EASA AR200

GUIDE

FOR THE REPAIR OF POWER AND DISTRIBUTION TRANSFORMERS

(Revised 2011)

Reliable Solutions
Today!

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The contents of this non-mandatory guide are advisory or informative in nature. The repair of power and distribution transformers requires specialized knowledge, skills and equipment.

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PURPOSE

The purpose of this document is to establish guidelines for each step of the repair of power transformers.

SCOPE

This document describes record keeping, tests, analysis, and general guidelines for the repair of power transformers. It is not intended to replace the manufacturer's or the customer's instructions or specifications. Transformers covered by this document are liquid-filled distribution or power transformers up to 10 MVA and 69 kV, and dry-type distribution and power transformers up to 5 MVA and 25 kV.

Section 1
General

The following section covers items that apply to virtually all transformers received for repair.

1.1 IDENTIFICATION

There are three identification items that are important when repairing power transformers: information to be retained for service center records, information that should remain with the transformer, and information that will allow the customer to clearly identify the service center that performed work on the equipment.

1.1.1 Records

A unique record or service order should be established each time a transformer is received for repair. This document should briefly describe the as-received condition of the transformer, any faults identified and a list of all damaged or missing components. Photographs or digital images may be attached to the record to confirm the as-received condition of the transformer and provide documentation of the repair process. If the transformer is liquid filled, the PCB concentration should also be clearly shown on the service order with supporting documentation from the customer or test lab. Technical information such as the nameplate data, electrical test data (before and after repair), details of the repairs requested by the customer, the repairs performed, and a list of all parts that were replaced should also be shown. This record should be made available for review by the customer when requested.

1.1.2 Nameplate

A transformer should have a permanent nameplate containing the principal information needed to put the transformer into service. If the transformer is redesigned, the original nameplate should remain on the unit, unless the customer requests otherwise. The new design information should appear on a new nameplate mounted adjacent to the original, unless the customer requests otherwise.

1.1.3 Service Center Labels

Before shipment, the service company's name or identifying logo should be permanently embossed or inscribed adjacent to the nameplate. If possible, the service order number for the most recent repair should also be clearly marked on the unit.

1.2 CONDITION ASSESSMENT AND FAILURE INVESTIGATION

Upon receiving a transformer, the service center should promptly inspect and test it to confirm its condition and obtain data for any failure investigation. For the latter, data collection should proceed before any other work is carried out on the equipment. Start with a visual inspection of major components and all accessories. Record in notes and photographs any evidence of distress, such as physical damage, overheating, tampering, oil levels, electrical tracking, or encounters with animals. If possible, information about the operating conditions at the time of failure should also be obtained. Debris from any fault should be collected and carefully examined. The position of all operating mechanisms and indicating devices should be noted. Once the visual inspection is complete the transformer can be tested to confirm its electrical integrity. Any of the tests described in Section 2 can be used for this purpose. Oil removal should be carried out according to the procedure described in Section 5.

1.3 CLEANING

Prior to disassembly it is often convenient to clean transformer tanks and enclosures to avoid contaminating the core and coil assemblies when they are removed. Once disassembled to the extent required for the repair, the components should be thoroughly cleaned. Local environmental regulations must be followed and the effects of the cleaning agent upon the insulated components should be known before proceeding. Care should be taken to avoid damaging the more delicate components. Any cleaning agent remaining on cleaned components should be allowed to evaporate. Any remaining residue should be removed. Parts should then be stored in a clean, dry location prior to assembly.

1.4 TERMINALS

1.4.1 Leads

A lead is often used to extend the start and/or finish of the coil to the terminals. Leads should have the correct temperature, voltage and current rating for the application. They should also be capable of withstanding any elevated temperatures experienced during the repair process. Leads can also be marked or colored to correspond to the connection identification shown on the nameplate or specified in ANSI, CSA, IEC, IEEE or NEMA Standards.

1.4.2 Connectors (Lugs)

Damaged or missing connectors should be replaced. Connectors that require crimping or pressure indenting of the connector barrel are recommended. The connector should be sized to fit the lead and terminal based on recommendations of the connector manufacturer.

1.4.3 Enclosures

Transformer terminals are often contained within metal enclosures. The integrity of these enclosures should be maintained. The enclosure should be large enough to accommodate leads and terminals without crowding or causing overheating and large enough to ensure that minimum electrical clearances and bending radii are maintained.

1.5 ACCESSORIES

All accessories that may be removed during disassembly (e.g., bushings, cooling fans, temperature gauges, liquid level gauges, current transformers, pressure relief devices, sudden pressure rise relays, gas relays, etc., and any associated wiring) should be confirmed to be sound and operating correctly before being returned to service. Replacement bushings should be similar to the originals in design, have the proper current rating, and have Basic Impulse Level (BIL) and 50/60 Hz test levels higher than the windings to which they are connected.

1.6 TANKS, RADIATORS AND ENCLOSURES

After cleaning, any rust or corrosion should be removed and the affected areas painted. Any areas where liquid was leaking should be repaired and painted. It is preferable to paint the whole tank, radiator or enclosure. After completion of repairs it is recommended that the radiators (and tank) be pressure tested if possible as outlined in Section 5.2.5.

1.7 PAINTING

At some point during the repair process, often just prior to shipping, the transformer should be painted. The customer should specify the color. Before using any paint product, one should know its characteristics, and be aware of the safety and health hazards the product presents. One should also be aware of any environmental regulations covering the use of the product. It is important that painting be carried out under controlled conditions according to the paint manufacturer’s instructions. The work should be carried out in a heated, well-ventilated area isolated from other personnel. For spray applications, a paint booth or spray recovery system is recommended. The person applying the paint should be supplied with all necessary safety equipment. For spraying, this may include a face shield and mask, air supply, protective gloves and coveralls. The surfaces to be painted should be clean and free from oils or grease and at the proper temperature. Items such as bushings or gauges should be protected. Once the paint is applied it should be allowed to cure properly. When the paint has cured, the coverings on the bushings and any other items should be removed.

1.8 PACKAGING AND TRANSPORTATION

After all repairs are complete, the transformer should be labeled as described in 1.1.3 and packaged to prevent damage during transportation to the customer. The type of packaging and method of transport should be arranged with the customer. Documents should be provided to the transport company and the customer that confirm the PCB concentration in liquid-filled transformers. For units larger than 5 MVA the oil may be shipped separately. In either case the transport agency should be equipped with an emergency response kit. Provide additional protection for fragile items such as bushings, gauges, etc. Extra care should be taken to secure and support enclosures for dry-type transformers to avoid damage by crushing during shipment. On larger units the enclosure may be disassembled or special supports can be fabricated to prevent damage. For small units this can be achieved by bolting the enclosure (and core and coil assembly) to a pallet. In all cases ensure that the transformer has been securely tied to the transport vehicle and that the transformer is properly protected against the weather. Unless instructed otherwise by the customer, the tap switch or tap connections should always be set at the 100% position.

Section 2
Testing, All Transformers

There are many tests that one can perform on a transformer. Some are used to assess the condition of the transformer; others are used to verify repair results or adequacy of design.

2.1 SAFETY CONSIDERATIONS

Handling and testing any piece of electrical apparatus can be hazardous, and transformers are no different. Items regarding safety of personnel, training, and equipment requirements are presented in Appendix A of this standard.

2.2 INSTRUMENT CALIBRATION

Accuracy becomes very important if tests are carried out to confirm performance characteristics. Each instrument required for test results should be calibrated at least annually against standards traceable to the National Institute of Standards and Technology (NIST) or other relevant national standards agencies. In addition, the test equipment should meet the accuracy requirements of IEEE Standards C57.12.00 and C57.12.90.

Each instrument should bear a mark or label verifying calibration and, if extreme importance is attached to the test results, the instrument should be calibrated immediately before and after the completion of the test procedure. In some cases, a calibration curve might be useful.

2.3 INSULATION CONDITION TESTS

Insulation condition assessment is fundamental to transformer operation. One or more of the following tests should be performed to gain information about the insulation system. Note that trended test results are usually more informative than a single test result. For this reason all test results should be recorded and retained for future reference.

2.3.1 Insulation Resistance Test

This test is usually performed to obtain three different winding insulation resistance values: high voltage to low voltage and ground; low voltage to high voltage and ground; and high voltage to low voltage. It can also be used to obtain insulation resistance values between the core and ground when there is a core-to-ground connector that can be removed so as to electrically isolate the core from ground. For best results the transformer should be clean and dry before performing this test.

If the transformer has more than two windings, the insulation resistance of each winding should be measured in turn with the other windings grounded. These insulation resistances should be measured with a DC insulation resistance tester–i.e., a megohmmeter. The test equipment should be suitably sized for the transformer or winding to be tested and the test performed at a voltage level consistent with the voltage rating of the winding under test. Suggested test voltages are given in the table below.

INSULATION RESISTANCE TEST VOLTAGES

Winding Voltage Class kV	Insulation Test Voltage (DC)
1.2	1000
2.5 – 5.0	2500
8.7 – 15.0	5000

The temperature of the winding should be measured at the same time as the insulation resistance value is obtained, which will allow the resistance reading to be corrected to a common temperature such as 20° C. Temperature correction factors are given in Figure 1 of Appendix B. Test voltages are applied for one minute. All accessories attached to the winding should be disconnected and grounded to the core. Recommended minimum insulation resistance values may be obtained from the manufacturer's operation manual. In absence of this information typical minimum values are shown below. If resistance values are obtained that are below these values, one should investigate to determine the cause of the low values. The significance of one insulation resistance reading is not well defined for liquid-filled or dry-type transformers; consequently, these values are best used to determine equipment suitability for overvoltage tests or for trending over time.

RECOMMENDED MINIMUM INSULATION RESISTANCES FOR DRY-TYPE TRANSFORMERS

Winding Voltage Class kV	Insulation Resistance in Megohms
1.2	600
2.5	1000
5.0	1500
8.7	2000
15.0	3000

Ref. IEEE C57.94

The recommended minimum one minute insulation resistance for oil-filled transformers is given by the relationship:

R_{min} = $C \times E/(kVA)^{1/2}$ where
R = the minimum insulation resistance in megohms
C = 1.5 for transformers at 20° C
= 30 for untanked core and coils
E = voltage rating in volts (phase-to-phase) for delta-connected transformers and phase-to-neutral for wye-connected transformers
kVA = rated capacity of the winding under test (If a three-phase winding is being tested where all three windings are being tested as one, the rated capacity of the three-phase winding is used)

Ref. IEEE C57.125

The resistance should be corrected to a reference temperature as follows.

R_{ref} = $k_t \times R_t$ where
R_t = measured value of resistance
k_t = correction factor for the temperature at which the measurement was taken. (See Figure 1 in Appendix B for correction factors for various temperatures.)

The insulation resistance for dry-type transformers can be affected by moisture. To confirm the presence of moisture, the insulation resistance can be measured at two different voltages. For example, if the insulation resistances at 500 volts DC and 1000 volts DC differ by more than 25%, this can indicate the presence of moisture in the winding.

2.3.2 Polarization Index Test

This is an extension of the one minute insulation resistance test described in 2.3.1, and has the advantage that moisture has little affect on these measurements. The same DC voltage used for the one minute test is applied for a period of ten minutes. Resistance measurements are recorded after one minute and ten minutes. The polarization index is the ratio of the ten-minute resistance to the one-minute resistance. Equipment with values below 2 should be investigated for possible insulation contamination. This test is most reliable for dry-type insulation systems; consequently, the results should be interpreted with caution for oil-filled equipment.

2.3.3 Recovery Voltage Test

This test is usually only performed on oil-filled units. Specialized equipment (e.g., a known capacitance, an adjustable DC voltage source and two switches where the opening and closing sequence can be controlled automatically) is required to carry out this test. The peak voltage on the capacitor, the charge time and the discharge time are the parameters that are measured. These are sensitive to moisture and aging products in the insulation system. The change of these values over several tests may indicate degradation of the insulation system.

2.3.4 Step Voltage Test

This test is not usually performed on oil-filled transformers. A controlled DC voltage is applied in steps, and as the voltage is increased, weak insulation will show decreased resistance. Changes in results over time may indicate insulation degradation.

2.3.5 Insulation Power Factor Tests

This test is usually performed on equipment rated 4 kV or higher. It is an AC test in which the loss angle between voltage and current is measured, and the capacitances of the windings are measured using a high-voltage dissipation factor bridge. These readings are taken HV to (LV and G), LV to (HV and G), and HV to LV and corrected to a common temperature base, usually 20° C. (HV indicates the high-voltage winding, LV indicates the low-voltage winding and G indicates ground.) The results are recorded and compared over time to detect deterioration of the insulation system. Such things as moisture, other contaminants, aging products, and cracks in rigid insulation materials can be detected. Unfortunately, there is no standard interpretation of the results. However, large data banks exist (e.g., Doble Engineering user data collection) that can be used for comparing test results. Results should be corrected to the reference temperature of 20° C. (See Figure 2 in Appendix B for suitable correction factors.) When the power factor is measured, the transformer charging current can also be measured. This is another means of detecting shorted turns in the winding or deterioration of the lamination insulation. If a winding short exists, the charging current will be very high. Note that on large transformers the test set may not have sufficient kVA to attain its full rated output voltage.

2.4 OTHER TESTS

There are other tests that can be performed on a transformer to assess its condition. These tests do not test the insulation systems directly but provide meaningful information about the other components.

2.4.1 Winding Resistance Test

To obtain accurate results, this test is usually performed using a winding resistance bridge. On a new or rewound transformer this information can be used to determine the copper or load losses that will occur in the transformer and separate them from eddy current losses in the winding. This test can also be used to detect faulty joints or tap switch contacts within the winding. Note that when measuring the resistance of the HV winding on large transformers, it can take several minutes for the measurement equipment to reach a stable value. At the same time as these measurements are taken, the temperature of the winding should also be measured. The resistance value can be corrected to a common temperature using the relationship:

R_{ref} = R_t x (T_{ref} + 235)/(T_t + 235) where
$_{ref}$ = reference temperature
$_t$ = test temperature at which the values were obtained.

2.4.2 Transformer Turns Ratio (TTR) Test

Low-voltage AC is applied to the low-voltage winding of the transformer, and the voltage induced in the high-voltage winding is measured through test set reference transformers and a null meter. Using the TTR test set one can determine the polarity of the transformer, phase relations, and turns ratio. Measurements should be taken on all taps. Unsatisfactory results can be an indication of loose connections, tap changer misalignment, short circuits, incorrect turns after rewind, or open circuits in the winding. The maximum variation of the measured value of the turns ratio with respect to the calculated value is 0.5 percent (Ref. IEEE C57.12.00).

Common TTR responses and the associated transformer condition are:

TTR Reading	Condition
Low current and no output volts	Open turn in the excited winding
Normal current, output voltage low or unstable	Open turn in output winding
High current and difficulty balancing the bridge	High resistance in test leads or tap changer

Ref. IEEE C57.125 1991

2.4.3 Polarity Test

This test can usually be performed with the TTR meter described in Section 2.4.2. Alternatively, a low amplitude AC voltage source and voltmeter can be used. One terminal of the HV winding and the LV winding are connected together and the low amplitude AC source connected to the HV winding. The voltage across the remaining terminals HV to LV is measured. The result, if greater than the voltage applied to the HV winding, indicates that the polarity is additive. Alternatively, if the voltage is lower than that applied to the HV winding, the polarity is subtractive. This test can also be performed on three-phase transformers if both ends of the HV and LV windings for each phase are accessible. The test is performed one phase at a time with all other terminals open circuited. For additive polarity, the HV and LV windings are wound in the opposite direction. When they are wound in the same direction, a transformer is described as having subtractive polarity. This characteristic becomes very important when more than one transformer is connected in parallel to supply a load. If the polarities are not the same, large voltage and current imbalances will occur that can damage the transformers or the connected load.

2.4.4 Phase Sequence Test

This test is used to determine the phase relationships between the high-voltage and low-voltage windings. It is particularly useful after a transformer has been rewound and connected following disassembly in the factory or in a service center. It is recommended that this test be performed any time the leads from the core and coil assembly are disconnected from the terminals. In this way, one can be sure they are connected properly after the work is complete. The test is similar to the polarity test except that the line and neutral coil leads are connected as they would be in service. Connect corresponding terminals together, one from HV and one from LV (usually H1 and X1). Connections for various winding configuration are shown in Figure 3 in Appendix B. A low amplitude (120 volts or less) three-phase AC voltage is then applied to the HV winding. The voltages between the remaining terminals are then measured and recorded. The magnitudes are then compared to the expected magnitudes based on overlaying the phase relation diagrams from the nameplate and calculating the phase relation sum of the voltages being measured.

2.4.5 No-Load Loss Test

On new transformers this test is performed to verify the core losses or iron losses. On transformers that have been or are about to be repaired the test is usually performed to determine whether there are shorts between laminations and to provide a reference for future tests. The test can be performed using one wattmeter on a single-phase transformer and one, two or three wattmeters on a three-phase transformer. The low-voltage winding is energized to rated voltage with the HV winding open circuit. The watts measured are the no-load losses, and the current is the excitation current. It is important that the supply waveform be sinusoidal and at the correct frequency. The losses are measured with a wattmeter suitable for use at low power factor. Unfortunately, without knowing the original losses it may be difficult to assess the condition of the core in a used transformer. As a rough guide, expect one watt loss per pound of core steel (2.2 watts loss per kilogram). The losses obtained in this manner include dielectric losses as well as stray losses and copper I^2R losses both due to the exciting current.

2.4.6 Single Phase Low Voltage Excitation Test

This test can be used at regular intervals over the life of a transformer. By comparing the test data from one test to another, one can monitor the condition of the transformer. The test can also be used as a diagnostic tool when troubleshooting transformer failures.

A single-phase 50/60 Hz test voltage of 10% of the rated voltage is applied to the HV winding. For wye-connected transformers, the test voltage is applied in turn between the high-voltage terminal and the neutral. For delta-connected transformers, the voltage is applied between high-voltage terminals in turn, and the third terminal is grounded. It is important to ensure the polarity of the test leads is the same for all tests. The current, voltage and watts are recorded.

When testing single-phase transformers, the voltage is applied to the high-voltage terminals twice. The second time the test leads are reversed so that the one originally on H1 is placed on H2, etc. The two currents should agree within 10%.

For three-phase transformers, the current through the coil on the center leg of the core will be somewhat less than the currents in the other two phases. The currents on the outside two phases should be within 15% of each other, and values for the center leg should not be more than either outside leg. In all cases, results from one test to another should agree within 5%.

2.4.7 Load Loss Test

This test is carried out to determine the losses within a transformer due to the resistance of the HV and LV windings. Once again the energizing source should have balanced voltages, and the waveform should be sinusoidal. If these two criteria are met, the measurement can then easily be made with one, two or three wattmeters. The usual method is to short circuit the LV winding and energize the HV winding on the 100% tap until rated current is achieved. The watts measured are the load losses, and the voltage required to circulate the rated current is the impedance voltage. The winding temperature should also be recorded at this time. The reference temperature used for determining copper losses is 85° C. The recorded readings will contain core losses as well as the load or copper losses. The core losses can usually be neglected unless the impedance of the transformer is unusually high. In the latter case, the core losses can be measured at the exciting voltage used to obtain the copper losses and subtracted from the value initially recorded. It is also important in this test to ensure that the method used to short circuit the LV winding does not appreciably change the resistance of the LV circuit; otherwise, the measured losses will be affected. The conductors used to make the short circuit connection should have a current-carrying capacity equal to or greater than that the corresponding transformer leads.

2.4.8 Single-Phase Impedance Test

This test is used to perform impedance tests on single-phase or three-phase transformer windings using reduced current. The test results will not match factory test results, but are particularly useful on three-phase transformers where one expects all three phases to be the same within 2%. The key item when doing this test on three-phase transformers is to establish single-phase flux paths in the core when testing each phase. The secondary windings are shorted for the test, then a single-phase voltage is applied to each phase, one at a time, and the current measured. The impedance can be calculated from the following formula:

$$\%Z = (1/60)x(E_{12}/I_{12}+E_{23}/I_{23}+E_{31}/I_{31})x\ (kVA_{3phase}/kV^2_{LL})$$

Ref. IEEE C57.125

Note: The “E” subscripts of the above formula identify the lead numbers of the phases under test.

The “I” subscripts identify the leads associated with the voltage being applied–e.g., if voltage is applied to leads 1 and 2, the current will be that of lead 1 or lead 2.

The “LL” subscript denotes line-to-line.

2.5 HIGH-POTENTIAL TESTS

To confirm that a particular transformer or accessory can withstand the electrical stresses in service, it is subjected to a high-potential test. This test can be performed using AC or DC. For transformers rated above 34 kV, the DC test should not be used. The electrical stress is usually applied between the windings and ground. The HV and LV windings are usually tested separately with the winding not being tested connected to ground. To avoid damaging the insulation, avoid application of the high-potential test voltage. High-potential tests should not be used on equipment with graded insulation systems. That is because the insulation level at the neutral end of the winding is less than at the line end.

2.5.1 50/60 Hz High-Potential Test

A 50/60 Hz single phase AC supply is connected to the HV and LV windings separately. The winding under test has all terminals shorted together. The other winding terminals are also shorted and connected to ground. The 50/60 Hz source should be suitably sized to provide the necessary charging current for the transformer being tested, and the waveform should be purely sinusoidal. The test voltage is raised to the test value at a slow, controlled rate. It should, however, not be so slow as to unnecessarily extend the test period. Usually, the above criterion can be met if the voltage is raised to 75% of the test value in 5 - 10 seconds and the rate of rise from there on is 2% - 3% of the test value per second. The test value is maintained for one minute, and the voltage smoothly but rapidly decreased after that time. The equipment is deemed to have passed the test if the test voltage is maintained for the one minute period without any disruptive discharge.

2.5.2 DC High-Potential Test

This test is performed using the same basic procedure as used for the 50/60 Hz test. Once again it is important that the test set be large enough to provide the charging current for the transformer under test. In addition, the AC supply to the DC set should be very stable to prevent unwanted oscillation of the test voltage. For this test the rate of voltage application should be determined using the guideline in 2.5.1. At the end of one minute the leakage current is recorded, then the voltage smoothly and quickly reduced to zero. The leakage current can be used as a reference for future high-potential tests on the equipment.

2.5.3 High Frequency Induced Potential Test

This test is used to verify the integrity of the turn-to-turn insulation in single-phase and three-phase transformers, as well as phase-to-phase insulation in three-phase transformers. It may also be used in place of the 50/60 Hz high-potential test for graded insulation systems. The test is carried out at high frequency to reduce the exciting current required to energize the transformer. Common frequencies are 120 Hz up to 400 Hz. To keep the severity of the test essentially constant for the various frequencies, the duration of the test is limited to 7200 cycles. The test supply is connected to each phase of the LV winding of the transformer under test. The HV winding is left open. The voltage is raised smoothly and quickly to the test value (less than 15 seconds), held for the 7200 cycles, then reduced smoothly and quickly (less than 5 seconds) to zero. The transformer is deemed to have passed the test if no disruptive discharge occurs during the test.

2.5.4 Test Levels, Windings

Test levels for transformer windings vary depending on the type of transformer and the voltage class. The manufacturer's recommended test values should be used. If the manufacturer's information is unavailable, see Appendix B, Figure 4, for the recommended test levels for new or completely rewound equipment. If the equipment has been overhauled or is being checked for suitability for service, values not less than 65% (Ref. ANSI/IEEE Std. C57.94) of those shown should be used. Values are shown for both liquid-filled and dry-type transformers. Caution: the values shown are for equipment with fully insulated neutrals. Equipment with reduced insulation at the neutral should be subjected to induced potential tests only. Altitude correction factors should be used for equipment tested above 3300 ft (1000m).

2.5.5 Test Levels, Accessories

New or fully reconditioned accessories containing voltage-sensing circuits should be tested at 1500 volts AC 50/60 Hz for one minute. Current-sensing circuits should be tested at 2.5 kV AC 50/60 Hz for one minute.

2.5.6 Gas-in-Oil Analysis

One of the more informative tests that can be performed on an oil-filled transformer is gas-in-oil analysis. During transformer operation the deterioration of the insulation materials generates gases that are dissolved in the oil. By determining the gases created and the rate of generation one can detect faults before they become catastrophic. This test should be performed regularly on all oil-filled transformers. Those who take samples should be well trained in this operation, as the accuracy of the results is very dependent on the sample being representative of the oil in the transformer. Results from this test can inform the operator about localized or general overheating, arcing or corona activity, and deterioration of the paper. For acceptance criteria refer to IEEE Std. C57.104, *Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers*. This test can also be used on other dielectric fluids. Some "less flammable" dielectric fluids, such as the natural or synthetic esters, are either non-gassing or exhibit gas generation characteristics quite different from mineral oils, and are not dealt with in industry–e.g., IEEE standards. For assistance, one should contact the transformer manufacturer or the fluid manufacturer.

2.5.7 Other Oil Tests

Additional information about the condition of the transformer can be obtained from furan analysis and oil quality tests. The former determines the quantity of furan (a by-product of paper breakdown) in the fluid. The latter test is used to assess the condition of the oil. Such things as moisture content, acidity, color, interfacial tension power factor and dielectric strength are measured. By drying and reconditioning the oil using filters and diatomaceous earth, the oil can be restored to virtually new condition. For acceptance criteria, refer to IEEE Std. C57.106, *Guide for Acceptance and Maintenance of Insulation Oil in Equipment*.

The physical condition of the paper can be determined by testing the tensile strength of a small sample, or by determining the degree of polymerization.

Section 3
Rewinding, All Transformers

The most common rewind is that which is based on the original design. The winding process has essentially three components: the investigation of the original failure, gathering physical data for the new coils, and the actual winding of the new coils.

3.1 INVESTIGATION

The rewind process starts with the investigation of the failure that necessitated the rewind. Information gathered about this incident may be helpful when rewinding the coils so that subsequent failures can be avoided or delayed. Some of the features that one should look for are: signs of overheating and its probable cause, material incompatibility, reduced electrical clearances, and the mechanical failure of components. If the fault cannot be located visually, electrical tests such as those described in Section 2 can be used to determine the nature and location of the failure.

3.2 GATHERING DATA

From the nameplate, the core and coil assembly and by removing and backwinding coils one should gather the following information:

- Nameplate data
- Basic coil design (cylindrical, spiral sheet wound or disc)
- Physical dimensions of the coils
- Electrical clearance dimensions, phases-to-phase and phase-to-ground
- Number of turns
- Direction the coils are wound
- Tap locations (physical and electrical)
- Insulation material
- Size of conductor
- Number of conductors in parallel
- Conductor material
- Coil resistances
- Special features such as extra supports, tying, main lead length

3.3 WINDING COILS

This should be done in a clean environment using a winding form made for the particular coil being wound. The winding form can be a metal cylinder upon which the ground insulation is applied, or it can be a pressboard cylinder that needs no additional ground insulation. The winding is built up according to the data obtained from the original. Particular attention is given to the size of cooling ducts, wire compaction and tension, tap locations, crossovers, connections and splices. Proper tension on the conductors ensures a tight, solid coil. The tension should not be so great as to stretch the conductor. All crossovers and leads should have additional insulation applied to avoid mechanical breakdown of the conductor insulation during processing or in service. Connections are made using a "T" joint (brazed or MIG-welded) and separately insulated. Splices within the coil are made using a scarf joint or simple butt joint (brazed or MIG-welded), then separately insulated. Care should be taken to minimize the insulation build. Once the coil is complete, the physical dimensions and resistance should be checked. Coils for dry-type transformers are dried and dipped or vacuum impregnated with a thermosetting resin. Coils for liquid-filled transformers rated less than 25 kV can also be dried and dipped or vacuum impregnated, because the cured resin gives the coil additional strength to withstand through faults. (See Appendix C: Replacing Aluminum Conductors with Copper Conductors in Power and Distribution Transformers 10 MVA and Smaller.)

3.4 CORE LAMINATIONS

Cores are generally stacked cores or wound cores.

3.4.1 Stacked Cores, Disassembly

Since these cores are often other than rectangular or square cross sections, an accurate dimensioned sketch should be made of the core cross section prior to disassembly. In addition, one should note the number of laminations stacked together; this is usually two or three, but can be more. In most cases, it will be only the yoke that will be unstacked. Upon removal, all laminations should be stacked together in the same order that they are to be put back and be well supported for storage in a safe location. Laminations from dry-type transformers may be bonded together with cured resin if the core and coil assembly was dipped as a unit. This makes unstacking the laminations difficult and requires extra care to avoid damaging them. Laminations should be well supported during storage and put in a safe, dry location.

3.4.2 Stacked Cores, Assembly

Prior to assembly, the laminations and clamping structure should be cleaned. The laminations should be inspected for signs of insulation breakdown, and for burrs that should be removed. The blocking between the core legs and the coils should be installed at this time to center the coils and secure them to the core. During assembly of the yoke, the laminations are replaced according to the sketch prepared prior to disassembly. Make sure that the laminations butt tightly against each other at all joints. Excessive gaps can drastically reduce the flux density in the core. Once all the laminations are in place, the clamping assembly is put in place, insulated and the securing bolts torqued to recommended values. Next, the transformer coils should be ratio-tested to confirm the overall ratio and the electrical location of the taps.

3.4.3 Wound Cores, Disassembly

These cores are often difficult to disassemble. The number of laminations stacked together should be noted prior to disassembly. Accurate overall dimensions also should be recorded. The bands securing the laminations are cut and the laminations are then carefully removed. The urge to straighten the laminations upon removal should be avoided. Too much bending will change the characteristics of the laminations and also make assembly very difficult. Avoid complete disassembly of the core. The fewer laminations removed, the easier it will be to achieve proper assembly. When laminations are removed, they should be well supported and stored in a clean, safe location.

3.4.4 Wound Core, Assembly

Prior to assembly the laminations and clamping structure should be cleaned. The laminations should be inspected for insulation breakdown and for burrs that should be removed. During assembly it is critical that the butt joints be tight. This can be very difficult to achieve on some transformers. To help in this process, the core can be tightened and banded in stages. That is, install a few laminations and apply temporary bands to tighten them. The temporary bands are then removed before additional laminations are installed. Once all laminations are assembled, the final clamping bands are applied and the steel clamping structure is put in place, insulated and the bolts torqued to the correct values. As mentioned in 3.4.2, the coils should be tested at this point to ensure the proper ratio and the correct electrical location of the taps.

3.5 CONNECTIONS

There are essentially two connections that should be made when winding a transformer, those in the winding and those external to the winding. All connections should be carefully prepared to ensure mechanical and electrical integrity.

3.5.1 Connections in the Winding

There are many methods of making joints and splices, and those described below serve as examples only. Connections in the winding can be used to connect various parts of the winding (as in a disc-style of winding), to splice in another spool of wire, or to provide tap connections for the winding. In all cases, the joint should be prepared and insulated to not only ensure electrical and mechanical integrity but to take up as little space as possible. For a splice to meet these needs within the winding, a brazed or MIG-welded scarf joint or butt joint is often used. Soldered or crimped connections are not recommended for this application. The two connecting pieces should be carefully prepared to ensure that all local insulation is removed and a good fit of one piece against the other is achieved. Once the brazing or welding is complete, all sharp protrusions and flux material should be removed. Strand insulation can be restored by applying a few layers of the appropriate insulation as described in Section 3.5.3 below. If the coils contain wire that is smaller than No. 14 AWG, splices within the winding should be avoided. If the joint is a tap connection, a "T"-joint can be used. If the joint connects two parts of the winding such as in a disc type of winding, a lap joint can be used if space permits; otherwise, a butt or scarf joint should be used. In all cases, all sharp protrusions should be removed after brazing or welding is complete. An additional piece of sheet insulation is often wrapped around the joint to protect adjacent turns. Where tap leads exit the winding, they are often securely tied into the winding to avoid breaking the conductor at this point.

3.5.2 External Connections

In most transformers, these connections are usually made to extend the tap leads or the main leads or to install a lug or similar connection device to the end of the leads. A piece of multistrand wire or cable can be attached to the coil conductor where the wire exits the winding, or the connection can be made well outside the coil. If the connection is made external to the coil conductor, the wire used for this purpose can be attached to the magnet wire by brazing, soldering or welding, or by using a crimp connector. Brazing or welding creates the most secure connection but requires additional skill on the part of the tradesman. In addition, any fluxes or cleaning agents should be removed after the connection is made. Crimp connectors should be used when joining dissimilar metals, or for attaching lugs or similar connection devices to the end of the leads.

3.5.3 Insulating Connections

When these connections require insulation, the materials should have the proper voltage and temperature ratings, and be rated for use in air or for use under the dielectric fluid. The insulation should extend beyond the connection in each direction to establish a creepage path to suit the voltage of the winding and to suit the environment (air or submerged in the liquid dielectric). The insulation should be secured in such a manner that it will not fall off during processing or in service. In addition, suitable sleeving is usually installed over any wire that extends beyond the coil.

3.6 LEADS

The requirements for dry-type and liquid-filled transformers differ slightly. The leads for dry-type transformers often have to withstand high temperatures. Leads for liquid-filled transformers should be able to withstand submersion in the dielectric fluid. When multistrand wire or cable is connected to the coil conductor, the cable or wire conductor is sized using a current density that is the same as or preferably lower than that used for the coil conductor. As a guide one can use a conductor the same as or a larger size than that used by the original manufacturer. On small transformers the coil conductor is often used as a lead. In this case, a sleeve is usually placed over the wire for added mechanical and electrical strength.

Section 4
Transfomer Repair–Dry Type

There are three basic levels of repair: verifying service suitability, overhaul, and rewind or other major component replacement. An outline for these three basic levels of service follows.

4.1 CHECKING FOR SERVICE SUITABILITY

All nameplate data should be recorded on the service order form as described in Section 1.1.1.

4.1.1 Tests

The following tests should be performed: the insulation resistance HV to LV, HV to G with LV grounded, LV to G with HV grounded; ratio check and winding resistance on all phases on all taps; energize the LV to attain full voltage, recording the magnetizing current and the energizing voltage.

4.1.2 Equipment Checks

Check all accessories and the enclosure (if available) for mechanical damage, noting the items inspected, those that are damaged, and the nature of the damage. Verify the operation of any cooling fans and controls. Check any standoff insulators in the enclosure or on top of the transformer for cracks or chips. Clean all insulators. Confirm the security of all leads and tap connections. Check any insulated supports used for the HV winding leads or tap connections for mechanical security and damaged components. Check bolted joints on all bus connections for tightness.

4.1.3 Summary of Results

As described in Section 1.1.1, all data and a list of damaged items should be shown on the service order form. This information should then be passed to the customer with recommended repairs for the damaged items. In this case, the customer may choose not to have the additional repairs carried out. However, the list of items requiring repair may be used at a future date to establish the amount of work required.

4.1.4 Preparation for Shipment

The transformer should be painted according to Section 1.7. After the paint is applied and cured, the customer should be advised that the work is complete and the transformer is ready for shipment. Follow any specific shipping instructions provided by the customer regarding carrier, routing, packaging, or shipping address. Prepare the transformer for shipment according to Section 1.8.

4.2 OVERHAUL

This operation requires more work than that described in the preceding sections. The purpose is to totally refurbish the transformer and accessories. In this case, with the customer's concurrence one should proceed to carry out the repairs (see Section 4.1.3). In addition, after cleaning the core and coil assembly, a coating of insulating resin may be applied. The enclosure may be sandblasted before painting to achieve a better result.

4.3 REWIND

Upon receiving the unit, set up the proper records and record the necessary information as outlined in Section 1.1.1.

4.3.1 Inspection, Test and Estimate

If the rewind was initiated by a fault, an investigation should be carried out as described in Section 3.1. Record all data. Once the fault has been located and the extent of the damage determined a cost estimate and scope of work should be prepared for the customer.

4.3.2 Dismantle (three-phase unit assumed)

If necessary, remove the core and coil assembly from the enclosure. Remove all of the superstructure and lead support systems. Remove the upper clamping structure, upper blocking and insulation between the core and the clamping structure. Store all components neatly for reassembly. Unstack the top yoke as described in Section 3.4.1. The laminations should be well supported.

At this point, the data for the items listed in Section 3.2 should be recorded. The coils can now be removed from the core by first removing all blocking between the core and the coil ground insulation. Using suitably fashioned lifting hooks, the coils can be lifted from the core limbs. Support the coils well at this stage to prevent unnecessary damage. Once removed from the core, the coil can be placed in a winding lathe, unwound and the remaining data obtained. Depending on coil construction, one may be able to separate the HV and LV windings and replace only one of these.

4.3.3 Winding New Coils

Winding the new coils should be carried out as described in Section 3.3.

4.3.4 Reassembly

The coils are set on the core limbs using the same equipment used to remove them. The core is then assembled according to Section 3.4. If the transformer has a wound core, the core should be placed in and around the coils as described in Section 3.4. The blocking or insulation layers between the core and coils are installed to center the coil and to secure the core and coil assembly. On wound core units this material also prevents the core from damaging the winding. Install the core clamping structure and the items for the superstructure. Ensure that the clamping structure is properly insulated from the core. At this time, install the blocking between the top of the coils and the clamping structure. The position of the clamping structure should be adjusted to ensure the blocks are tight. Once the bolts for the clamping structure are properly tightened, install the lead support structure and secure the line leads and the tap leads.

4.3.5 Final Tests

Once the transformer is completely assembled, the unit should be tested to ensure that the repair was successful and to provide a record of the transformer condition after the repair. Recommended tests are: ratio check (TTR), phase relation and polarity check, winding resistance, insulation resistance, AC or DC high-potential test, induced potential test, core loss test, and copper loss test. Optional tests are power factor, recovery voltage, and DC step voltage. All are described in Section 2.3.

4.3.6 Shipment

The transformer is prepared for shipment according to Section 1.8.

Section 5
Transformer Repair–Liquid Filled

The operations to repair a liquid-filled transformer are similar to those described for dry-type transformers. Much of the additional work required relates to the dielectric fluid and the tank.

5.1 CHECKING FOR SERVICE SUITABILITY

All nameplate data should be recorded on the service order form as described in Section 1.1.1. If applicable, the PCB concentration should be verified.

5.1.1 Tests

The following tests should be performed: the insulation resistance HV to LV, HV to G with LV grounded, LV to G with HV grounded; check ratio and winding resistance on all phases on all taps; if possible, energize the LV winding to attain full voltage, recording the magnetizing current and the energizing voltage.

5.1.2 Equipment Checks

Check all accessories for mechanical damage, noting the items inspected, those that are damaged, and the nature of the damage. Verify the operation of any cooling fans and controls. Check radiators, threaded fittings and gaskets for leaks. Check the bushings for cracks and clean them. Check the proper operation of the tap changer, if any. Alternatively, check the security of the tap connections in the tank.

5.1.3 Summary of Results

As described in Section 1.1.1, all data and damaged items should be listed on the service order form. This information should then be passed to the customer with recommended repairs for the damaged items.

5.1.4 Preparation for Shipment

The transformer should be painted according to Section 1.7. After the paint is applied and cured, the customer should be advised that work is complete and the transformer is ready for shipment. Follow any specific instructions provided by the customer. Prepare the transformer for shipment according to Section 1.8.

5.2 OVERHAUL

This operation usually requires considerably more work for oil-filled transformers than for dry-type transformers. The purpose is to totally refurbish the transformer and accessories.

5.2.1 Preliminary Inspection and Tests

Perform a quick visual inspection to identify and record any mechanical damage to the tank or radiators and any fluid leaks that may exist. The following tests should be performed: the insulation resistance HV to LV, HV to G with LV grounded, LV to G with HV grounded; ratio check all phases on all taps; winding resistance check. Take oil samples for PCB analysis, quality analysis, gas-in-oil analysis, and furan analysis (see Section 2.5.7).

5.2.2 Removal of Core and Coils

The oil should be drained from the tank and stored in tanks specially designated for the purpose. This will protect the oil from contamination by other substances. Know the PCB concentration before commencing any draining procedures. When draining the oil from a damaged transformer, any contaminants in or floating on the oil can foul the transformer windings. A filter should be used in the suction line to prevent contamination or damage to the pump. Precautionary measures should be taken to prevent all leaks. Once the oil is drained, all components are removed, such as the conservator, the bushings, tap switch operators, and temperature gauge wells. The cover is then removed by removing the clamp that holds it in place, unbolting it or cutting the weld. For the latter case, the tank should be purged with and pressurized with nitrogen prior to cutting the weld. Bushings should be removed or protected from metal splatter. After the cover is removed, any remaining accessories that require access from inside the tank can be removed. The core and coil assembly can then be carefully lifted from the tank. Allow the core and coil assembly to drain over the tank for a short time and then place it on the floor over a drip tray. Cover the assembly with a polyethylene sheet.

5.2.3 Major Inspection and Tests

With the unit well lit, perform a detailed inspection of the core and coil assembly, the inside of the tank, and all the accessories that were removed. Items that require special attention are: the tap changer and its connections; the core clamping assembly; insulation between the core and the clamping structure; blocking; coil insulation; coil leads; any accessible conductor joints; the bushings; the inside of the tank; the conservator; radiators; and all accessories. Tests performed at this time are: insulation resistance between the core and the clamping structure; functional tests on all accessories; and a degree of polymerization test on the paper. The results listing the deficiencies, recommendations, and repair costs should be provided to the customer. The customer may choose to repair only the most critical deficiencies. These should be repaired along with the "standard" repairs listed by the service center as part of the overhaul.

5.2.4 Cleaning and Repairs

All items are cleaned using methods appropriate for each item. The core and coil assembly is flushed using oil at very low pressure. The tank, cover, conservator, control boxes and bushing terminal boxes should be sandblasted and thoroughly cleaned. On larger transformers, cleaning the inside of the tank can expose personnel to additional unwanted hazards, such as toxic, flammable or suffocating vapors from solvents in a confined work space. These issues should be resolved to avoid undue risk to service personnel and to satisfy the local regulating authorities. After sandblasting and prior to cleaning is the appropriate time to add or replace any radiators or cooling tubes. Replace the gaskets and seals with materials resistant to deterioration by transformer oil. The oil should be processed to remove particulates, gases and acids. Alternatively, it can be replaced with new oil. Once all the repairs have been completed, the unit can be reassembled.

5.2.5 Reassembly

Reassembling the transformer starts with drying the core and coil assembly. This is best accomplished by placing the core and coils into an oven where the temperature does not exceed 95° C (203° F). Dissipation factor measurements can be taken during the drying cycle to determine when the insulation is dry. Ensure that an absorbent material is around the base of the core and coil assembly to soak up oil that will drain from the insulation. Prior to removing the core and coil assembly from the oven, ensure that the work area is clean and that cleanliness will be maintained throughout the assembly process. When the core and coil assembly is removed from the oven or drying tank, the clamping bolts should be checked for tightness. The assembly is then lifted, quickly lowered into the tank, and all hold down supports installed and tightened. The tank is then quickly filled with oil to the top of the transformer core. The oil should be at or above room temperature, preferably above. Install all sidewall components, replacing any damaged control wiring. Install the cover and all cover-mounted components. Fill the transformer with the remaining oil until the correct oil level is shown on the oil level gauge. For large transformers, drying can be carried out at site. However, the methods used will not be described in this document. The security of all joints is confirmed by pressurizing the transformer tank with approximately 3 psig of dry air and inspecting all joints for leaks. If time permits, the transformer should remain pressurized overnight and the pressure checked in the morning. Mask off all bushings, gauges and valves and paint the unit as described in Section 1.7.

5.2.6 Final Tests

The following tests are recommended: insulation resistance core-to-ground; insulation resistances between each winding and between each winding and ground; turns ratio test; phase relation check or polarity check; winding resistance; open circuit core loss; copper loss; AC high-potential test for HV and LV windings; and an induced potential test. All tests are described in Section 2. Once all tests are complete, oil samples should be taken for gas-in-oil analysis and quality assessment. The results confirm that no internal problems occurred during testing and form a record for comparison with future test results.

5.2.7 Packaging and Shipment

The transformer can be prepared for shipment as described in Section 1.8.

5.3 REWIND

Upon receiving the unit, establish documentation and record the necessary information as outlined in Section 1.1.1.

5.3.1 Inspection, Test and Estimate

If a fault initiated the need for a rewind, investigation should be carried out as described in Section 3.1. Record all data. The core and coil assembly should then be removed as described in Section 5.2.2. Once the coil and coil assembly is removed, the extent of the damage should be determined and a cost estimate and scope of work should be prepared for the customer.

5.3.2 Dismantle (three-phase unit assumed)

Remove all of the superstructure and lead support systems. Remove the upper clamping structure, upper blocking and insulation between the core and the clamping structure. Store all components neatly for reassembly. Unstack the top yoke as described in Section 3.1.

At this point some of the data listed in Section 3.2 should be recorded. To free the coil from the core, all blocking between the core and the ground insulation should be removed. Using suitably fashioned lifting hooks, the coils can be carefully lifted from the core limbs. It is important to support the coils well at this stage to prevent unnecessary damage. Once removed from the core, the coil can be placed in a winding lathe, unwound and the remaining data obtained. Depending on coil construction, one may be able to separate the HV and LV windings and replace only one of these.

5.3.3 Winding New Coils

Winding the new coils should be carried out as described in Section 3.3.

5.3.4 Reassembly

The coils are set on the core limbs using the same equipment used to remove them. The core is then assembled according to Section 3.4. If the transformer has a wound core, the core should be placed in and around the coils as described in Section 3.4. The blocking or insulation layers between the core and coils are installed to center the coil and to secure the core and coil assembly. On wound-core units this material also prevents the core from damaging the winding. Install the core clamping structure and the superstructure assembly. Ensure that the clamping structure is properly insulated from the core. One should also at this time install the blocking between the top of the coils and the clamping structure. The position of the clamping structure should be adjusted to ensure that the blocks are tight. Once the bolts securing the clamping structure are properly tightened, install the lead support structure and secure the line leads and the tap leads.

5.3.5 Final Tests

Once the transformer is completely assembled, test the unit to ensure that the repair was successful and to provide a record of the transformer condition after the repair. Recommended tests are: ratio check (TTR), phase relation and polarity check, winding resistance, insulation resistance, AC or DC high-potential test, induced potential test, core loss test and the copper loss test. Optional tests are power factor, recovery voltage and DC step voltage. All are described in Section 2.3.

5.3.6 Shipment

The transformer is prepared for shipment according to Section 1.8.

Appendix A
Electrical Testing Safety Considerations

(This Appendix is not a part of EASA AR200 Guide for the Repair of Power Transformers.)

A.1 PERSONNEL SAFETY

A.1.1 Training

Employees should be trained in the safe operation of all that they are expected to use in their daily activities. This includes all test equipment, hand tools and lifting or handling equipment. Training should be provided using relevant equipment operation manuals, hands-on training and/or video training tapes. When properly trained in the use of the service center equipment, employees should be expected to carry out their activities in a safe manner.

A.1.2 Clothing

Local regulatory agencies responsible for work place safety will have requirements that must be met. One should determine what these rules are and ensure that they are followed. As a minimum, clothing should be suitable for the work to be performed. Flame-retardant material is recommended. Wearing exposed jewelry should be avoided. Safety glasses and safety shoes should be worn at all times.

A.1.3 Supervision

Inexperienced employees should work under the direction of an experienced and qualified person within the test area. At least two persons should be in the test area at all times.

A.1.4 First Aid

Personnel should be trained in the procedure for obtaining emergency medical aid.

A.2 TEST AREA

A.2.1 Enclosure

The test area should be enclosed by a fence or colored rope (preferably yellow). Red or yellow warning lights may also be placed at the corners of the test area.

A.2.2 Gates

When a metallic fence is used for the enclosure, it should be grounded. If the fence is made from many stand-alone sections, or includes gates, the separate sections should be interlocked with the power source. The power source will be shut off when one of the sections is parted or the gate opened.

A.2.3 Signs

Electrical hazard signs should be posted around the perimeter of the test area. Unauthorized personnel should not enter the test area.

A.2.4 Lighting

The test area should be well illuminated.

A.2.5 Safety Equipment

Fire equipment and first aid equipment should be readily available and personnel should be trained in their use. When oil-filled equipment is being tested, an emergency oil spill response kit should be available if there is risk that a large oil leak will occur.

A.2.6 Test Unit Clearance

The test area should be large enough to allow personnel to move around the equipment with ease to facilitate set-up and inspection. Proper electrical clearances between energized test equipment and adjacent apparatus must be maintained. Proper electrical clearances between energized test equipment and personnel performing the test must be maintained.

A.2.7 Exclusivity

Only the unit under test and the pertinent test equipment should be in the test area during the test.

A.2.8 Grounding

Items on the test unit that are normally at ground potential should be grounded. In addition, a portable ground and appropriate “hot stick” should be available to ground the energized components when the tests are complete.

A.3 UNIT UNDER TEST

A.3.1 Suitability for Test

Test personnel should verify that the unit is physically and electrically suitable to undergo the proposed test procedures.

A.4 TEST PANELS

A.4.1 Construction

All test panels should be constructed to protect the operator from the energized equipment they contain (dead front design). There should be no exposed, bare, energized items that the operator could accidentally touch. The test panel should also contain appropriate fault current interrupting equipment (fuses or circuit breakers) to limit the fault current to the test panel capacity or less. A separate interrupting device is preferred for high-voltage AC or DC tests that can restrict the fault current to very low values, thus avoiding excess damage.

A.4.2 Test Voltages

The voltage level on all voltage sources should be clearly marked. For voltage levels above 600 volts, a special interlock procedure should be incorporated to prevent inadvertent application of the wrong test voltage. Voltage sources should be free of harmonics, and the phase voltages and currents should be balanced.

A.4.3 Indication of Energization

It is recommended that a light, clearly visible in the vicinity of the test area, be illuminated when the test panel is energized and voltage may appear on the unit under test.

A.4.4 Disconnect

A means of providing a visible disconnect between the panel and the power source should be clearly seen from the test area. The purpose of this device is to provide isolation of the test panel from the power source. This is often a manually operated switch or thermal-magnetic breaker.

A.4.5 Safety Switch

A highly visible switching device should be mounted on the panel that will disconnect it from the power source. This is frequently an electrically operated device such as a contactor or breaker. It is usually operated by a clearly identifiable and easily accessible push button. A hand-held push button or foot operated switch should also be available to one or more of the test participants to provide an additional means of interrupting the test.

A.4.6 Test Leads

Test leads and clips used for testing should be used for that purpose only. They should have the proper current and voltage rating for the test to be performed, and should be maintained in good physical condition.

Appendix B
Reference Information

Figure 1

Temperature Correction Factors for Insulation Resistance Tests

Temperature ° C	Transformers	
	Oil Filled	Dry Type
0	0.25	0.40
5	0.36	0.45
10	0.50	0.50
15.6	0.74	0.75
20	1.00	1.00
25	1.40	1.30
30	1.98	1.60
35	2.80	2.05
40	3.95	2.50
45	5.60	3.25
50	7.85	4.00
55	11.20	5.20
60	15.85	5.40
65	22.40	8.70
70	31.75	10.00
75	44.70	13.00

Ref. Paul Gill, Electrical Power Equipment Maintenance and Testing (New York: Marcel Dekker, Inc., 1998).

Figure 2

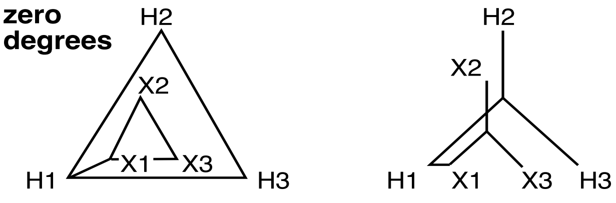
Temperature Correction Factors for Insulation Power Factor Tests for Liquid-Filled Transformers

Test Temperature ° C	Correction Factor K
10	0.80
15	0.90
20	1.00
25	1.12
30	1.25
35	1.40
40	1.55
45	1.75
50	1.95
55	2.18
60	2.42
65	2.70
70	3.00

Ref. ANSI/IEEE Std. C57.12.90

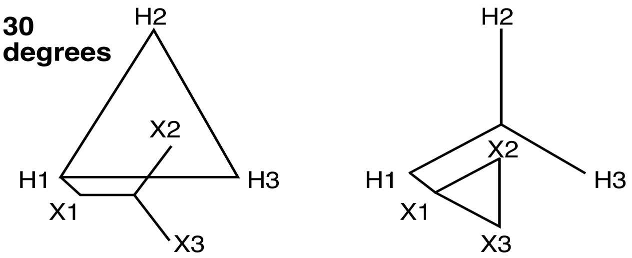
Figure 3

Various Winding Connections for a Phase Sequence Test



Connect H1 to X1:
measure H2-X2, H3-X2,
H1-H2, H2-X3, H3-X3

H2-X3 = H3-X2
H2-X2 < H1-H2
H2-X2 < H2-X3
H2-X2 = H3-X3



Connect H1 to X1:
measure H3-X2, H3-X3,
H1-H3, H2-X2, H2-X3

H3-X2 = H3-X3
H3-X2 < H1-H3
H2-X2 < H2-X3
H2-X2 < H1-X3

Ref. ANSI Std. C57.12.9

Figure 4

Recommended Test Levels for New Windings

DRY-TYPE EQUIPMENT

LINE TERMINAL VOLTAGE BIL kV	EQUIPMENT	APPLIED TEST VOLTAGE–60 HZ RMS		INDUCED VOLTAGE—60 HZ RMS	
		Winding-to-winding and winding-to-ground		HV to ground, grounded Y	HV phase-to-phase, grounded Y or D
		grounded Y	ungrounded Y or D		
10	120 - 1200		4		
	1200grdY/693	4		1386	2400
20	2520		10		5040
	4360grdY/2520	10		5040	8720
	4160		12		8320
30	7200				14400
	8720grdY/5040	10		10800	17440
45	8320		19		16640
	12000		31		24000
	13800				27600
60	13800grdY/7970	10		15940	27600
	18000		34		36000
95	22860grdY/13200	10		26400	45720
110	23000		37		46000
	24940grdY/14400	10		28800	49880
	27600		40		55200
125	34500grdY/19920	10		39840	69000
150	34500		50		69000

OIL-FILLED EQUIPMENT

BIL kV	SYSTEM VOLTAGE kV	DISTRIBUTION TRANSFORMERS		phase-to-phase kV rms	CLASS I POWER TRANSFORMERS		phase-to-phase kV rms
		TEST VOLTAGE 60 HZ KV TO GROUND			TEST VOLTAGE 60 HZ KV TO GROUND		
		single phase	three phase		single phase	three phase	
10							
30	1.2	10	10				
45	2.5	15	15		10	10	
60	5.0	19	19		15	15	
75	8.7	26	26		19	19	
95	15.0	34	34		26	26	
110					34	34	
125	25.0	40	40	50			
150	25, 34.5	50	50	69	50	50	
200	34.5, 46.0	70	70	92	70	70	76
250	46.0, 69,0	95	95	115	95	95	115
350	69.00	140	140		140	140	

Data from ANSI C57.12.00, C57.12.01, C57.12.90 and C57.12.91

Appendix C
Replacing Aluminum Conductor With Copper Conductor in Power and Distribution Transformers 10 MVA and Smaller

C.1 INTRODUCTION

There are many 10 MVA and smaller transformers in use that have aluminum conductors. When one of them is damaged or selected for rewind, the aluminum conductors are often replaced with copper. This appendix describes routine conductor changes that can be made within the bounds of the original transformer design; it does not explain how to completely redesign a transformer. (Note: All coil dimensions should remain as close to the originals as possible.)

Before undertaking a conductor change such as outlined above, it is important to consider:

- How differences in the thermal characteristics of the materials will affect short-term overload capability.
- How differences in material properties will affect the original blocking and bracing system.
- How the difference in conductivity will affect conductor size.
- How the difference in conductor size may affect coil resistance and reactance.
- How the different conductor size may affect the size of the coil (axial length) and hence its the ability to withstand short circuits.

C.2 MATERIAL CHARACTERISTICS

An aluminum alloy frequently used for magnet wire applications is 1350-O (E-Al 99.5–O). A common copper alloy used for magnet wire is C11000–O (CW004A–O). In both cases, the letter “O” indicates that the material is fully annealed. Table 1 shows selected electrical, physical, thermal and mechanical properties of aluminum and copper.

C.2.1 Electrical Properties

Differences in electrical conductivity/resistivity allow a copper conductor with a cross section 61% as large to replace an aluminum conductor (see Table 1).

Since a smaller conductor size will obviously require less space for the same number of turns, it is necessary to consider how this change will affect coil diameter, mean length per turn (MLT) and coil height. These factors can impact the resistance and leakage reactance of the coils.

C.2.2 Physical properties

Copper has a lower thermal coefficient of linear expansion than aluminum, so on large coils provisions for expansion need not be as great for copper.

Alternatively, any such provisions incorporated into the original design for aluminum will be more than adequate for copper.

Copper is also 3.3 times as dense as aluminum, so an equivalent copper conductor that has only about 61% of the cross-sectional area would weigh about twice as much as the original aluminum conductor. Therefore additional or stronger supports or blocking may be required for the copper coils.

C.2.3 Thermal Properties

Due to differences in the thermal properties of the materials, a copper coil can absorb more energy for a given temperature rise than an aluminum coil. Therefore a copper coil can withstand higher short-circuit currents than an equivalent aluminum coil, or the same short-circuit current for a longer time.

C.2.4 Mechanical Properties

The mechanical properties of copper exceed those of aluminum, so copper coils can withstand all mechanical operating stresses better. This assumes that the width-to-depth ratio of the conductors is the same or similar and that the coils are blocked and supported in a manner similar to the original.

This last point is important. When copper replaces aluminum, the winding on the new coils may be shorter than the originals. If the heights of the old and new coils differ significantly, the style of blocking may have to be changed to withstand the expected increase short-circuit forces. As part of any change in conductor material, make sure the replacement coil is the same height as the original. (Note that leakage reactance will also increase as the coils become shorter.)

C.3 TRANSFORMER IMPEDANCE

Any detailed discussion of how conductor size affects resistance and reactance should first consider the interrelationship of resistance, reactance and impedance.

Impedance (Z) is usually shown on the nameplate as a percentage. It has two components, resistance (R) and reactance (X), that define it according to the relationship: $Z = R + jX$.

The X/R ratio can be used to establish the relative magnitudes of the two components. For transformers up to 10MVA, this ratio can vary from approximately

Table 1

Selected Properties of Aluminum and Copper

	Aluminum 1350-O		Copper C11000-O	
Property	**Metric**	**Imperial**	**Metric**	**Imperial**
ELECTRICAL				
Electric Conductivity	0.362 MS/cm	61.8% IACS	0.591 MS/cm	101% IACS
Electric Resistivity	2.83 x 10^{-6} ohm cm	2.83 x 10^{-6} ohm cm	1.71 x 10^{-6} ohm cm	1.71 x 10^{-6} ohm cm
PHYSICAL				
Coefficient of Linear Expansion	23.8 x 10^{-6} m/m° C	13.2 x 10^{-6} in/in° F	17.3 x 10^{-6} m/m° C	9.6 x 10^{-6} in/in° F
Density	2.705 g/cm^3	0.09772 lb/in^3	8.91 g/cm^3	0.322 lb/in^3
THERMAL				
Thermal Conductivity	234 W/m° K	135 BTU ft/hr ft^{2}° F	391.1 W/m° K	226 BTU ft/hr ft^{2}° F
Mean Specific Heat	0.900 J/g° C	0.215 x 10^{-3} BTU/lb° F	0.394 J/g° C	0.092 x 10^{-3} BTU/lb° F
Melting Point	660° C	1220° F	1085° C	1985° F
MECHANICAL				
Modulus of Elasticity	68.9 GPa	10000 ksi	117 GPa	17000 ksi
Tensile Strength, Ultimate	82.7 MPa	12000 psi	221 MPa	35000 psi
Shear Strength	55.2 MPa	8000 psi	152 MPa	22000 psi

Notes

- The data in the above table are typical values only, DO NOT USE for design purposes.
- S = Siemens
- IACS is "International Annealed Copper Standard" where 100% conductivity is defined as having a volume resistivity of 1.7241 x 10^{-6} ohm cm.

5 to 15 depending on transformer size, with smaller transformers at the lower end of the range and larger transformers at the higher end of the range.

Changes in coil geometry may affect both the resistance and reactance of the transformer, which in turn may affect its impedance. Therefore any changes that will affect the coil geometry require careful consideration.

Note: Although relevant standards specify a manufacturing tolerance of ±7.5% on the stated impedance, some transformers exceed this value [1, 2, 3]. It is best to consult the appropriate standards and confirm the tolerance for the transformer under consideration (see Bibliography).

C.3.1 Coil Diameter vs. Reactance

Now consider how changing from aluminum to copper may affect coil diameter and resistance.

The resistance of a transformer coil is determined by the resistivity, cross-sectional dimensions and length of the conductor. As C.2.1 indicates, differences in resistivity/conductivity will allow a smaller cross section of copper to replace an aluminum conductor of the same length.

For a simple layer-wound cylindrical coil:

Conductor length = MLT x Turns

For any change that involves only conductor material or geometry, the number of turns will not change.

When changing from aluminum to copper, the choice of conductor dimensions may affect the MLT and hence the conductor length. Similarly, a change in conductor dimensions will also affect the coil dimensions (and therefore its reactance).

Note: The radial dimension of rectangular conductors is measured in the radial direction of the transformer coil. The axial dimension is measured in the axial direction of the coil (see Figure 1).

Two extreme situations can occur when selecting a replacement copper conductor: 1) the radial dimension remains the same; or 2) the axial dimension remains the same.

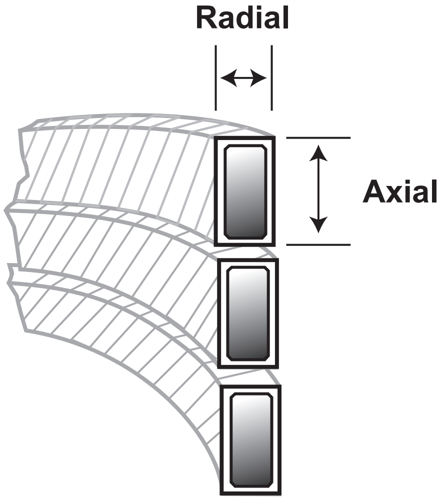


Figure 1. Conductor dimensions are measured in the axial and radial directions of the transformer coil.

• **The radial dimension remains the same.** If the copper conductor has the same radial dimension as the original aluminum conductor, the MLT will remain the same, but its axial dimension must be smaller to achieve the desired cross section.

In that case, it may be necessary to add space between winding turns or coils to ensure that the new coil or winding is exactly the same height as the original. (In layer windings, this is often accomplished by winding a suitable insulating cord adjacent to the conductor.)

Changes of this kind will increase leakage flux around the turns [4], so they require careful consideration. To minimize undesirable effects, keep any increased spacing between turns small with respect to the axial dimension of the conductor.

• **The axial dimension remains the same.** If the copper conductor has the same axial dimension as the original aluminum conductor, its radial dimension must be reduced to provide the correct cross section. Decreasing the radial dimension will effectively reduce the MLT and the total radial build of the coil.

Example. To illustrate the above cases, assume a three-phase transformer (13.8 kV - 600 volts, Y-Δ, 2 MVA, X/R = 5.75) with aluminum conductors. The HV coil has 4 layers that are separated by 10 mm duct spacers; the conductor is 4 mm (radial dimension) x 7 mm. The LV coil has 2 layers that are separated by a cooling duct, resulting in a "b1" dimension of 12 mm (see Figure 2). The space between the HV and LV windings (dimension "a") is 20 mm.

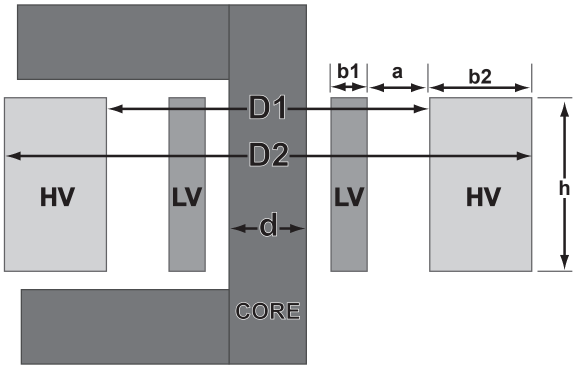


Figure 2. Schematic diagram of transformer core and coils

Referring to Figure 2, if the inner diameter of the HV coil (D_1) is 350 mm, its outer diameter (D_2) would be 442 mm:

$$b2 = (4 \times 4\ \text{mm}) + (3 \times 10\ \text{mm}) = 46\ \text{mm}$$

$$D_2 = D_1 + (2 \times b2) = 350 + 92 = 442\ \text{mm}$$

A copper conductor that is 2.4 mm x 7 mm would have the same conductivity as the original aluminum conductor, since 2.4 mm is approximately 61 percent of 4 mm (see Table 1).

C.3.2 Transformer Leakage Reactance

Transformer leakage reactance (X) is largely determined by the coil dimensions and the spacing between the HV and LV windings. For layer-wound cylindrical coils, this relationship can be described by the equation:

$$\%X = \frac{7.9N \times I \times MLT \times freq}{\frac{V}{N} \times h} \times \left(a + \frac{b1 + b2}{3}\right) \times 10^{-7} \qquad [5]$$

Where:

X = leakage reactance
N = turns
I = current
V = voltage
MLT = mean length per turn
a, b1, b2, h = coil dimensions and spacing, in mm (Figure 2)

Case A–Original aluminum conductor. In the above example, the dimensions and spacing of the original aluminum conductor are:

a = 20 mm (distance between HV and LV windings)
b1 = 12 mm
b2 = (4 x 4 mm) + (3 x 10 mm) = 46 mm

Solving the parenthetical terms of the reactance equation for these dimensions would yield:

$$a + \frac{b1 + b2}{3} = 20 + \frac{12 + 46}{3} = 39.3 \text{ mm}$$

Case B–Replacement copper conductor. Again referring to Figure 2, if "D1" and "a" do not change, the dimensions and spacing for the replacement copper conductor would be:

a = 20 mm
b1 = 12 mm
b2 = (4 x 2.4 mm) + (3 x 10 mm) = 39.6 mm

Solving the parenthetical term of the reactance equation for these dimensions would yield:

$$20 + \frac{12 + 39.6}{3} = 37.2 \text{ mm}$$

The transformer leakage reactance would therefore *decrease* by 5.3 percent:

$$1 - \left(\frac{37.2}{39.3}\right) \text{x } 100 = 5.3\%$$

Case C–Matching the original reactance. One way to make the reactance of the new copper winding match that of the original aluminum winding is to change the space between the HV and LV coils. With the new spacing, the product of the parenthetical term of the reactance equation must be of the same magnitude as the original:

$$a + \frac{b1 + b2}{3} = 39.3 \text{ mm}$$

$$a = 39.3 - \frac{b1 + b2}{3}$$

$$= 39.3 - \frac{12 + 39.6}{3}$$

$$= 39.3 - 17.2 = 22.1 \text{ mm}$$

In this case, a 22.1 mm increase in the spacing between the HV and LV coils will make the leakage reactance of the new winding virtually the same as the original.

Such changes in coil geometry must be considered carefully, however, because they also impact other transformer characteristics, such as the amount of stray flux and therefore efficiency.

C.3.3 Coil Diameter vs. Resistance

As stated earlier, coil resistance is based on the cross section, conductivity and length of the conductor. If the number of turns remains the same, the effect of length can be demonstrated through the mean length per turn (MLT).

In Case A, for instance, the MLT of the original aluminum conductor is:

b2 = (4 x 4) + (3 x 10) = 46 mm
MLT = π (D_1 + b2)
MLT = π (350 + 46) = 1244 mm

In Case B, where the only change was to replace the aluminum conductor with copper, the MLT is:

b2 = (4 x 2.4) + (3 x 10) = 39.6 mm
MLT = π (D_1+ b2)
= π (350 + 39.6) = 1224 mm

Here the resistance would *decrease* proportionally by 1.6 percent:

$$1 - \left(\frac{1224}{1244}\right) \text{x } 100 = 1.6\%$$

For Case C the space between the HV and LV coils was increased by 22.1 mm, so the MLT is:

D_1 = 350 + 2 (22.1 - 20)
= 350 + 4.2 = 354.2 mm
b2 = (4 x 2.4) + (3 x 10) = 39.6 mm
MLT = π (D_1+ b2)
= π (354.2 + 39.6) = 1237 mm

In this case, the resistance would *decrease* from the original by 0.6 percent:

$$1 - \left(\frac{1237}{1244}\right) \text{x } 100 = 0.6\%$$

C.3.4 Summary

Leakage reactance. For the original aluminum conductor, the value of the parenthetical term in the reactance equation was 39.6 mm. Substituting a copper conductor with no other changes produced a value of 37.2 mm for this same term, which reduced the reactance by 5.3 percent.

Increasing the space between the HV and LV coils by 22.1 mm resulted in a reactance virtually identical to the original. This change, however, would increase the stray flux from the transformer windings.

Resistance. The MLT of the original aluminum conductor on the HV coil was 1244 mm. Substituting a copper conductor resulted in an MLT of 1224 mm and a 1.6 percent decrease in the resistance of the winding.

Increasing the space between the HV and LV windings resulted in an MLT of 1237 mm and decreased the resistance by 0.6 percent.

Impedance. Substituting a copper conductor for the original aluminum conductor in the above example would change the magnitude of the impedance. To illustrate this, assume the original impedance is $|Z| = 1$ per unit (pu), and that the X/R ratio = 5.75. In that case:

$R = 0.1713$ pu, and $X = 0.9852$ pu

Therefore the impedance equation for the original aluminum winding would be:

$$|Z| = \sqrt{(0.1713)^2 + (0.9852)^2} = 1 \text{ pu}$$

As explained earlier, substituting the copper directly decreases the resistance by 1.6 percent and the reactance by 5.3 percent. Therefore:

$$|Z| = \sqrt{(0.1713 - 0.1713 \times 0.016)^2 + (0.9852 - 0.9852 \times 0.053)^2} = .9481 \text{ pu}$$

This is a decrease in impedance of 5.2 percent:

$0.9481 - 1 = -0.052$
$-0.052/1 = -0.052 \times 100 = -5.2\%$

If the spacing between the replacement HV and LV coils is increased by 22.1 mm as suggested above, the magnitude of the impedance will also change:

$$|Z| = \sqrt{(0.1713 - 0.1713 \times 0.006)^2 + (0.9852)^2}$$
$$= \sqrt{(0.1703)^2 + (0.9852)^2} = .9996 \text{ pu}$$

This is a reduction in impedance of only 0.04 percent:

$0.9996 - 1 = -0.0004$
$-0.0004/1 = -0.0004 \times 100 = -0.04\%$

In other words, adjusting the spacing between the HV and LV copper coils would keep the impedance virtually the same as that of the original aluminum winding.

The degree to which such a change may alter transformer characteristics is uncertain, however, and therefore must be carefully assessed. For example, an increase in stray flux may cause heating in the tank and decrease the overall efficiency of the transformer. Although changes in stray flux will undoubtedly be small, no guidelines are available that can reliably predict the magnitude of the effects.

An iterative approach is often needed to reach a suitable solution regarding changes in resistance and reactance and hence impedance. Any resulting changes in impedance must be balanced against the risks posed by modifications of coil geometry that might ensue.

The "windability" of the chosen conductor size must also be considered. That is, the conductor dimensions must afford sufficient strength to allow the coils to be wound with adequate tension. Alternatively, the dimensions cannot be so large as to require unusually high tension to wind the coil.

There are advantages and disadvantages to the changes in resistance and impedance. Changes in resistance will affect overall efficiency because copper losses are a direct function of current squared and resistance. Decreasing the impedance increases the inrush and short-circuit currents, thus raising the risk of mechanical damage to the transformer.

Decreasing the impedance also improves the regulation of the transformer–i.e., how well it maintains the secondary voltage over a range of load currents.

$$\text{Regulation } \% = \frac{V_{nl} - V_{fl}}{V_{fl}} \times 100$$

Where:
V_{nl} = no-load secondary voltage
V_{fl} = full-load secondary voltage

The preceding analysis has been greatly simplified for illustrative purposes. Much more sophisticated algorithms can be used to arrive at an optimal solution. In addition, the impedance calculation for transformers with different coil configurations than used for this example will require different geometric factors in the reactance formula. These factors can be calculated from first principles or found in references listed in the Bibliography.

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[3] IEC Std. 60076-1, *Power Transformers–Part 1*, 2nd ed. (Geneva, Switzerland: International Electrotechnical Commission, 2000).

[4] Ralph R. Lawrence and Henry Richards, *Principles of Alternating Current Machines* (McGraw Hill, 1953).

[5] S. Austin Stigant and A.C. Franklin, *J&P Transformer Book*, 10th ed. (Newnes-Butterworth, 1973).

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Standards Organizations and Other Resources

The following organizations produce documents and standards, some of which are referenced in this guide.

ANSI–American National
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Headquarters
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IEC–International Electrotechnical
Commission*
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* IEC and ISO standards are available through ANSI and the IHS Standards Store.

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