding tension remains within close limits so as to ensure that there is no relative axial movement of foils and film.The encapsulation process involves placing the wire or foil-wound sections within steel moulds into which the resin may be admitted under high vacuum. Resin, hardener and fillers, that is the material which gives the resin its bulk, are mixed immediately prior to being admitted to the mould. To ensure that the filler material is fully mixed, part quantity can be fully mixed with the resin and the remainder fully mixed with the hardener before the two are then mixed together. The windings are located within the moulds by means of axial strips of resin material of the same quality as that used for encapsulation. These are placed between the winding and the outer mould so that the resin covering the inner surface of the winding, which will be subjected to the HV to LV test voltage, will be totally seamless. It is important that the resin should penetrate fully the interstices between the conductors if the winding is of the wire-wound type. In some processes this is assisted by initially admitting low viscosity resin into the mould. This is then followed by the encapsulation resin which displaces it except in any difficult to penetrate places, which, of course, was the purpose of the low-viscosity resin. The resin hardening process is endothermic, that is it generates heat. In order to ensure freedom from stress within the cured resin to minimise the likelihood of resin cracking, it is necessary to carefully control the temperature of the curing

process by cooling as and when required. Achieving the precise temperature/time relationship is critical to the integrity of the encapsulated winding so that this process is usually done under microprocessor control.   It is usual to provide cast resin transformers with off-circuit tappings on the HV winding at 2.5 and 5% of open-circuit voltage. These are selected by means of bolted links on the face of the HV winding. The windings are mounted concentrically over the core limb with shaped resilient end blocks, usually of silicone rubber, providing axial location and radial spacing. The HV delta connection is made by means of copper bars taking the most direct route between winding terminals.

We can see an 10MVA cast resin transformer in picture 1.26.1 :

Picture 1.26.1

1.27 Liquid-Filled vs. Dry Type

The vast majority of distribution transformers on utility systems today are liquid-filled. Liquid-filled transformers offer the advantages of smaller size, lower cost, and greater overload capabilities compared with dry types of the same rating. We can see a dry type transformer in picture 1.27.1.

Picture 1.27.1
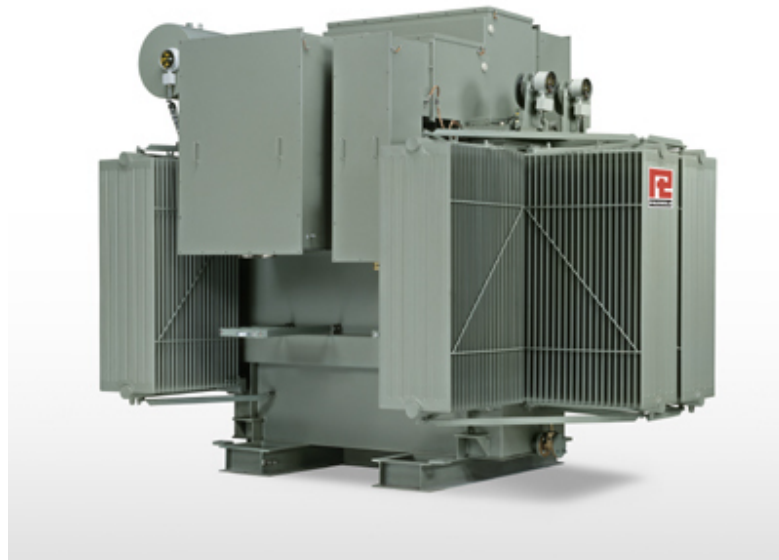
1.28 Class C dry-type transformers

Class C dry-type transformers are those based on glass fiber-reinforced boards, aromatic polyamide paper conductor insulation and similar materials capable of operating at temperatures up to around 220° C. They have now been somewhat eclipsed by cast resin encapsulated types. However, they do have some advantages over cast resin; they are a little more compact and thus lighter, they generally have lower losses and are up to 20% cheaper than cast resin, and, most significantly, they have better overload and short-circuit withstand capability. Although they are not capable of withstanding the same extreme environmental conditions as cast resin, present day dry types are greatly superior in this respect to those of the 1960s when they were initially

introduced. At that time, the conductor insulation or 'paper' covering was largely asbestos based in order to be able to achieve the required temperature withstand capability. Even when properly impregnated, this material was inclined to absorb moisture, which greatly reduced its insulation properties. It was therefore very important to ensure that transformer windings were properly dried out before energizing, and even while in service it was important to ensure that transformers were given a good dry environment. The availability of aromatic polyamide paper from the mid-1970s greatly improved this situation. The construction of class C dry-type transformers is very similar to oil-filled units. They may have conventional helically wound LV windings or these may be foil wound. For all but the lowest ratings the HV winding conductor will be rectangular in section so that HV windings may generally be disc wound. Disc windings are to be preferred to the multilayer helical type, since the former arrangement gives a uniform distribution of the phase voltage throughout the length of the winding thus ensuring that the electrical stresses are minimized. As previously mentioned, air is a poorer cooling medium than oil and in order to ensure adequate cooling air flow through the windings vertical ducts should be a minimum of 10 mm wide and horizontal ducts a minimum of 6 mm. transformer.

1.29 Installation of class C dry types

The method of installing class C dry-type transformers is very similar to that used for cast resin transformers. The transformer core and windings will normally be mounted on rollers and housed in a sheet-steel ventilated enclosure incorporated into the LV switchboard with its LV bush bars connected directly to the switchboard incoming circuit breaker. It is not so convenient to provide molded HV connections directly onto the winding as is the case with cast resin and, in addition, the paper insulated windings are more easily damaged than those of a cast resin transformer so it is best to avoid carrying out any unnecessary work in the close vicinity. It is desirable, therefore, that the HV supply cable is not terminated internally within the enclosure but connected into an externally mounted cable box. Adequate access to the enclosure should be provided, however, to enable the windings to be cleaned and inspected about once per year. This should preferably be a vacuum cleaning rather than by blowing out dust deposits a procedure which may embed foreign material in undesirable locations.

1.30   Stacked vs. Wound Cores

Stacked-core construction favors the manufacturer that makes a small quantity of widely varying special designs in its facility. A manufacturer that builds large quantities of identical designs will benefit from the automated fabrication and processing of wound cores.

1.31 Single Phase

The vast majority of distribution transformers used in North America are single phase, usually serving a single residence or as many as 14 to 16, depending on the characteristics of the residential load. Single-phase transformers can be connected into banks of two or three separate units. Each unit in a bank should have the same voltage ratings but need not supply the same kVA load.

1.32 Core-Form Construction

A single core loop linking two identical winding coils is referred to as core-form construction. A picture of core type distribution transformer is below at picture 1.32.1.

Picture 1.32.1

1.33 Shell-Form Construction

A single winding structure linking two core loops is referred to as shell-form construction. There is a core type transformer type below at picture 1.33.1

Picture 1.33.1

1.34 Winding Configuration

Most distribution transformers for residential service are built as a shell form, where the secondary winding is split into two sections with the primary winding in between. This so-called

LO-HI-LO configuration results in a lower impedance than if the secondary winding is contiguous. The LO-HI configuration is used where the higher impedance is desired and especially on higher-kVA ratings where higher impedances are mandated by standards to limit short-circuit current. Core-form transformers are always built LO-HI because the two coils must always carry the same currents. A 120/240 V service using a core-form in the LO-HI-LO configuration would need eight interconnected coil sections.

1.35 Three Phase

Most distribution transformers built and used outside North America are three phase, even for residentialservice. In North America, three-phase transformers serve commercial and industrial sites only. All three-phase distribution transformers are said to be of core-form construction, although the definitions out-lined above do not hold. Three-phase transformers have one coaxial coil for each phase encircling a vertical leg of the core structure. Stacked cores have three or possibly four vertical legs, while wound cores have a total of four loops creating five legs or vertical paths: three down through the center of the three coils and one on the end of each outside coil. The use of three vs. four or five legs in the core structure has a bearing on which electrical connections and loads can be used by a particular transformer. The advantage of three-phase electrical systems in general is the economy gained by having the phases share common conductors and other components.

There are Three phase distribution transformers with rolled iron core in picture 1.35.1 below:

Picture 1.35.1

1.36 Duplex and Triplex Construction

Occasionally, utilities will require a single tank that contains two completely separate core-coil assemblies. Such a design is sometimes called a duplex and can have any size combination of single-phase core-coil assemblies inside. The effect is the same as constructing a two-unit bank with the advantage of havingonly one tank to place. Similarly, a utility may request a triplex transformer with three completely separate

and distinct core structures (of the same kVA rating) mounted inside one tank.

1.37 Serving Mixed Single and Three-Phase Loads

The utility engineer has a number of transformer configurations to choose from, and it is important to match the transformer to the load being served. A load that is mostly single phase with a small amount of three phase is best served by a bank of single-phase units or a duplex pair, one of which is larger to serve the single-phase load. A balanced three-phase load is best served by a three-phase unit, with each phase's coil identically loaded.

1.38 Transformer Connections, Single-Phase Primary Connections

The primary winding of a single-phase transformer can be connected between a phase conductor and ground or between two phase conductors of the primary system.

1.39 Grounded Wye Connection

Those units that must be grounded on one side of the primary are usually only provided with one primary connection bushing. The primary circuit is completed by grounding the transformer tank to the grounded system neutral. Thus, it is imperative that proper grounding procedure be followed when the transformer is installed so that the tank never becomes "hot." Since one end of the primary winding is always grounded, the manufacturer can economize the design and grade the high-voltage insulation. Grading provides less insulation at the end of the winding

closest to ground. A transformer with graded insulation usually cannot be converted to operate phase-to-phase.

1.40 Fully Insulated Connection

Single-phase transformers supplied with fully insulated (not graded) coils and two separate primary connection bushings may be connected phase-to-phase on a three-phase system or phase-to-ground on a grounded wye system as long as the proper voltage is applied to the coil of the transformer.

1.41 Single-Phase Secondary Connections

Distribution transformers will usually have two, three, or four secondary bushings, and the most common voltage ratings are 240 and 480, with and without a mid-tap connection.

1.42 Two Secondary Bushings

A transformer with two bushings can supply only a single voltage to the load.

1.43 Three Secondary Bushings

A transformer with three bushings supplies a single voltage with a tap at the midpoint of that voltage. This is the common three-wire residential service used in North America. For example,

a 120/240 V secondary can supply load at either 120 or 240 V as long as neither 120-V coil section is overloaded. Transformers with handholes or removable covers can be internally reconnected from three to two bushings in order to serve full kVA from the parallel connection of coil sections. These are designated 120/240 or 240/480 V, with the smaller value first. Most pad-mounted distribution transformers are permanently and completely sealed and therefore cannot be reconnected from three to two bushings. The secondary voltage for permanently sealed transformers with three bushings is 240/120 V or 480/240 V.

1.44 Four Secondary Bushings

Secondaries with four bushings can be connected together external to the transformer to create a mid-tap connection with one bushing in common, or a two-bushing connection where the internal coil sections are paralleled. The four-bushing secondary will be designated as 120/240 or 240/480 V, indicating hat a full kVA load can be served at the lower voltage. The distinction between 120/240 and 240/120 V must be carefully followed when pad-mounted transformers are being specified.

1.45 Three-Phase Connections

When discussing three-phase distribution transformer connections, it is well to remember that this can refer to a single three-phase transformer or single-phase transformers interconnected to create a three-phase bank. For either an integrated transformer or a bank, the primary or secondary can be wired in either delta or wye connection. The wye connections can be either grounded or ungrounded. However, not all combinations will operate satisfactorily, depending on the transformer construction, characteristics of the load, and the source system. Some connections that are of special concern are listed below.

1.46 Ungrounded Wye–Grounded Wye

A wye–wye connection where the primary neutral is left floating produces an unstable neutral where high third-harmonic voltages are likely to appear. In some Asian systems, the primary

neutral is stabilized by using a three-legged core and by limiting current unbalance on the feeder at the substation.

1.47 Grounded Wye–Delta

This connection is called a grounding transformer. Unbalanced primary voltages will create high currents in the delta circuit. Unless the transformer is specifically designed to handle these circulating currents, the secondary windings can be overloaded and burn out. Use of the ungrounded wye–delta is suggested instead.

1.48 Grounded Wye–Grounded Wye

A grounded wye–wye connection will sustain unbalanced voltages, but it must use a four- or five-legged core to provide a return path for zero-sequence flux.

1.49 Three-Phase Secondary Connections–Delta

Three-phase transformers or banks with delta secondaries will have simple nameplate designations such as 240 or 480. If one winding has a mid-tap, say for lighting, then the nameplate will say 240/120 or 480/240, similar to a single-phase transformer with a center tap. Delta secondaries can be grounded at the mid-tap or any corner.

1.50 Duplex Connections

Two single-phase transformers can be connected into a bank having either an open-wye or open-delta primary along with an open-delta secondary. Such banks are used to serve loads that are predominantly single phase but with some three phase. The secondary leg serving the single-phase load can have a mid-tap, which may be grounded.

1.51 Preferred Connections

In the earliest days of electric utility systems, it was found that induction motors drew currents that exhibited a substantial third harmonic component. In addition, transformers on the system that were operating close to the saturation point of their cores had third harmonics in the exciting current. One way to keep these harmonic currents from spreading over an entire system was to use delta-connected windings in transformers. Third-harmonic currents add up in-phase in a delta loop and flow around the loop, dissipating themselves as heat in the windings but minimizing the harmonic voltage distortion that might be seen elsewhere on the utility's system. With the advent of suburban underground systems in the 1960s, it was found that a transformer with a delta-connected primary was more prone to ferroresonance problems because of higher capacitance between buried primary cables and ground. An acceptable preventive was to go to grounded-wye-grounded-wye transformers on all but the heaviest industrial applications.

1.52 Ferro resonance

Ferroresonance is an overvoltage phenomenon that occurs when charging current for a long underground cable or other capacitive reactance saturates the core of a transformer. Such a resonance can result in voltages as high as five times the rated system voltage, damaging lightning arresters and other equipment and possibly even the transformer itself. When ferroresonance is occurring, the transformer is likely to produce loud squeals and groans, and the noise has been likened to the sound of steel roofing being dragged across a concrete surface. A typical ferroresonance situation is consists of long underground cables feeding a transformer with a delta-connected primary. The transformer is unloaded or very lightly loaded and switching or fusing for the circuit operates one phase at a time. Ferroresonance can occur when energizing the transformer as the first switch is closed, or it can occur if one or more distant fuses open and the load is very light. Ferroresonance is more likely to occur on systems with higher primary voltage and has been observed even when there is no cable present. All of the contributing factors delta or wye connection, cable length, voltage, load, single-phase switching must be considered together. Attempts to set precise limits for prevention of the phenomenon have been frustrating.

1.53 Transformer Locations-Overhead

With electric wires being strung at the tops of poles to keep them out of the reach of the general public, it is obvious that transformers would be hung on the same poles, as close as possible to the high-voltage source conductors. Larger units are often placed on overhead platforms in alleyways, or alongside buildings, or on ground-level pads protected by fencing. Overhead construction is still the most economical choice in rural areas, but it has the disadvantage of susceptibility to ice and wind storms. The public no longer perceives overhead wiring as a sign of progress, instead considering it an eyesore that should be eliminated from view. We can see in picture 1.53.1 locations of overhead transformers

picture1.53.1

1.54 Underground

Larger cities with concentrated commercial loads and tall buildings have had underground primary cables and transformers installed in below-grade ventilated vaults since the early part of the 20th century. By connecting many transformers into a secondary network, service to highly concentrated loads can be maintained even though a single transformer may fail. In a network, temporary overloads can be shared among all the connected transformers. The use of

underground distribution for light industrial and commercial and residential service became popular in the 1960s, with the emphasis on beautification that promoted fences around scrap yards and the elimination of overhead electric and telephone lines. The most common construction method for residential electric services is underground primary cables feeding a transformer placed on a pad at ground level. The problems of heat dissipation and corrosion are only slightly more severe than overheads, but they are substantially reduced compared with transformers confined in below-grade ventilated vaults. Since pad mounts are intended to be placed in locations that are frequented by the general public, the operating utility has to be concerned about security of the locked cabinet covering the primary and secondary connections to the transformer. The industry has established standards for security against unauthorized entry and vandalism of the cabinet and for locking provisions. Another concern is the minimization of sharp corners or edges that may be hazardous to children at play, and that also has been addressed by standards. The fact that pad-mounted transformers can operate with surface temperatures near the boiling point of water is a further concern that is voiced from time to time. One argument used to minimize the danger of burns is to point out that it is no more hazardous to touch a hot transformer than it is to touch the hood of an automobile on a sunny day. From a scientific standpoint, research has shown that people will pull away after touching a hot object in a much shorter time than it takes to sustain a burn injury. The point above which persons might be burned is about 150 C.

Underground distribution transformer in picture 1.54.1:

picture 1.54.1

1.55 Directly Buried

Through the years, attempts have been made to place distribution transformers directly in the ground without a means of ventilation. A directly buried installation may be desirable because it is completely out of sight and cannot be damaged by windstorms, trucks and automobiles, or lawn mowers. There are three major challenges when directly buried installations are considered: the limited operational accessibility, a corrosive environment, and the challenge of dissipating heat from the transformer. The overall experience has been that heat from a buried transformer tends to dry out earth that surrounds it, causing the earth to shrink and create gaps in the heat-conduction paths to the ambient soil. If a site is found

that is always moist, then heat conduction may be assured, but corrosion of the tank or of cable shields is still a major concern. Within the last several years, advances in encapsulation materials and techniques have fostered development of a solid-insulation distribution transformer that can be installed in a ventilated vault or directly buried using thermal backfill materials while maintaining loadability comparable with overhead or pad-mounted transformers.

1.56 Installation

The complete unit is normally mounted on rollers so that it can be easily moved around for installation and is fitted within a sheet-steel ventilated enclosure. Since cast resin transformers are frequently associated with a 415 V distribution switchboard, the enclosure can be made an integral part of this, with the transformer LV bus-bars connected directly to the switchboard incoming circuit breaker or switch fuse. The HV supply cable may be gladded and terminated within the enclosure with cable tails taken directly to the winding terminals. If the cable comes from below, so that the cable tails pass in front of the face of the HV coil, the transformer manufacturer will specify a minimum clearance between these and the coil face. Some users may prefer to keep the cable termination external to the transformer enclosure and mount a cable box on the outside with through bushings taking the connections into the enclosure so that these may be linked across to the winding terminals.

1.57 Interior Installations

Building codes generally prohibit the installation of a distribution transformer containing mineral oil inside or immediately adjacent to an occupied building. The options available include use of a dry-type transformer or the replacement of mineral oil with a less-flammable coolant.

1.58 Underground Distribution Transformers

Underground transformers are self-cooled, liquid-filled, sealed units designed for step-down operation from an underground primary-cable supply. They are available in both single- and three-phase designs. Underground transformers can be separated into three subgroups: those designed for installation in roomlike vaults, those designed for installation in surface-operable enclosures, and those designed for installation on a pad at ground level.

Underground transformer picture 1.58.1:

picture 1.58.1

1.59 Vault Installations

The vault provides the required ventilation, access for operation, maintenance, and replacement, while at the same time providing protection against unauthorized entry. Vaults used for

transformer installations are large enough to allow personnel to enter the enclosure, typically through a manhole and down a ladder. Vaults have been used for many decades, and it is not uncommon to find installations that date back to the days when only paper-and-lead-insulated primary cable was available. Transformers for vault installations are typically designed for radial application and have a separate fuse installation on the source side.

Vaults can incorporate many features:

- Removable top sections for transformer replacement

- Automatic sump pumps to keep water levels down

- Chimneys to increase natural air flow

- Forced-air circulation

Transformers designed for vault installation are sometimes installed in a room inside a building. This ,of course, requires a specially designed room to limit exposure to fire and access by unauthorized personnel and to provide sufficient ventilation. Both mineral-oil-filled units and units with one of the less-flammable insulating oils are used in these installations. These installations are also made using dry-type or pad-mounted transformers. Transformers for vault installation are manufactured as either subway transformers or as vault-type transformers.

• Vault-type transformers are suitable for occasional submerged operation.

• Subway transformers are suitable for frequent or continuous submerged operation.

From the definitions, the vault type should only be used when a sump pump is installed, while the subway-type could be installed without a sump pump. The principal distinction between vault and subway is their corrosion resistance. In utility application, vault and subway types may be installed in the same type of enclosure, and the use of a sump pump is predicated more on the need for quick access for operations than it is on whether the transformer is a vault or subway type.

Vault distribution transformer in picture 1.59.1:

picture 1.58.1

1.60 Surface-Operable Installations

The subsurface enclosure provides the required ventilation as well as access for operation, maintenance, and replacement, while at the same time providing protection against unauthorized entry. Surface-operable enclosures have grade-level covers that can be removed to gain access to the equipment. The enclosures typically are just large enough to accommodate the largest size of transformer and allow for proper cable bending.

These transformers are designed for loop application and thus require internal protection. Submersible transformers are designed to be connected to an underground distribution system that utilizes 200-A-class equipment. The primary is most often #2 or 1/0 cables with 200-A elbows. While larger cables can be used with the 200-A elbows, it is not recommended. The extra stiffness of 4/0 cable makes it very difficult to avoid putting strain on the elbow-bushing interface, which may lead to early failure. The operating points of the transformer are arranged on or near the cover. The installation is designed to be hot-stick operable by a person standing at ground level at the edge of the enclosure. There are three typical variations of submersible transformers.

1.61 Pad-Mounted Distribution Transformers

Pad-mounted transformers are the most commonly used type of transformer for serving loads from underground distribution systems. They offer many advantages over subsurface, vault, or subway transformers.

• Installation: less expensive to purchase and easier to install

• Maintenance: easier to maintain

• Operability: easier to find, less time to open and operate

• Loading: utilities often assign higher loading limits to pad-mounted transformers as opposed to surface-operable or vault units.

Many users and suppliers break distribution transformers into just two major categories – overhead and underground, with pad-mounted transformers included in the underground category. The IEEE standards, however, divide distribution transformers into three categories – overhead, underground, and pad-mounted. Pad-mounted transformers are manufactured as either:

• Single-phase or three-phase units: Single-phase units are designed to transform only one phase. Three-phase units transform all three phases. Most three-phase transformers use a single-, three-, four-, or five-legged core structure, although duplex or triplex construction is used on occasion.

• Loop or radial units: Loop-style units have the capability of terminating two primary conductors per phase. Radial-style units can only terminate one primary cable per phase. The primary must end at a radial-style unit, but from a loop style it can continue on to serve other units.

• Live-front or dead-front units: Live-front units have the primary cables terminated in a stress cone supported by a bushing. Thus the primary has exposed energized metal, or "live," parts. Dead-front units use primary cables that are terminated with high-voltage separable insulated connectors. Thus the primary has all "dead" part no exposed energized metal.

This is a pad mounted distribution transformer in picture 1.61.1:

picture 1.61.1

1.62 Single-Phase Pad-Mounted Transformers

Single-phase pad-mounted transformers are usually applied to serve residential subdivisions. Most single-phase transformers are manufactured as clamshell, dead-front, loop-type with an internal 200-A primary bus designed to allow the primary to loop through and continue on to feed the next transformer. The standard assumes that the residential subdivision is served by a one-wire primary extension. It details two terminal arrangements for loop-feed systems. The primary is always on the left facing the transformer bushings with the cabinet hood open, and the secondary is on the right. There is no barrier or division between the primary and secondary. In the Type 1 units, both primary and secondary cables rise directly up from the pad. In Type 2 units, the primary rises from the right and crosses the secondary cables that rise from the left. Type 2 units can be shorter than the Type 1 units, since the crossed cable configuration gives

enough free cable length to operate the elbow without requiring the bushing to be placed as high. Although not detailed in the national standard, there are units built with four and with six primary bushings. The four-bushing unit is used for single-phase lines, with the transformers connected phase-to-phase. The six-primary-bushing units are used to supply single-phase loads from three-phase taps. Terminating all of the phases in the transformer allows all of the phases to be sectionalized at the same location. The internal single-phase transformer can be connected either phase-to-phase or phase-to-ground. The six-bushing units also allow the construction of duplex pad-mounted units that can be used to supply small three-phase loads along with the normal single-phase residential load. In those cases, the service voltage is four-wire, three-phase, 120/240 V.

1.63 Three-Phase Pad-Mounted Transformers

Three-phase pad-mounted transformers are typically applied to serve commercial and industrial three-phase loads from underground distribution systems. Traditionally, there have been two national standards that detailed requirements for pad-mounted transformers one for live front andone for dead front . The two standards have now been combined into one for all pad mounts.

single phase pad mounted transformer in picture 1.63.1:

picture 1.61.1

1.64 Leads and tapings

Most distribution transformers will be provided with off-circuit tapings, generally at 2.5 and 5%
on the HV winding, selectable by means of a padlockable switch on the outside of the tank
operable only when the transformer is isolated. This enables the user, probably no more than
once or twice at the time the transformer is commissioned, to select very conveniently the most
appropriate LV voltage for its location on the system. At these low-current ratings off-circuit
switches are not subject to any of the problems of pyrolytic carbon which beset the high-current
applications and which, as a result, lead to a preference for tap changing by the use of off-circuit
links on these very much larger units. Multilayer windings and crossover coils are not as
convenient as disc windings as regards the ability to make tapping connections from the outside
face of the coil. It is common practice to make a tapping connection within a layer so that the
lead is brought out along the surface of the layer and with possibly an additional layer of
presspaper insulation above and below it to provide insulation as it crosses the adjacent turns
within the layer. The tapping connections can be seen emerging from the ends of the central

crossover coils . Simplification of the arrangement and method of forming leads internal to the tank has been made possible by the use of round wire rather than flat copper bar for these wherever possible. Round wire or bar, being stiffer, usually requires fewer supporting cleats and since it can be bent with equal ease in all planes it can usually be taken from point to point in a single formed length, whereas flat bar might require several specially formed bends and joints in order to follow a complex route. Joints external to windings are generally formed by crimping and are nowadays rarely brazed. Crimping has the advantage that it avoids the need to bring a blowtorch into the close proximity of windings with its associated risk of fire or, at the very least, overheating of insulation. Crimped joints are also made very much more quickly than brazed or sweated joints, leading to cost savings.

Widespread use is also made of preformed insulation sections, for example flexible crO ped paper tubes threaded onto leads to provide external insulation for these, and corrugated pressboard to form interwinding ducts.

1.65 Live Front

Live-front transformers are specified as radial units and thus do not come with any fuse protection. The primary compartment is on the left, and the secondary compartment is on the right, with a rigid barrier separating them. The secondary door must be opened before the primary door can be opened. Stress-cone-terminated primary cables rise vertically and connect to the terminals on the end of the high-voltage bushings. Secondary cables rise vertically and are terminated on spades connected to

the secondary bushings. Units with a secondary of 208Y/120 V are available up to 1000 kVA. Units with a secondary of 480Y/277 V are available up to 2500 kVA . Although not detailed in a national standard, there are many similar types available. A loop-style live front can be constructed by adding fuses mounted below the primary bushings. Two primary cables are then both connected to the bottom of the fuse. The loop is then made at the terminal of the high-voltage bushing, external to the transformer but within its primary compartment.

Live front distribution transformer picture 1.65.1 below:

picture 1.65.1

1.66 Dead Front

Both radial- and loop-feed dead-front pad-mounted transformers are detailed in the standard. Radial-style units have three primary bushings arranged horizontally. Loop-style units have six primary bushings arranged in a V pattern, . In both, the primary compartment is on the left, and the secondary compartment is on the right, with a rigid barrier between them. The secondary door must be opened before the primary door can be opened. The primary cables are terminated with separable insulated high-voltage connectors, commonly referred to as 200A elbows. These plug onto the primary bushings, which can be either bushing wells with an insert, or they can be integral bushings. Bushing wells with inserts are preferred, as they allow both the insert and elbow to be easily replaced.

Dead front distribution transformer in picture 1.66.1 below:

picture 1.66.1
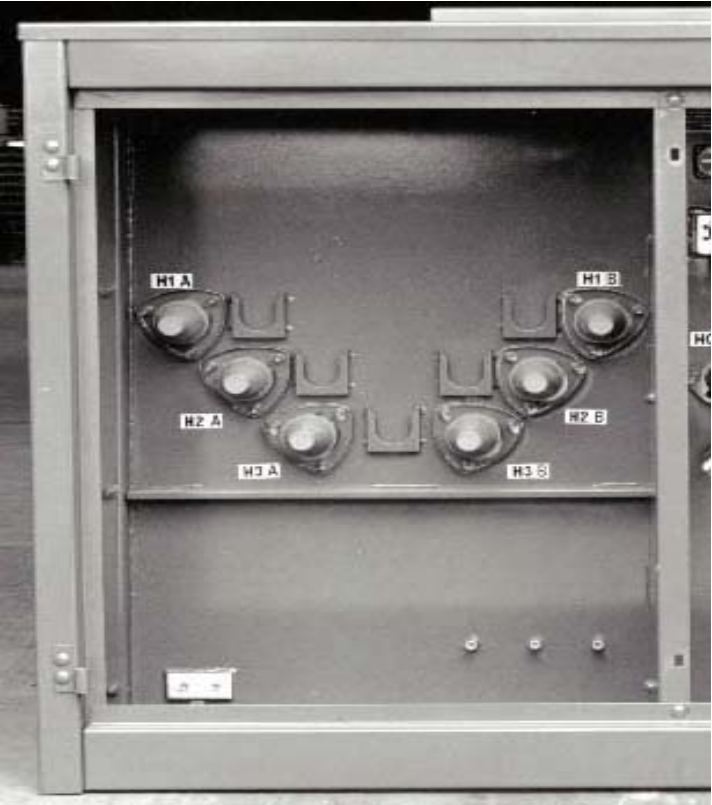
2.1 Maintenance of distribution transformers

2.2 Transformer protection

The subject of transformer protection falls naturally under two main headings.

These are:

- Protection of the transformer against the effects of faults occurring on any part of the system.

- Protection of the system against the effects of faults arising in the transformer.

2.3 Protection of the transformer against faults occurring in the system

Considering first the means to be adopted for protecting the transformer itself against the effects of system faults, three distinct types of disturbances (apartfrom overloads) have to be provided for. These are:

- Short-circuits.

- High-voltage, high-frequency disturbances including lightning.

- Pure earth faults.

To this list could be added ferroresonance, which can occur under certain conditions in any system containing capacitance and inductance elements such as those associated respectively

with cables and transformers. The problem usually arises when some external system disturbance causes a transformer to go into saturation thus greatly changing its inductance. This may lead to excess voltages and currents arising on the system which can cause damage to transformers and other plant. Although certain protective equipment may operate under ferroresonance conditions, ferroresonance is not normally regarded as a 'fault' in the normal sense of the word, rather as a condition to be avoided by careful system design. The non-linearity of core steel is a property which exists and cannot be eliminated. Whilst the design of transformers to operate at low flux densities might reduce the likelihood of core saturation, this would lead to very uneconomic designs and it is generally considered that it would have very little effect on the conditions which can lead to ferroresonance.

2.4   Short-circuits

System-short circuits may occur across any two or even three lines, or, if the neutral point is solidly earthed, between any one line and the earthed neutral. The effect of a system short-circuit is to produce over currents, the magnitude of which are dependent on the short-circuit level of the system feeding the fault, the voltage which has been short-circuited, the impedance of the circuit up to the fault and the impedance of the fault itself. The short-circuit currents produce very high mechanical stresses in the equipment through which they flow, these stresses being proportional to the square of the currents. The magnitude of these short-circuit currents can be limited by increasing the system impedance, usually incorporating this into the supply transformers. Unfortunately, increasing system impedance increases the regulation and this is not usually acceptable because of its effect on system performance and operation. On EHV and HV systems close control of system voltage is required in order to control power and VAr flows. On HV and MV systems there are close statutory limits on voltage variation at consumers' supply terminals which are necessary to ensure that the consumers' equipment will function correctly, particularly the starting of motor drives. Although on the EHV and HV systems the transmission authorities are able to make use of on-load tap-changers on transformers and other devices such as VAr compensators to control system voltages, it is desirable from the transformer practical and economic viewpoint that the extent of tapping ranges is limited on MV systems tappings are usually only selectable off-circuit, so that no means of continuous voltage control is available. Consequently the system designer is normally striving to achieve minimum regulation by keeping supply impedance as low as possible, limited only by the fault interruption capability of the available switchgear. Whereas some years ago the capability of the supply transformers to withstand the resulting short-circuit currents also provided an important constrain ton selection of the system fault level, nowadays transformer manufacturers must be prepared to supply a transformer which is capable of withstanding whatever fault level the system designer decides is necessary, so that modern transformers designed to comply with the current issue of IEC 76 are

capable of withstanding, without damage while in service, the electromagnetic forces arising under short-circuit conditions, as determined by the asymmetrical peak value of the current in the windings. In recent times the widespread adoption of solid-state 'soft-start' equipment for 415 V motor drives has generally reduced motor starting currents so that regulation of medium voltage systems may no longer be quite so critical to the system designer. This might enable the smaller distribution transformers providing 415 V supplies to have higher impedances and consequently lower short-circuit withstand capability. In reality, however, this is unlikely to have much impact on distribution transformer specifications and designs since once low impedance and a high level of short-circuit withstand strength has been shown to be possible this will tend to dictate accepted design practices and cost savings resulting from a reduction in this will prove to be minimal.

2.5 High-voltage, high-frequency disturbances

High-voltage, high-frequency surges may arise in the system due to lightning, external flashover on overhead lines, switching operations and to the effects of atmospheric disturbances. These surges principally take the form of travelling waves having high amplitudes and steep waveforms, and often successive surges may follow rapidly upon one another. On account of their high amplitudes the surges, upon reaching the windings of a transformer, pose a significant threat to the winding insulation. The effects of these surge voltages may be minimized by designing the windings to withstand the application of a specified surge test voltage and then ensuring that this test value is not exceeded in service by the provision of suitable surge protection installed adjacent to the transformer terminals. All types of surge protection aim at attaining the same results, namely that of shunting surges from lines to earth or line to line to prevent their reaching the transformer. Protection may take the form of a rod gap, known as a coordinating gap, connected across the transformer bushings and designed to flash over at a given voltage level, or alternatively surge arresters may be used. Until quite recently surge arresters employed several spark gaps in series with a non-linear resistor material, normally silicon carbide, and, although this type is still used in significant quantities on rural distribution networks at 33 kV and below, elsewhere these have now been almost entirely superseded by the gapless metal oxide variety. The arresters are connected from each line to earth, or they may be occasionally connected from line to line. When a high-voltage surge reaches the arrester the metal oxide becomes conducting or the spark gaps break down and the disturbance is discharged through the device by reason of the fact that at the high voltage involved the arrester resistance is low. As the surge voltage falls the arrester resistance automatically increases and prevents the flow of power current to earth or between lines. An arrester of this type is therefore entirely automatic in action and self-extinguishing. The internal surge impedance of a transformer winding is not a constant single valued quantity but has a range of values corresponding to the frequencies of the incident surge waveform. Changes in the surge impedance due to oscillation and decay of the surge voltages within the windings do not appreciably affect the terminal conditions. Moreover, the transformer

terminal impedance is so high when compared with the line surge impedance that its assigned value, so long as it is of the right order, has little influence upon the shape of the resulting surge waveform given. The wave diagrams in this section show the variation of voltage and current with time at the transformer terminals and not the phenomena occurring throughout the windings subsequent to the application of the surge waves to the terminals. Consider, first, what happens when rectangular finite voltage and current waves reach a transformer from an overhead line, there being no protective apparatus installed to intercept the disturbance. The amplitudes of the waves in the overhead line and at the transformer terminals depend upon the respective values of their surge impedance, which is given by the formula:

$$Z = \sqrt{L/C}$$

Where Z = surge impedance in ohms, L = inductance in henrys, C = capacitance in farads of the circuit concerned. L and C may be taken for any convenient length of circuit. When any travelling waves of voltage and current pass from a circuit of a certain surge impedance to a circuit of a different surge impedance, such waves in their passage to the second circuit undergo changes in amplitudes. The oncoming incident waves when reaching the transition point between the two circuits are, if the surge impedances of the two circuits are different, split up into two portions, one being transmitted into the second circuit, and the other reflected into the first. The transmitted waves always have the same sign as the incident waves, but the reflected waves may have the same or opposite sign to the incident waves depending upon the ratio of the two surge impedances. This applies both to the voltage and the current waves. If the incident waves are of finite length, the reflected waves travel back into the first circuit alone, and they are only transient waves in that circuit. If, on the other hand, the incident waves are of infinite length, the reflected waves in their passage backwards along the first circuit combine with the tails of the incident waves, so that the resultant waves in the first circuit are a combination of the two respective incident and reflected waves. The table gives formulae for determining the conditions when the incident waves are finite in length, and they are based on the assumption that no distortion of the shape occurs, due to losses in the circuit. The transmitted and reflected waves are constructed from the formulae given on the diagrams (distortion being ignored), and it will be seen that a voltage wave arrives at the transformer terminals having an amplitude considerably higher than that of the original incident wave. It is due to this sudden increase of voltage at the transformer terminals that so many failures of the insulation on the end turns of windings have occurred in the past, as the increased voltage may be concentrated, at the first instant, across the first few turns of the winding only, though ultimately voltage is distributed evenly throughout the whole winding. The transmitted current wave is correspondingly smaller in amplitude than the incident current wave and, as such, is usually of no particular danger.

2.6   Surge protection of transformers

Modern practice of surge protection of transformers is aimed at preventing excessive voltage surges from reaching the transformer as a unit, that is not only the HV and LV windings but also the bushings, where flashover and insulation breakdown will result in serious damage and system disconnections. In the surge protection is implemented by the addition of rod gaps or surge arresters adjacent to the transformer to shunt the surges to earth. These attenuate the surge magnitudes seen by the windings and their resulting insulation stresses to levels which can be withstood by suitably proportioned insulation distribution without causing resonant instability and dangerous oscillations within the windings. Bushing flashover would generally protect the windings but this is not tolerable in practice for several reasons, notably the likelihood of damaging the bushing. The breakdown characteristic is most unfavorable and after initial breakdown to earth, via the bushing surface, tank and tank earth connection, the low impedance path to earth will allow a power-frequency current to flow if the system neutral is earthed or if two bushings flash over simultaneously. This current will cause protective schemes to operate, leading to system disconnections even when the bushings are undamaged. The desired characteristic is one where the path to earth presents a high impedance to normal supply frequency voltages but which falls to a low impedance under high-voltage transient conditions, followed by a rapid recovery to the original impedance levels as the voltage falls again. The two methods commonly adopted to obtain surge protection are:

(a) Coordination of rod gaps, and

(b) Surge arresters.

Both methods have advantages and disadvantages but are applicable on systems operating at voltages down to 3.3 kV which are reasonably insulated and where the cost of surge protection of these types can be justified for system reliability.

2.7   Protecting the system against faults in the transformer

Consider next the means to be adopted for protecting the system against the effects of faults arising in the transformer; the principal faults which occur are breakdowns to earth either of the windings or terminals, faults between phases generally on the HV side, and short-circuits between turns, usually of the HV windings. The protection of transformers, in common with the protection of other electrical plant, is an area in which there has been a great deal of change in recent years, brought about by the development of digital solid-state relays. The use of

microelectronics makes possible the provision of high-reliability, rugged, compact and inexpensive relays having accurate tailor-made characteristics to suit almost any situation, so that the bulky and delicate electromagnetic devices on which protective gear has relied for so many years are becoming consigned to history. However, the principles and objectives of transformer protection have not changed. It is simply the case that the protection engineer now has available relays which come much closer to meeting all his requirements and they will do so at a price which enables a degree of sophistication to be applied to the protection of a 500 kVA transformer which might hitherto have only been considered economically justified for one rated 30 MVA or more. There are many thousands of electromagnetic relays in service and their life and reliability is such that they will continue to be so for a good many years. The following description of transformer protection principles will therefore consider initially those 'traditional' schemes based on electromagnetic relays before considering briefly how these have been developed to make use of the latest technology. Breakdowns to earth may occur due to failure of the major insulation of transformers or of bushing insulators, these failures being due to the absence of any external surge protective apparatus or upon the failure of such apparatus to operate. When such a breakdown occurs it is essential that the transformer is isolated from the supply with as little delay as possible. For small transformers, single overload and earth leakage devices will provide the necessary degree of protection to ensure that the transformer is disconnected automatically from the circuit. On larger transformers forming parts of important transmission or distribution networks, it is necessary to employ some form of automatic discriminative protective equipment. This will remove from the circuit only the faulty apparatus leaving the sound apparatus intact, while the disconnection is performed in the shortest space of time and the resulting disturbance to the system is reduced to a minimum. The automatic protective gear systems which are most commonly used are described in the following sections. In considering the problems of protection across a power transformer, note should first be made of what is known as a differential rough balance scheme. This scheme can be applied where existing over current and restricted earth-fault protection has become inadequate but provision of a separate differential scheme is considered unjustified. By using over current relays and current transformers, lower fault settings and faster operating times can be obtained for internal faults, with the necessary discrimination under external fault conditions. The taps on interposing transformers are adjusted so that an inherent out-of-balance exists between the secondary currents of the two sets of current transformers but is insufficient to operate the over current relays under normal load conditions. With an over current or external fault the out-of-balance current increases to operate the relay and choice of time and current settings of the IDMT relays permit grading with the rest of the system. The scheme functions as a normal differential system for internal faults but is not as fast or sensitive as the more conventional schemes. It is, however, an inexpensive method of providing differential protection where IDMT relays already exist.

2.8 High-speed protection of power transformers by biased differential harmonic restraint

For many years the GEC Type DMH relay has provided differential protection for two-winding or three-winding power transformers with a high degree of stability against through-faults and is immune to the heavy magnetizing current in-rush that flows when a transformer is first energised. The relay is available in two forms:

(a) for use with line current transformers with ratios matched to the load current to give zero differential current under healthy conditions;

(b) with tapped interposing transformers for use with standard line current transformers of any ratio.

In this relay the preponderance of second harmonic appearing in the in- rush current is detected and is used to restrain its action, thus discriminating between a fault and the normal magnetising current in-rush. The relay employs rectifier bridge comparators in each phase which feed their outputs through transistor amplifiers to sensitive polarized relays, resulting in:

 (i) an operating current which is a function of the differential current;

 (ii) a restraining current, the value of which depends on the second harmonic of the differential current;

(iii) a bias current which is a function of the through-current and stabilizes the relay against heavy through-faults.

   The relay is provided with an instantaneous over current unit in each phase to protect against faults heavy enough to saturate the line-current transformers, under which conditions the harmonics generated would tend to restrain the main unit. These over current units have a fixed setting of eight times the current-transformer secondary rating and are fed from saturable current transformers to prevent operation on peak in-rush current which may momentarily exceed this value. The operation of the main unit is briefly as follows:

   Under through-current conditions, current is passed by the two restraint rectifier bridges through the polarized relay in the non-operating direction. In conditions of internal fault there

will be a difference between primary and secondary current, and the difference flows in the operating circuit so that the operating rectifier passes a current to the polarized relay in the operative direction. Operation depends on the relative magnitude of the total restraint and differential currents, and the ratio of these currents to cause operation is controlled by a shunt resistor across the restraint rectifiers. Under magnetizing in-rush conditions, the second-harmonic component is extracted by the tuned circuit and the current is passed to the relay in the non-operating condition.

2.9 Over current and earth leakage protection

As indicated earlier, it is not always economical to fit circulating current protection for the smaller sizes of power transformers up to, say, 1000 kVA (and in some cases larger than this). Adequate protection can be provided by means of simple over current and earth fault relays, the latter preferably of the restricted form on the LV side. HV side comprises three over current and one earth leakage relays, while the LV arrangement is similar with the addition of a neutral current transformer if the power transformer neutral is earthed. With this type of protection no balancing of current transformers on the primary and secondary sides of the power transformer is necessary, and hence similar characteristics and definite ratios are unnecessary. Further, the earth leakage relays are instantaneous in operation and earth fault settings as low as 20% can usually be obtained without difficulty. Line to line faults are dealt with by the over current relays,

which operate with a time lag and are graded with the over current relays on other parts of the system. For unearthed windings (delta or star) the apparatus would consist of a three-pole over current relay of the inverse, definite minimum, time lag type and a single pole instantaneous earth leakage relay with or without series resistor depending on the type of relay.   If the power transformer neutral point is earthed, an additional current transformer is provided in the neutral connection with its secondary winding in parallel with the three line current transformers; this protection is known as the over current and restricted earth leakage system. With an external earth fault (say to the right of the current transformers on the star-connected side of the power transformer), current flows in one of the line current transformers and in the neutral current transformer and the polarities are so arranged that current circulates between the two secondary's. The earth leakage relay is thus connected across equip-potential points; no current flows in it, and it does not operate. With an internal earth fault, fault current flows either in the neutral current transformer only, or in opposition in the line and neutral current transformers; the relay is then energized and operates.

2.10   Distribution Transformer Maintenance

The present maintenance trend is to reduce cost, which in some cases means lengthening the intervals of time to do maintenance or eliminating the maintenance completely. The utility, or company, realizes some savings on manpower and material by lengthening the maintenances cycle, but by doing this, the risk factor is increased. A few thousand dollars for a maintenance program could save your utility or company a half-million dollar transformer. Consider the following:

1. The length of time to have a transformer rebuilt or replaced

2. The extra load on your system

3. Rigging costs to move the transformer

4. Freight costs for the repair, or buying a new one

5. Disassembly and reassembly costs:

6. Costs to set up and use a mobile transformer

7. Costs for oil handling of a failed unit

8. Vacuum oil filling of the rebuilt or new transformer

9. Customer's dissatisfaction with outage

10. Labor costs, which usually cover a lot of overtime or employees pulled away from their normal work schedule

Time spent on a scheduled maintenance program is well worth the expense. There are many systems available to monitor the transformer which can assist you in scheduling your maintenance program. Many transformer manufacturers can supply monitoring equipment that alerts the owner to potential problems. However, relying solely on monitoring equipment may not give your notice or alert you to mechanical problems. Some of these problems can be: fans that fail, pressure switches that malfunction, or oil pumps that cease to function. You could also have oil leaks that need to be repaired. Annual inspections can provide a chance for correcting a minor repair before it becomes a major repair.

2.11   Maintenance Tests

There are two important tests that could prevent a field failure. Using an infrared scan on a transformer could locate "hot spots". The high temperature areas could be caused by a radiator valve closed, low oil in a bushing, or an LTC problem. Early detection could allow time to repair the problem.   Another important test is dissolved gas analysis test of the oil by a lab. A dissolved gas analysis lab test will let you know if high levels of gases are found and they will inform you as to the recommended action. Following the lab report could let you plan your course of action. If there seems to be a problem, it would be worthwhile to take a second dissolved gas in oil sample and send it to a different lab and compare the results (IEEE C57 104-1991). Maintenance inspection and tests can be divided into two sections: (1) minor and, after a set period of years, (2) major inspection. Annual tests are usually done while the transformer is in service, and consist of the following:

1. Check the operation of the LTC mechanism for misalignment or excessive noise.

2. Take an oil sample from the LTC.

3. Change silica gel in breathers.

4. Inspect fan operation.

5. Take an oil sample from the main tank.

6. Check oil level in bushings.

7. Check tank and radiators for oil leaks.

8. Check for oil levels in main tank and the LTC.

9. Make sure all control heaters are operating.

10. Check all door gaskets.

11. Record the amount of LTC operations and operate through a couple of positions.

12. Most importantly, have your own check-off list and take time to do each check. This record (check- off list) can be used for future reference.

Major inspections require the transformer to be out of service. Both primary and secondary bushings should be grounded before doing the work. Besides the annual inspection checks that should be made, the following should also be done:

1. Power factor the bushings and compare to the values found during the installation tests.

2. Power factor the transformer and check these valves.

3. Make a complete inspection of the LTC and replace any questionable parts. If major repair
   is   required during this inspection, a turns ratio test should be done.

4. Painting rusty areas may be necessary.

5. Test all pressure switches and alarms.

6. Check the tightness of all bolted connections.

7. Check and test the control cabinet components.

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