IEEE

# CONFERENCE RECORD OF 1981 THIRTY-THIRD ANNUAL CONFERENCE OF ELECTRICAL ENGINEERING PROBLEMS IN THE RUBBER AND PLASTICS INDUSTRIES

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# CAST COIL TRANSFORMERS

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## ABSTRACT

The cast coil transformer, through design and performance, can fill the needs of today's power distribution systems. Recent changes in codes and regulations have made it more attractive as compared to other transformers available today. This paper will outline the design and manufacturing of the cast coil transformer, and detail the advantages of its construction.

## INTRODUCTION

Current regulations concerning the use and placement of liquid-insulated transformers have led to a resurgence of interest in dry-type transformers. With askarel no longer acceptable as an insulating medium, high-fire point liquids received attention as the focus shifted from askarel.

This shift to high-fire point liquids has recently come under scrutiny via a NEMA study to determine the flammability of such liquids under fault conditions. In addition, the 1981 National Electric Code has placed some new restrictions on their use indoors, including a requirement for catch basins in all indoor installations and the use of a protective vault for units installed in combustible building or combustible occupancy areas not meeting the clearance requirements of the liquid listing. The combination of these restrictions and requirements has rekindled the interest and use of dry-type transformers, especially in indoor locations.

## BACKGROUND

The cast coil transformer has been developed to reduce or eliminate the difficiencies inherent in conventional open-wound, dry-type transformer construction. Some problems specifically addressed were:

1. Basic Impulse Levels
2. Short circuit strength
3. Moisture Problem - Dry-out Time
4. Environmental Contamination
5. Insulation Deterioration Due to Corona

The design philosophy of the American cast coil transformer is actually a merger of European and United States technology. In the 1950's dry-type transformer technology revolved around the use of solid insulation materials and air clearance to provide dielectric strength. With these materials, units could be designed with temperature classifications up to and including 150 Degree C over a 40 Degree C maximum ambient.

European cast coil transformers incorporate bare or film-coated magnet wire and epoxy resin. The epoxy resin provides both dielectric and mechanical strength. It also provides superior environmental protection for the windings as opposed to open-wound construction. U.S. development focuses on two basic elements of the transformers--the high voltage coil, and the low voltage coil.

The high voltage coil is considered the most important and has received the most attention. Past history indicates that the high voltage is the most vunerable due to the fact that most electrical failures occur in the high voltage coil by virtue of the voltage levels involved. Switching surges, lightning surges, moisture, etc., cause severe problems in an unprotected open-wound transformer.

The low voltage coil has been deemed satisfactory for most installations and has received less initial attention.

## DESIGN & MANUFACTURING OF THE HIGH VOLTAGE COIL

To provide maximum mechanical, electrical, and environmental protection, the high voltage windings are insulated and protected with both solid insulation and epoxy resin. Bare magnet wire is wrapped with a high temperature insulation to provide turn-to-turn protection. Each progressive layer of wires are then insulated with sheets of high temperature insulation. Clearances are maintained by mechanical separation between sections. At this point the design is essentially the same as conventional open-wound construction. When the winding is complete, it is placed into a metal mold. This mold is designed at close tolerances to provide an even dispursement of epoxy within and around the windings. All taps and leads are brought out to the surface by means of an embedded fitting.

The mold and winding are then preheated in an oven to release any gasses which might be trapped within the windings and also remove any moisture which could be present. When the preheating cycle is complete, the unit is placed within a vacuum chamber. The chamber is then pumped down to a state of hard vacuum.

The mixing of the epoxy is done in several steps--premixing and final mixing.

The premixing process involves two steps:

1. Resin and color mix
2. Hardener and flexibilizer mix

When the premixing process has been completed, the two epoxy components are then combined within a vacuum mixing chamber. At this point, final mixing of the epoxy components is complete.

The epoxy mixture is introduced into the mold. The viscosity of the resin allows it to flow between the windings, filling all voids. The mold is removed from the vacuum chamber and placed in an oven for a time/temperature curing sequence. After curing the mold is released, and the coil is ready for assembly.

The choice of winding design is important when the winding is to be encapsulated. Three basic considerations must be examined:

1. Electrical Design
2. Mechanical Design
3. Thermal Characteristics

In typical open-wound transformer construction, the high voltage coil can be wound in several different manners:

CAST COIL TRANSFORMERS

1. Barrel Wound

2. Section Wound

3. Disk Wound

The type to be used is determined by the KVA, the KV Class and the BIL Level. In many high voltage transformer designs, the disk-type winding is used to reduce the volts per turn and the voltage stress between turns. This design, however,is inappropriate for cast coil. Because of spacing between disks, large sections of epoxy would be present. The unit would be incapable of proper heat transfer and would be subject to considerable overheating.

Thermal considerations would suggest that a barrel wound design would be most appropriate. With no gaps along the coil, the continuous wire surface is ideal for epoxy encapsulation.

However, barrel wound construction would be most cumbersome from an electrical design standpoint. Without sections or disks, the voltage between turns would be very high and require extensive use of solid insulation materials.

Since barrel wound and disk wound designs were found to be inappropriate, the section wound design was selected for cast coil transformers. The section wound design optimizes the relationship between electrical design considerations and the thermal release characteristics of the epoxy resin.

## DESIGN & MANUFACTURING OF THE LOW VOLTAGE COIL

As mentioned earlier, the low voltage coil has received less attention because of the low failure rate experienced on the secondary side of dry-type transformers. For this reason, most cast coil transformers designed in the United States incorporate an open-wound secondary coil. Design and construction is identical to a conventional open-wound transformer.

In some instances, to be discussed at a later point, an epoxy cast low voltage coil is desirable. For this reason, cast secondary coils are made available. There is, however, a distinct contrast in the design and manufacturing process when compared to the vacuum casting of the primary coils.

The winding procedure is essentially identical to a typical open-wound design, but with different materials. The design incorporates the use of sheet conductor rather than magnet wire conductor. The sheets are interweaved with epoxy impregnated cloth. The cloth provides layer-to-layer insulation. The entire coil consists of several groups of layered conductor, separated by air ducts to provide cooling. After winding, the entire coil is wrapped with fiberglass cloth and coated with epoxy resin.

The coil is placed in an oven for time/temperature curing. The heat releases the epoxy impregnated in the cloth between the conductors and fuses the entire coil into a rigid, solid cylinder. The ends of the coil are capped with epoxy to provide total encapsulation of the windings.

Because of operating temperature differences between primary and secondary coils, extra precautions must be taken to assure continuity of service and expected service life. This thermal casting process was developed to replace the vacuum cast process. There are several advantages to this method as compared to vacuum casting:

1. Better Heat Dissipation

2. Uniform Temperature Rise

3. Reduced Hot Spot Potential

4. Lower Cost

Better heat dissipation is derived from the minimal use of epoxy resin during construction of the coil. The thin layer of epoxy on each conductor is sufficient to maintain excellent strength, but will not act as a serious thermal release barrier.

Sheet conductor also provides a more uniform temperature gradient along the length of the coil. In wire wound units, the bottom one-third of the coil will operate at a lower temperature than the upper one-third of the coil. Sheet conductor will be relatively equal in temperature from top to bottom.

The use of sheet conductor also reduces this possibility of operating hot spots. Hot spots will typically occur at the shoulders of wire conductors or at joints. Since no wire is used, that area of hot spot activity is eliminated.

Costs can also be reduced with the exclusion of the mold and the vacuum process.

## ENVIRONMENTAL CHARACTERISTICS

The cast coil transformer is highly resistant to the effects of moisture. All materials are non-hygroscopic. This allows for immediate energization of the unit even after extended periods of de-energization. Dry-out time is not necessary.

The epoxy resin is also highly resistant to chemicals and industrial atmospheres. The epoxy provides excellent protection for the coils and allows the transformer to be used in locations previously unsuitable for conventional open-wound transformers. The severity of the environment determines the type of low-voltage coil to be used. The following chart describes typical situations and the proper coil selection:

| Application | Conventional Open | Cast |
|---|---|---|
| Low to moderate dust | X | |
| Heavy Dust | | X |
| Low to moderate chemical contamination | X | |
| Heavy chemical contamination | | X |
| Tropical zones | | X |
| Conductive dust in atmosphere | | X |
| Salt air | | X |
| High available fault current | | X |
| Caustic vapors in atmosphere | | X |

The epoxy resin is virtually inert. In normal operating conditions, it will not emit gasses or other materials. If a constant flame is held to the epoxy, it will burn and release some gasses, but none of the emitted gasses are toxic. The epoxy is self-extinquishing when flame source is removed.

## ELECTRICAL & MECHANICAL CHARACTERISTICS

Corona. Epoxy encapsulation of the coils without voids or porosity provides complete elimination of corona generation.

Dielectric Strength. The dielectric properties of the solid insulation remain consistently high due to the lack of corona and the resistance of the epoxy resin itself.

Short Circuit Strength. The dynamic short circuit strength of the cast coil exceeds that of a conventional dry-type or liquid-filled transformer. The epoxy resin provides exceptional high mechanical strength to the coils. That combined with the inherent strength provided by the geometry of a round coil, provides excellent protection against the axial and radial forces associated with short circuit conditions.

Basic Impulse Levels. The cast coil design can provide BIL Levels equal to liquid-filled standards. These standards are the conventional dry-type transformer standards. The following table shows comparative information:

BASIC IMPULSE LEVELS (KV)

| Voltage Class (KV) | Std* Oil | Std* Open Dry | Opt** Open Dry | Std** Cast | Opt** Cast |
|---|---|---|---|---|---|
| 2.4 | 45 | 20 | 45 | 45 | 60 |
| 5 | 60 | 25 | 60 | 60 | 75 |
| 8.6 | 75 | 35 | 75 | 75 | 95 |
| 15 | 95 | 50 | 95 | 95 | 110 |
| 25 | 150 | - | 125 | 125 | 150 |
| 34.5 | 200 | - | 150 | 150 | 200 |

*Standard as established in ANSI C57.12.00
**Options and standard as manufactured by GTE Electrical Products

## PERFORMANCE CHARACTERISTICS

The losses associated with transformer operation have rapidly gained predominance in transformer selection and analysis. The cast coil transformer is among the most efficient available today. Typically, the cast coil transformer will have higher no load losses as compared to open-wound or liquid-filled units; but will have significantly lower load losses which result in lower total losses. The following chart demonstrates the loss differences between the various types of transformers (chart at top of next column).

## APPLICATIONS

The cast coil transformer has been designed for use where the transformer cannot be protected from harsh environments or severe duty-cycle requirements. It is especially attractive for indoor installations where requirements or restrictions place physical and financial burdens on most liquid-filled units. It is also suitable as a direct replacement transformer for existing askarel-filled units. The cast

| Type Transformer Temp. Rise° C | No Load Loss KW | 100% Load Loss in KW | 75% Load Loss in KW |
|---|---|---|---|
| Liquid 65° C | 4.0 | 21.0 | 11.8 |
| Dry Type 150° C | 5.0 | 22.5 | 12.7 |
| Dry Type 80° C | 5.4 | 16.5 | 9.3 |
| Cast Coil 80° C | 5.6 | 13.5 | 7.6 |

coil is also attractive as a spare transformer since storage and moisture do not distruct the integrity of the unit and immediate energization is possible.

## CONCLUSION

The cast coil transformer offers many advantages over conventional open-wound and liquid-filled units:

1. No liquid coolants required
2. No danger from fire or explosion
3. High short circuit strength
4. High B.I.L. Levels
5. Greater efficiency
6. Environmental protection from chemical and industrial contamination.

With its inherent advantages, the cast coil is an attractive substitute for askarel and flammable liquid-filled transformers.

# THE VALUE OF TRANSFORMER TESTS

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Abstract - Tests have evolved over the years to determine the electrical, mechanical and thermal suitability of transformers. This paper discusses the value of these tests in verifying the transformer for operation.

## INTRODUCTION

In the manufacture of transformers many processes, inspections and audits of operations are performed on the core and coil assembly, bushings and other electrical components to assure that they are built to the highest quality standards. However, the determination of how effective these functions have seen can only be verified through transformer tests.

These tests have evolved over the years and have been devised to determine the electrical, mechanical and thermal suitability of the transformer for operation on a given system. The standards organization responsible for defining these tests is the Power Transformer Subcommittee of the Institute of Electrical and Electronics Engineers (IEEE). These tests have also been incorporated into both the National Electrical Manufacturers' Association (NEMA) and the American National Standards Institute (ANSI) transformer test standards, ANSI 057.12.90 and NEMA Standards Publication No. TR-1.

The Standards, while quite thorough in the methodology of performing the tests and providing testing values and limits, do not explain the value or purpose of the test. This will be the objective of this paper.

For discussion purposes, transformer tests can be grouped into two categories, reliability tests and functional tests. Reliability tests are defined as those which determine the adequacy of the insulation system, while functional tests are those that verify design criteria and specification requirements.

| Functional Tests | Reliability Tests |
|---|---|
| Ratio | Dielectric Tests |
| Polority | Applied Potential |
| Phase Relations | Induced Potential |
| Exciting Current | Impulse |
| No Load Loss | Sound |
| Resistance Measurement | Temperature |
| Load Loss | Corona (Partial Discharge) |
| Impedance | Insulation Resistance |
| Regulation | Insulation Power Factor |

There are also a number of other tests that could have been included in the list. However, to discuss them all would require a much too lengthy paper. So only those which are most often specified will be discussed.

## Function Tests

### Ratio Test

The function of a transformer is to transform power from one voltage level to another. The ratio test ensures that the transformer windings have the proper turns to produce the voltages required. The ratio is a measure of the RMS voltage applied to the primary terminals* to the RMS voltage measured at the secondary terminals.

The Standards state that when rated voltage is applied to one winding of the transformer, all other rated voltages at no load shall be correct within one half of one percent of the nameplate readings. It also states that all tap voltages shall be correct to the nearest turn if the volts per turn exceed the one half of one percent of the desired voltage. The ratio test verifies that these conditions are met.

The calculated ratios for a transformer with a rated primary phase voltage of 12470 with 2.5% taps above and below rated voltage and a rated secondary phase voltage of 480 are shown below. The ratio limits given permit a tolerance of one half of one percent from the rated voltage.

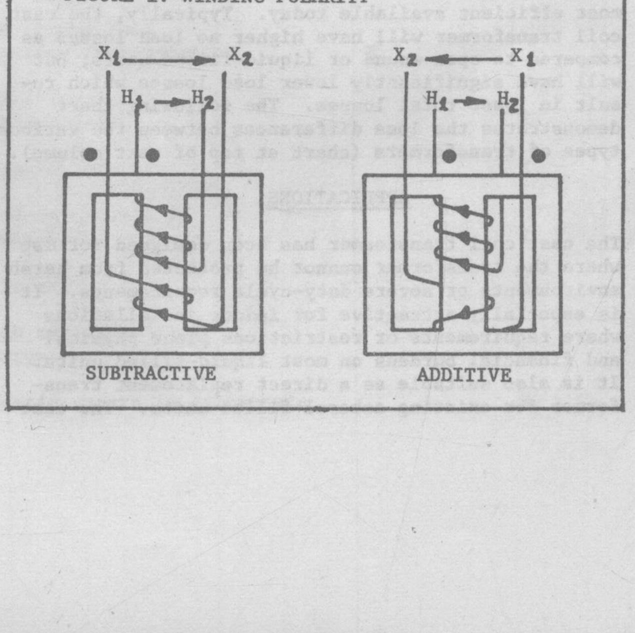
| Voltage | Ratio | Ratio Limits Upper | Ratio Limits Lower |
|---|---|---|---|
| 13095 | 27.281 | 27.417 | 27.145 |
| 12780 | 26.625 | 26.758 | 26.492 |
| 12470 rated | 25.979 | 26.109 | 25.849 |
| 12160 | 25.333 | 25.460 | 25.207 |
| 11850 | 24.687 | 24.810 | 24.564 |

*The primary terminals are defined as the energy input terminals and may be either the high voltage or low voltage side of the transformer.

### Polarity and Phase Relations

The polarity and phase relation tests are important when two or more transformers are to be paralleled. Paralleled transformers must have the same polarity and phase relation to avoid partial or

FIGURE 1: WINDING POLARITY



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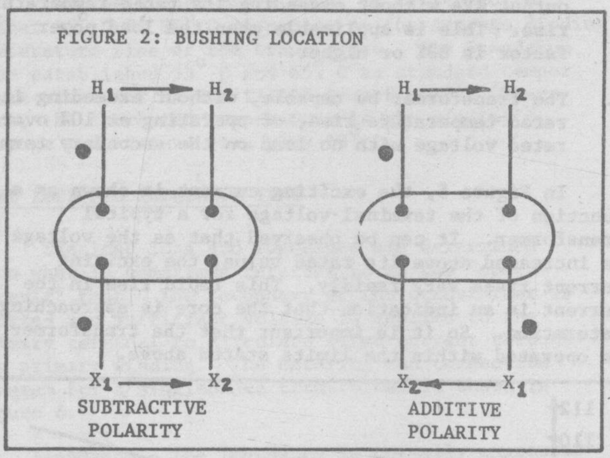
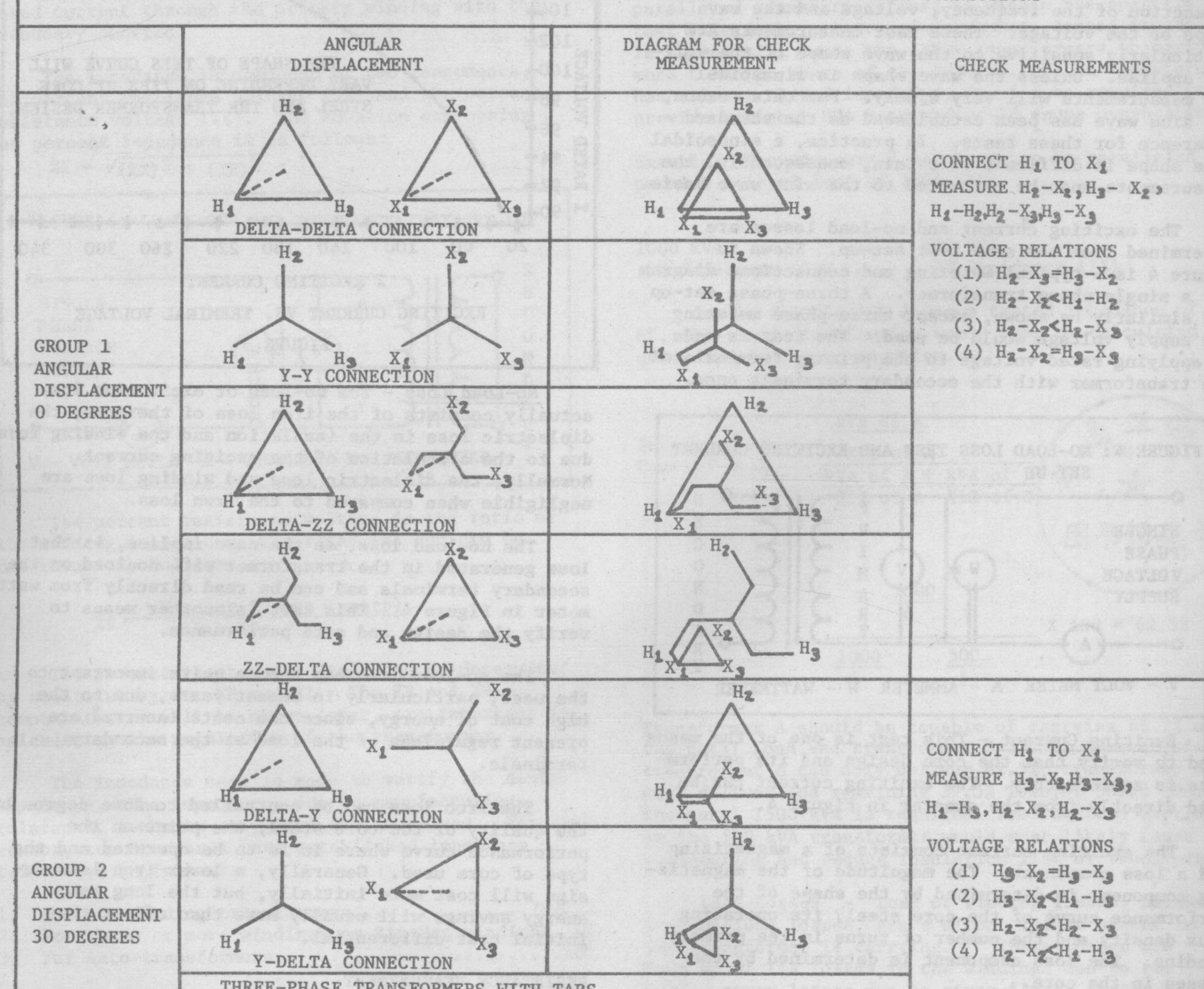



FIGURE 2: BUSHING LOCATION

complete short circuits. The polarity, or phase relation (phasor diagram) as the case may be, is shown on the transformer nameplate.

Single phase transformers may have subtractive or additive polarity. A.N.S.I. C57.12.00 specifies that single phase transformers sized 200 KVA and below, having a high voltage rated 6660 and below, shall have additive polarity. All other single phase transformers shall have subtractive polarity. A representation of both additive and subtractive polarity is shown in Figure 1. The normal bushing arrangement for these polarities is shown in Figure 2.

FIGURE 3: TRANSFORMER VOLTAGE-PHASOR DIAGRAMS FOR THREE-PHASE TRANSFORMER CONNECTIONS



Polarity in a three-phase transformer, when measured phase-to-phase, is no different than the single phase transformer. Polarity alone, however, cannot describe the relation between the primary and secondary windings. The angular displacement and phase sequence must be considered also.

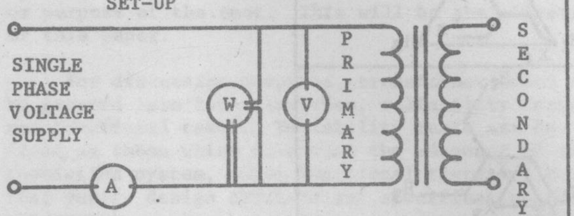
The primary and secondary windings in a three-phase transformer may be connected in a delta, wye or other configuration, and depending upon which of the individual windings are connected to each other the angular displacement between the primary and secondary can be varied. Shown in Figure 3 are some of the more common three-phase connections as well as check measurements for verifying the connection. The check is made by connection $H_1$ to $X_1$ and applying any convenient three-phase source to $H_1$,$H_2$ and $H_3$ and then making the voltage comparisons.

EXCITING CURRENT AND NO-LOAD LOSS TESTS

The exciting current and the no-load losses are a function of the frequency, voltage and the wave shape of the voltage. These test measurements are particularly sensitive to the wave shape of the voltage applied. Unless the wave shape is sinusoidal the measurements will vary widely. For this reason, the sine wave has been established as the standard reference for these tests. In practice, a sinusoidal wave shape is difficult to obtain, consequently, the measurements must be corrected to the sine wave basis.

The exciting current and no-load losses are determined from the same test set-up. Shown in Figure 4 is a typical metering and connections diagram for a single phase transformer. A three-phase set-up can similarly be shown, except three-phase metering and supply voltage would be used. The test is made by applying rated voltage to the primary terminals of the transformer with the secondary terminals open.

FIGURE 4: NO-LOAD LOSS TEST AND EXCITING CURRENT SET-UP




V - VOLT METER A - AMMETER W - WATTMETER

Exciting Current - This test is one of the means used to verify that the core design and its performance is satisfactory. The exciting current can be read directly from the ammeter in Figure 4.

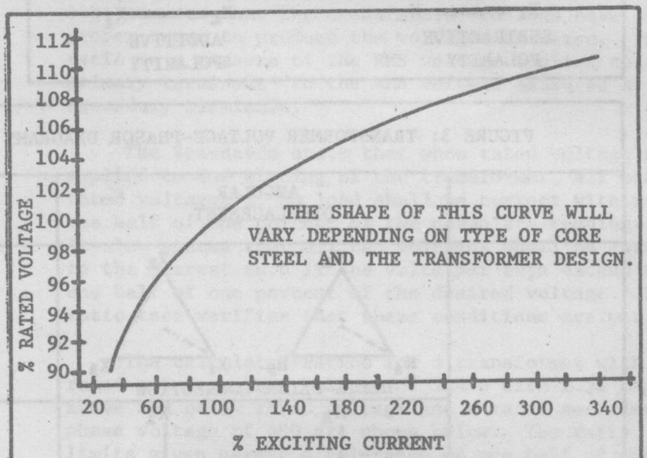
The exciting current consists of a magnetizing and a loss component. The magnitude of the magnetizing component is determined by the shape of the performance curve of the core steel, its operating flux density and the number of turns in the primary winding. The loss component is determined by the losses in the core.

Transformers are usually designed to operate at the knee of the performance curve. This permits an economical core design and still permits the transformer to be operated in accordance with the Standards, which require that:

1. The transformer be capable of being operated at 5% over rated voltage while delivering rated output KVA without exceeding its rated temperature rise. This is applicable when the load power factor is 80% or higher.

2. The transformer be capable, without exceeding its rated temperature rise, of operating at 10% over rated voltage with no load on the secondary terminals.

In Figure 5, the exciting current is shown as a function of the terminal voltage for a typical transformer. It can be observed that as the voltage is increased above its rated value, the exciting current rises very rapidly. This rapid rise in the current is an indication that the core is approaching saturation. So it is important that the transformer be operated within the limits stated above.




EXCITING CURRENT VS. TERMINAL VOLTAGE

FIGURE 5

No-Load Loss - The no-loss or excitation loss actually consists of the iron loss of the core, the dielectric loss in the insulation and the winding loss due to the circulation of the exciting current. Normally, the dielectric loss and winding loss are negligible when compared to the iron loss.

The no-load loss, as the name implies, is that loss generated in the transformer with no load on the secondary terminals and can be read directly from watt meter in Figure 4. This test is another means to verify the design and core performance.

The no-load loss has become quite important to the user, particularly in recent years, due to the high cost of energy, since the costs incurred are present regardless of the load at the secondary terminals.

The iron loss can be controlled to some degree by the quality of the core steel, the point on the performance curve where it is to be operated and the type of core used. Generally, a lower iron loss design will cost more initially, but the long range energy savings will usually more than offset that initial cost differential.

RESISTANCE MEASUREMENT

This is a measure of the resistance of the conductors in the transformer windings. The resistance measurements have two important functions:

1. For calculation of the temperature of the windings during the temperature test.
2. For calculation of the $I^2 R$ component of the winding losses.

The resistance measurement is corrected to either 75° C or 85° C depending on the average winding temperature rise of the transformer. The Standards have established 55° C and 65° C as standard temperature rises for liquid filled transformers. Therefore, the corrected temperature is the winding's average temperature rise plus 20° C.

LOAD LOSS AND IMPEDANCE TEST

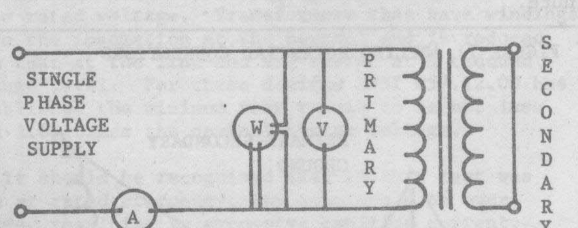
The load loss and impedance are determined from what is sometimes referred to as the "short-circuit" test. The secondary of the transformer is shorted and sufficient voltage is applied to the primary terminal to circulate rated current through the primary winding. The metering and connection diagram for a singlephase transformer is shown in Figure 6.

Impedance - The impedance is normally expressed in terms of percent of rated voltage. The impedance voltage is that voltage required to circulate the rated current through the primary winding with the secondary shorted.

The impedance is composed of two components, the percent reactance voltage (%X) and the percent resistance voltage (%R). The equation expressing the percent impedance is as follows:

$$\%Z = \sqrt{(\%X)^2 + (\%R)^2}$$

FIGURE 6: LOAD LOSS AND IMPEDANCE TEST SET-UP




V - VOLT METER  A - AMMETER  W - WATTMETER

The percent resistance voltage is the ratio of the winding losses over the rated KVA and can be determined as follows:

$$\%R = \frac{\text{Winding losses (watts)}}{10 \times \text{KVA}}$$

The percent reactance voltage can be determined by substituting for %R and %Z. The %R and %X components, as will be shown later, are important in calculating the regulation of the transformer.

The impedance test is made to verify the design impedance. The impedance, due to manufacturing tolerance, tends to vary from design values. For this reason, the Standards have established impedance tolerances as follows:

1. For two winding transformers ...............7-1/2%
2. For three or more windings or Zig-Zag windings.10%
3. For Auto-transformers...........................10%

The user and the designer are interested in the measured impedance primarily because it determines the amount of current which will flow in the windings during short circuit. Table 1 gives the magnitude of short circuit (at the transformer terminals) for various percentages of impedance.

TABLE 1

Short circuit current at various impedances

| Maximum RMS symmetrical current in any winding | Impedance |
|---|---|
| 25 times rated current | 4.0% |
| 20 times rated current | 5.0% |
| 17.4 times rated current | 5.75% |
| 16.7 times rated current | 6.0% |
| 14.3 times rated current | 7.0% |

The magnitude of the short circuit current is important to the designer because it establishes design criteria for the mechanical strength of the internal assemblies, and to the user in determining breaker capacities and selecting correct fuses and properly coordinating relaying schemes.

The impedance is also important when paralleling two or more transformers. The impedance of the paralleled transformers must be within the specified test tolerances. A transformer whose tested impedance is higher will cause the other transformers to carry more than its share of the load or, if the transformer has a lower tested impedance, it will be required to provide a higher KVA load and could cause overheating.

Example: Transfromers A and B are to be paralleled to provide a total load of 1500 KVA.

| A | B |
|---|---|
| 1000 kVA | 500 kVA |
| 5% Impedance (IZ) | 5% Impedance (IZ) |

Assume transformer A has a tested impedance of 6%. The load distribution would then be calculated using the following equation.

$$\text{Percent Load Carried By A} = \frac{\dfrac{\text{kVA of A}}{\%\text{IZ of A}}}{\dfrac{\text{kVA of A}}{\%\text{IZ of A}} + \dfrac{\text{kVA of B}}{\%\text{IZ of B}}} \times 100$$

$$= \frac{\dfrac{1000}{6}}{\dfrac{1000}{6} + \dfrac{500}{5}} \times 100 = 62.5\%$$

Transformer A should be capable of carrying 66.7% of the total load and transformer B 33.3%. However, since transformer A can only deliver 62.5%, transformer B must deliver the remaining 37.5% load, or 562.5 kVA, if the total 1500 kVA is required. The required overload on the 500 kVA transformer would most likely cause overheating and reduce insulation life of transformer.

Load Losses - Load or winding losses, unlike the non-load losses, are a direct result of the load the transformer is carrying. These losses are made up of $I^2R$ losses in the windings due to the load, stray losses due to stray fluxes in the winding, tank, assembly parts, etc. and the eddy losses due to circulating currents. The $I^2R$ component is by far the largest component and since the resistance (R) of the conductor is temperature sensitive, it must be corrected to either 75°C or 85°C depending on the temperature rise of the transformer. The uncorrected winding losses can be determined from the wattmeter in Figure 6, (Page 7) while the $I^2R$ losses are calculated using the ammeter reading and the measured resistance.

These losses, as was the case with the no-load losses, have become increasingly important to the user because of rising energy cost. Transformer designs with low load losses can be designed but at a cost premium. Some manufacturers have developed optimization programs where, when provided the energy costs by the user, the lowest evaluated cost (cost of energy plus cost of transformer) design can be built.

## REGULATION

Transformers are designed to meet a specified secondary voltage with no load applied to its terminals when a specified primary voltage is applied. However, with the primary voltage constant, as load is applied to the secondary terminals there is a resultant secondary voltage drop. This voltage drop is due to the regulation of the transformer. Regulation is defined as the change in output (secondary) voltage which occurs when the load is reduced from rated kVA to zero, with the applied (primary) voltage maintained constant and is expressed as a percentage of the full-load secondary voltage.

Regulation is calculated using the two components that make up the impedance of the transformer, namely the percentage resistance voltage and the percentage reactance voltage. The following equation can be used to calculate the regulation at any load power factor (cos Ø).

$$\%\ \text{Regulation} = (\%\ R)(\cos \text{Ø}) + (\%\ X)(\sin \text{Ø}) + \frac{\{(\%\ X)(\cos \text{Ø}) - (\%R)(\sin \text{Ø})\}^2}{200}$$

From a user's standpoint, a transformer with low regulation is most desirable. However, this can be a serious disadvantage from a design standpoint.

To obtain a low regulation, the reactance must also be low. This will require an impedance which may result in excessively high short circuit currents. As was observed in Table 1, the maximum available short circuit current increases as the impedance decreases, assuming the system can supply the short circuit kVA. The mechanical forces experienced during short circuit vary approximately as the square of the short circuit current. Thus, a transformer with an impedance of 4% could have short circuit forces of 625 times normal while a transformer with a 2% impedance could have forces as much as 2500 times normal.

Short circuit forces introduced because of lower than normal impedance can be a problem with transformers particularly as the kVA increases. While transformers can be designed to withstand the forces at normal impedance levels, withstanding forces above this can present unique design and operational problems. Therefore, regulation should not be considered from an operational point of view only, but from a safety and reliability standpoint also.

## RELIABILITY TESTS

### DIELECTRIC TESTS

The insulation in a transformer is probably the most important of its constructional materials. A transformer can function if the efficiency and regulation are poor, temperature rise is too high or if the mechanical strength is marginal, but if the insulation is inadequate and fails, the transformer is unusuable. The effectiveness of the insulation in a transformer can be measured by its dielectric strength.

The purpose of the dielectric tests is to verify the dielectric strength of the insulation or in the case of the manufactured transformer to demonstrate the suitability of the insulation to withstand the test levels defined in the Standards. There are three dielectric withstand tests that can be performed on a transformer: (1) applied potential test, (2) induced potential test, and (3) impulse test. Each of these tests, as will be shown, has a specific purpose in verifying the major and minor insulation system of the transformer. The major insulation consists of the phase-to-phase and phase-to-ground insulation and the insulation separating the primary and secondary windings. The layer-to-layer, turn-to-turn and section-to-section insulation make up the minor insulation.

Applied Potential Test - This test is sometimes referred to as the "high Pot" or the low-frequency test. The purpose of this test is to check the adequacy of the major insulation to ground and to all other windings being tested.

In this test all windings are short circuited and all windings except the one being tested and the tank are grounded. The voltage to be applied to the ungrounded winding has been established by A.N.S.I. C57.12.00 and is given in the low-frequency test column of Table II (Page 7). This test is usually made at 60 hertz and has a duration of one minute.

FIGURE 7: APPLIED POTENTIAL CONNECTIONS

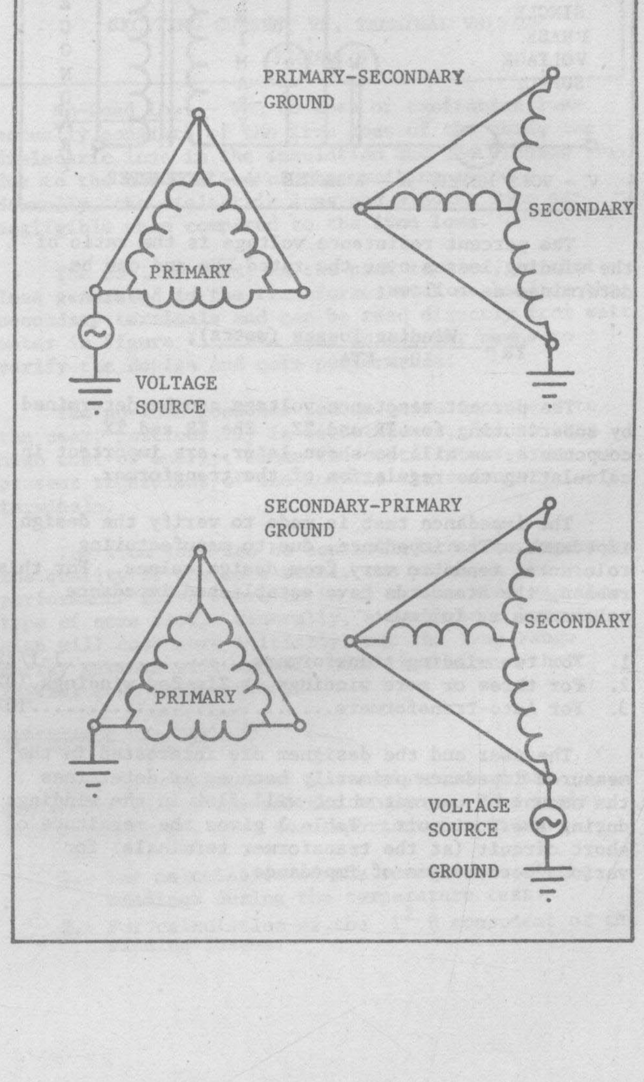
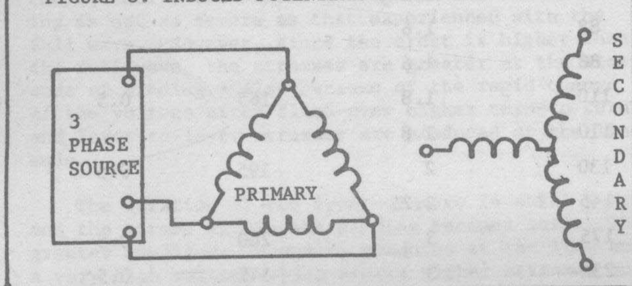


Figure 7 shows the applied potential test connection for a typical two-winding transformer. The voltage applied creates a stress on the insulation which exceeds that encountered during normal operating conditions and thus demonstrates its suitability for the application. It should be pointed out that when one end of the winding is solidly and permanently grounded this test is omitted.

Induced Potential Test - The purpose of this test is to check the minor insulation of the transformer. This test is accomplished by applying a single phase or a three-phase source, as the case may be, to one set of line terminals of the transformer with the other set open circuited, see Figure 8.

FIGURE 8: INDUCED POTENTIAL CONNECTIONS




The induced voltage for fully insulated transformers has been established by the Standards to be twice rated voltage. Transformers that have windings where the insulation at the neutral end is reduced from that at the line end are tested at a reduced voltage level. For these designs ANSI C57.12.00 has established the minimum test values to be not less than 1.65 times the nominal system voltage.

It should be recognized that if this test was made at rated frequency, the core would be overexcited resulting in excessive exciting current. For this reason the test frequency is somewhat higher than rated frequency, generally 120 Hertz (cycles) or higher.

When the frequency exceeds 120 Hertz, the severity of the test is greatly increased. Recognizing this the Standards have limited the duration of the test to 7200 cycles. Table III lists some of the most commonly used frequency-time combinations.

Table III

Induced test frequency and duration

| Frequency (Hertz) | Duration (seconds) |
|---|---|
| 120 | 60 |
| 180 | 40 |
| 240 | 30 |
| 360 | 20 |
| 300 | 18 |

As was the case in the applied potential test, the induced voltage applied to the windings creates a stress on the turn and layer insulation which exceeds that experienced under normal operating voltages, thus showing that the insulation strength satisfies the required test levels.

IMPULSE TEST

In the early years of transformer design, it was accepted that the applied and induced potential tests were adequate to demonstrate the dielectric strength of transformer insulation. However, as more was learned about lightning phenomena and switching surges, it became apparent that the distribution of the voltage stress from these sources was quite different from that experienced from the induced and applied tests. Thus, to prove the capability of the insulation to withstand the lightning and switching surges, the impulse tests were devised.

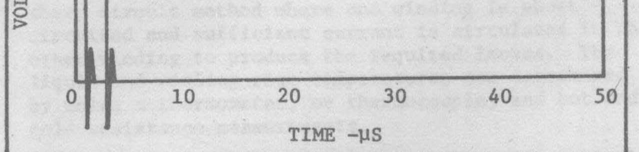
Over the years as system voltages have become standardized, impulse levels corresponding to these voltage classes have been established. The impulse levels, referred to as Basic Impulse Insulation Levels or BIL, have been standardized by A.N.S.I. and N.E.M.A. and are also listed in Table II. (Page 7)

Impulse tests are made with wave shapes that simulate those a transformer may experience in service. There are three basic wave shapes used: full wave, chopped wave and front-of-wave. These are shown in Figure 9.

Full Wave - This represents a disturbance that occurs some distance from the transformer and travels along the transmission lines to the transformer. This is the wave shape shown in Figure 9a. The Standards have defined the amplitude and the wave shape used in this test to ensure that the transformer insulation meets minimum dielectric strength. The wave shape is generally described as a 1.2 x 50 wave. This is a wave that rises from zero to the crest value in 1.2 microseconds and decays to half the crest value in 50 microseconds.

Chopped Wave - This represents a traveling wave created by a disturbance some distance from the transformer that flashes near the transformer terminals after reaching its crest. This is simulated by the wave shown in Figure 9b. As can be seen, the wave is chopped just after the crest is reached. The chopped wave is chosen by Standards to 115% of the full wave impulse. The amplitude and flash-over time for the chopped wave as specified in A.N.S.I. C57.12.00 are algo given in Table II. (Page 7)

FIGURE 9: IMPULSE WAVE SHAPES




Front-of-Wave - The disturbance represented by this wave is a direct or very close proximity hit of a lightning stroke on the transformer terminals. The surge voltage rises very fast until it flashes

## TABLE II

### INSULATION CLASSES AND DIELECTRIC TESTS FOR OIL - IMMERSED TRANSFORMERS

| Insulation Class [1] (kV) | Low-Frequency Test (kV rms) | BIL and Full Wave (kV Crest) | Chopped Wave (kV Crest) | Chopped Wave Min.Time to Flashover (μS) | Front-of-Wave (kV Crest) | Front-of-Wave Min. Time to Flashover (μS) |
|---|---|---|---|---|---|---|
| 1.2A | 10 | 30 | 36 | 1 | | |
| 1.2 | 10 | 45 | 54 | 1.5 | | |
| 2.5A | 15 | 45 | 54 | 1.5 | | |
| 2.5 | 15 | 60 | 69 | 1.5 | | |
| 5.0A | 19 | 60 | 69 | 1.5 | | |
| 5.0 | 19 | 75 | 88 | 1.6 | | |
| 8.7A | 26 | 75 | 88 | 1.6 | | |
| 8.7 | 26 | 95 | 110 | 1.8 | 165 | 0.5 |
| 15A | 34 | 95 | 110 | 1.8 | - | - |
| 15 | 34 | 110 | 130 | 2 | 195 | 0.5 |
| 18 | 40 | 125 | 145 | 2.25 | - | - |
| 25 | 50 | 150 | 175 | 3 | 260 | 0.5 |
| 34.5 | 70 | 200 | 230 | 3 | 345 | 0.5 |
| 46 | 95 | 250 | 290 | 3 | 435 | 0.5 |
| 60 | 120 | 300 | 345 | 3 | 510 | 0.51 |
| 69 | 140 | 350 | 400 | 3 | 580 | 0.58 |
| 92 | 185 | 450 | 520 | 3 | 710 | 0.71 |
| 115 | 230 | 550 | 630 | 3 | 825 | 0.825 |
| 138 | 275 | 650 | 750 | 3 | 960 | 0.96 |
| 161 | 325 | 750 | 865 | 3 | 1070 | 1.07 |
| 180 | 360 | 825 | 950 | 3 | 1150 | 1.15 |
| 196 | 395 | 900 | 1035 | 3 | 1240 | 1.24 |
| 215 | 430 | 975 | 1120 | 3 | - | - |
| 230 | 460 | 1050 | 1210 | 3 | 1400 | 1.40 |
| 260 | 520 | 1175 | 1350 | 3 | 1530 | 1.53 |
| 287 | 575 | 1300 | 1500 | 3 | * | * |
| 315 | 630 | 1425 | 1640 | 3 | | |
| 345 | 690 | 1550 | 1780 | 3 | | |
| 375 | 750 | 1675 | 1925 | 3 | | |
| 400 | 800 | 1800 | 2070 | 3 | | |
| 430 | 860 | 1925 | 2220 | 3 | | |
| 460 | 920 | 2050 | 2360 | 3 | | |
| 490 | 980 | 2175 | 2500 | 3 | | |
| 520 | 1040 | 2300 | 2650 | 3 | | |
| 545 | 1090 | 2425 | 2800 | 3 | | |

[1] The letter "A" under Insulation Class refers specifically to distribution levels for distribution transformers.

* Above 260 kv insulation class, the chopped wave and front-of-wave approach the same rate of rise and, therefore, only the chopped waves shall be applied.

over, causing the voltage to collapse very rapidly. The simulated test wave shape can be seen in Figure 9c. The wave is chopped just before it reaches its crest. The amplitude and flash over time from A.N.S.I. C57.12.00 are given in Table II (Page 7).

The duration and rate of rise and decay of the above wave shapes, as can be observed, are quite different. Likewise, the reactions within the windings of the transformer are also quite different. The long duration of the full wave develops relativel high voltage stress as compared to rated voltage throughout the winding turn-to-turn, layer-to-layer as well as between the winding and ground.

The chopped wave is of shorter duration and consequently, the stress throughout the entire winding is not as severe as that experienced with the full wave. However, since the crest is higher than the full wave, the stresses are greater at the line ends of winding. Also because of the rapid change of the voltage after flash-over higher turn-to-turn and layer-to-layer stresses are produced at the line ends.

The duration of the front-of-wave is still shorter and the stress within the winding becomes less. The greater amplitude, however, produces at the line ends a very high voltage which exerts higher stresses on the insulation to ground, turn-to-turn and layer-to-layer.

Impulse tests, due to their severity, are listed in the Standards as optional. However, when specified they can be performed. While these tests are not usually done on a routine test basis, manufacturers of transformers have done extensive testing on the insulation separately and within the transformer.

Generally, users do not specify these tests primarily due to the experience of the manufacturers and the severity of the tests. When an impulse test is specified, it is usually the A.N.S.I. full wave or the manufacturer's quality control test. This usually meets the needs of most users. The front-of-wave tests are generally limited to substation transformers where there is a strong likelihood of a direct lightning stroke.

When impulse tests are required, the Standards have defined the test sequence to be: one reduced full wave (used for comparison) two chopped-waves, and one full wave. If a front-of-wave impulse test is required, then the sequence is: one reduced full wave, two front-of-waves, two chopped-waves and one full wave.

SOUND TEST

The sound test measures the average sound level generated by the transformer when energized at rated voltage and frequency with no load. The main sound source, since there are no moving parts in a transformer, comes from the core. The core laminations, when in the presence of a magnetic field, elongate and contract. These periodic mechanical movements produce sound vibrations in the core. These vibrations have fundamental frequencies of 120 cycles per second and harmonics thereof.

Sound tests are considered optional tests by the Standards and are infrequently made by the manufacturers. Most manufacturers have an abundance of core steel data that has been collected over the years and can calculate the sound level for a particular design quite accurately.

N.E.M.A. Standards have established sound level requirements for transformers which are listed in Table IV. These levels are generally acceptable to the user. However, occasionally they do have applications that require a lower sound level; such as, the transformer being located in a building, in close proximity of occupants or simply to meet local codes and may for the purpose of verifying the design ask for a sound test.

Table IV

Sound levels for oil-filled transformers(350 BIL&Below)

| Equivalent Two-winding kVA | Avg. sound level, Decibels(db) Self-Cooled Sealed |
|---|---|
| 0-50 | 48 |
| 51-100 | 51 |
| 101-300 | 55 |
| 301-500 | 56 |
| 501-700 | 57 |
| 701-1000 | 58 |
| 1001-1500 | 60 |
| 1501-2000 | 61 |
| 2001-2500 | 62 |
| 2501-3000 | 63 |
| 3001-4000 | 64 |
| 4001-5000 | 65 |
| 5001-6000 | 66 |
| 6001-7500 | 67 |
| 7501-10000 | 68 |

TEMPERATURE TESTS

The rating of a transformer is determined by the allowable operating temperature of its insulation or, as more commonly referred to in transformer application, the temperature rise above an ambient temperature. The temperature that the insulation reaches depends upon the load on the transformer and the ambient surrounding the transformer.

Temperature limits for windings in liquid-filled transformers have been established by A.N.S.I. and N.E.M.A. Standards to be 95° C, which consists of an average winding temperature rise of 65° C over a 30° C average ambient. These Standards further limit the hottest-spot temperature in the winding to be 110°C. These limits were established to provide normal life expectancy of the insulation based on the current state of the art.

Transformers are designed to meet the temperature limits as imposed by the Standards. The temperature test is a means to verify that these limits are met. This test is made by simulating the rated load on the transformer on the highest loss tap connection. There are several methods that can be used to simulate loading. Probably the most frequently used is the short circuit method where one winding is short circuited and sufficient current is circulated in the other winding to produce the required losses. The liquid and winding rise temperatures are determined by using a thermometer, or thermocouple, and hot and cold resistance measurements.

The hottest-spot temperature measurement is not made during production line testing. The hottest-spot occurs within the winding and there is no convenient way to measure it or for that matter to find it. This measurement, if made, is determined by prototype