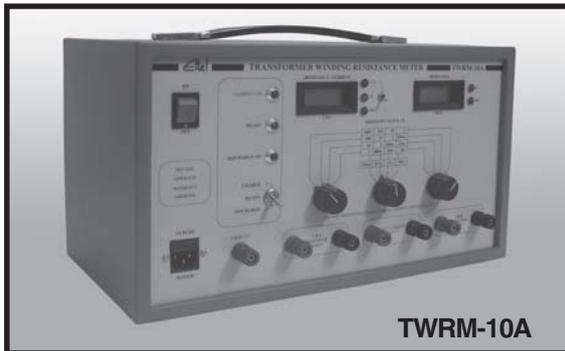


# THE ART AND SCIENCE OF MEASURING THE WINDING RESISTANCE OF POWER TRANSFORMERS

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TWRM-10A



ATWRM-25

This article describes many of the techniques and problems that may be encountered when measuring resistance in the presence of inductance, especially as applied to measuring the winding resistance of Power Transformers.

## 1. RESISTANCE MEASUREMENTS:

Resistance of a conductor can be determined by dividing the voltage across the conductor by the current flowing through it. This technique is employed when measuring many resistance samples including the windings of transformers to be discussed here. It should be pointed out that such resistance measurement assumes steady state conditions where the current through the sample remains steady and so does the voltage drop across it. This must be true throughout the measurement period. Most professional knowledgeable in the field of electrical measurements will recognize that if inductance or capacitance is associated with the resistance to be measured, a transient will be generated on the application of voltage/current to the test sample. Accurate measurements of resistance will not be possible in R/L/C circuits until the transient is allowed to die

down and steady state conditions prevail. Most electrical engineers will recognize that the windings of most electrical power equipment such as motors, generators and transformers have sizeable inductance associated with the resistance of the windings. When measuring the windings of such equipment, special techniques and precautions need to be employed if accurate measurements are to result.

## 2. MEASURING RESISTANCE ASSOCIATED WITH INDUCTANCE:

Electrical laws and principles tell us that when inductance and resistance are associated in a circuit, a transient will occur upon the application of power and that the time constant of this transient will be equal to  $L/R$  seconds, where  $L$  is the inductance in Henries and  $R$  is the Resistance in Ohms. To make measurements in such a circuit, a time constant of several (5 to 9) time constants will be required to settle the circuit before meaningful measurements of resistance can be undertaken. The number of time constants required will depend on the accuracy desired. 5 time constant will provide an accuracy of 1% and 9 time constants will provide an accuracy of 0.1%, approximately.

The error in resistance measurements under unstable or transient condition is all due to the inductance which will have a voltage developed across it equal to  $V=L.di/dt$ , where L is the inductance in Henries and di/dt is the rate of change of current in amperes per second. In order to make an error-free measurement, the inductance must be eliminated from the circuit or the current must remain perfectly steady.

### **3. TRANSFORMERS:**

It should be pointed out that the inductive effects are more serious with large pieces of equipment as large pieces of equipment will have a larger L/R time constant. The above considerations assumed relatively linear inductors, such as are associated with motors, generators or reactors. An additional complication occurs when measuring the winding resistance of transformers. The core of the transformer comprises of a closed magnetic circuit and therefore the winding exhibits a very large inductance. The core must be fully or partially saturated in order to reduce the high inductance and allow the current to flow.

After the current is established one must still wait several time constants before readings can be taken. This time constant depends on the ratio of the residual inductance of the winding and the resistance of the measuring circuit.

### **4. DELTA CONNECTED TRANSFORMERS:**

Delta connected transformers present special problems when their winding resistance is to be measured. This problem is due to the transient current that will be established within the delta connection during the initial transient (start-up) period. As this current is coupled by transformer action to all the windings on the transformer, it must be allowed to die down before accurate measurement can be accomplished. This transient is an additional complication when testing delta

transformers, being relatively large, this transient typically controls the time required to complete a measurement on a delta connected transformer.

It should be pointed out that this transient will occur regardless of which winding is tested (primary or secondary) and regardless of the measuring connection (phase-to-phase-to-neutral). The time constant of the transient within the delta is proportional to the ratio of the inductance to resistance within the delta circuit. This time constant increases with the increase in the KVA rating of the transformer as well as with the efficiency of the transformer.

### **5. SAFETY CONSIDERATIONS:**

Most professional in the electric power field will recognise that there is a danger when testing inductive equipment using Direct Current. The danger is due to the energy that is stored in the inductance ( $E=1/2I.L$ ). This is the energy that must be applied to the specimen upon initiation of the test. The same energy must be dissipated in a safe manner upon completion of the test and before opening of the current circuit. Should the current circuit be interrupted during the test, the stored energy will be dissipated in a High Voltage arc. Such an arc may damage the test specimen, the test equipment or cause injury or death to personnel. The safe dissipation of the energy cannot be stressed enough. Safe ways of disposing of the stored energy include, the shorting of the test specimen (inductance) before disconnection, the use of suitable surge or transient protectors, or by using electronic techniques. Shunt reactors due to their linearity store more energy than transformers and are therefore more dangerous.

### **6. DISCUSSION OF PROBLEMS:**

#### *6.1 INDUCTANCE WITH RESISTANCE*

The inductance typically associated with the measurement of winding resistance of power equipment to be measured causes a transient upon initiation. This transient

may have a time constant of 1 to 100 secs. A delay of 5 to 10 time constants may be required before a stable reading is obtained. This time constant may be effectively reduced by suitable test equipment. This test equipment would provide additional circuit resistance, thereby reducing the L/R ratio i.e. Time Constant.

### **6.2 CORE SATURATION:**

The measurement of transformer winding resistance has an additional complication that of saturating the core to allow the current to flow in the winding. The typical time required to saturate the core depends on the voltage rating of the transformer winding being tested. Thus the test equipment must apply "volt seconds" equivalent to the rated voltage of the winding before any appreciable current will be established. The volt-seconds can be calculated by integrating the area under one half cycle of the voltage and dividing this value by 2. Thus, a winding rated at 100KV at 50 Hz will be rated at approx 450 volt-second while a 100KV, 60 Hz winding will have a rating of 375 volt-seconds, approximately. The 50 Hz winding will need the application of 6 volts for 75 seconds before the current is established. The saturation will occur much faster if a higher voltage is applied. Thus only 15 seconds will be required if a voltage of 30 volts is applied.

It must be pointed out that the above calculations assume no residual flux (residual magnetism) in the core of the test transformer. As the residual flux in a transformer may be as high as 75% of the saturation flux density, the actual time for the current flow may be 0.25 to 1.7 times the calculated value.

To reduce the time required to saturate the core of a high voltage winding, a large test voltage is indicated. The use of a high test voltage will automatically provide a higher resistance in the test circuit that reduces the L/R time constant. At the same time, the use of a higher voltage increases the VA rating and complexity of the power supply.

### **6.3 DELTA CONNECTIONS:**

Transformers with delta connected windings encounter an additional transient and causes a delay due to the L/R time constant within the delta circuit. The test person has little control over this time constant except to try and modify the inductance by selecting a higher or lower test current. IT MUST NOT be automatically assumed that a higher current will reduce the inductance. In fact when testing the low voltage windings of a large transformer, the inductance of the winding will increase with an increase in current, the current in such situations must be reduced or increased past the knee point to effectively reduce the inductance. In numerous test laboratories, the delta connection is opened by means of a test link to facilitate the winding resistance measurement.

## **7. PRACTICAL SUGGESTIONS AND SOLUTIONS:**

### *7.1 MEASURING MOTORS AND GENERATORS:*

The measurement of motor and generator winding should present little difficulty to the test person. Although the inductance of such equipment can be substantial, it can readily be dampened by incorporating resistance in the test circuit to reduce the time constant of the start-up transient. Unless currents in the order of 50 to 200 amperes are used the energy stored in the circuit is modest and does not present a dangerous condition when terminating the test.

### *7.2 USING DIGITAL MULTI-METERS OR OHM-METERS:*

A variety of commercial digital multi-meters or ohm-meters all using a "constant current source" upto 1 amp will work well when used on small power transformers and motor/generators. When the size of the test specimen increases and the L/R ratio increases, the constant current sources within these instruments become unstable and the instrument reading becomes unstable. Instruments that use passive

circuitry (resistors) for controlling the test current will work properly on all sizes of equipment from smallest to the largest. These "passive current sources" waste a lot of power in resistors which convert voltage to current to stabilize the measurement circuit.

### 7.3 KELVIN AND THOMPSON BRIDGES:

The traditional method of measuring low resistance values has been the Kelvin or Thompson bridges. These bridges continue to be used to date to measure the winding resistance of power equipment. When used to measure low resistance values, these bridges would be equipped with a battery and an adjustable resistor to provide the bridge with excitation current. The exact value or stability of the current is not important when making measurements on resistances using a bridge circuit.

However, when measuring the value of resistances associated with inductance, the STABILITY of current is of great importance. If the current is not stable, the operator will determine a "fictitious" resistance. This resistance will be stable over a considerably long period of time and provide the operator with a false impression that he has made an accurate measurement. It is therefore very important to use electronic current stabilizers for the test current in addition to the usual current setting resistor.

An e.g. of a typical "fictitious resistance" measurement is as follows:

Assume a 12V battery source and a 1 ohm current setting resistor that provides a test current of 12 amperes. The battery voltage will fall continuously under the load of 12 amperes and for our example we will assume a fall of 0.010 volt/min (this is a good battery!). This means that the test current will also fall by 0.001 amperes/min. This type of reduction in test current of battery voltage would not be noticeable, as the battery would fall only to 11.400 volts from 12.000 volts after one hour of operation. This continuous current

reduction would allow the bridge to be properly balanced and remain in balance for a long time. The reading of the bridge, however, would NOT BE CORRECT and the error would depend on the magnitude of inductance associated with the sample (winding) being measured.

Assuming that the 11kv winding of a 10 MVA transformer is being measured (winding resistance 30 milli ohms, inductance about 5 Henries) the error in resistance measurement under the above conditions would be - 0.08 milli ohms or 0.25%. It should be noted that the reading will ALWAYS be lower under a falling voltage battery condition and that the error becomes larger for a low-loss transformer (lower resistance and higher inductance)

Calculations:

$$R \cdot I = 0.030 \text{ ohms} \cdot 12 \text{ amperes} = 0.360 \text{ volts}$$
$$L \cdot di/dt = 5 \text{ Henries} \cdot 0.0005 \text{ a/s} = 0.0025 \text{ volts}$$

$$\text{Error} = 0.0025/0.36 = 0.0069 \text{ or } 0.69\%$$

### 7.4 VOLT-METER AMMETER METHOD:

Many find it more convenient to use a shunt and two milli voltmeters to measure the resistance of a winding. By using quality digital voltmeters, one can make measurements over a wide range of resistance provided that a suitable current source and shunt are available. As this method is very similar to the Kelvin bridge, all the advantages, disadvantages and errors that were discussed in section 7.3 are equally applicable here including the "false reading" examples.

### 7.5 THERMAL EMFs:

As typical measurements discussed here involve the measurements of DC millivolts, it is important to take precautions against the introduction of thermal EMFs. This means that ALL connection to be made are copper-to-copper. Quality instruments for this application will have copper binding posts rather than the usual plated brass terminals. Of extreme importance is the connection of the leads to the test specimen.

As these are typically made using clips, ONE MUST use SOLID COPPER clips. Very large errors can be introduced by using "copper plated steel clips", especially during heat run situations where the bushing terminals are hot.

#### 7.6 SELECTION OF TEST CURRENT:

The statements by many in the industry is that "the more current you apply, the faster the reading will stabilize". Although this may be true of many cases, this is NOT true in all cases. For best results, the test current should be selected according to requirements of the test specimen. Thus, when measuring transformer winding resistance, it is desirable to use a current that is larger than the excitation current for that winding. This will tend to saturate the core and reduce the settling time for the measurement. The selected current should be less than 10% of the rated current for that winding, as excessive current will be heating up the winding and causing its resistance to increase. A current of 10% will cause only 1% of the normal heating of the winding. Caution should be exercised when selecting the test current as some manufacturers claim that excessive DC excitation of the core produces undesirable stresses. These stresses are similar to the stresses when a transformer is energized, saturates, and draws in-rush current.

Therefore it may be desirable to limit the test current to 2-4 times the excitation current for the winding being tested. As the excitation currents for larger transformers are typically less than 1% of rated, one should consider test currents in the range of 2-4% rated. This range would increase for medium and small power transformers which draw a larger percentage of excitation current.

#### 7.7 TIME REQUIRED FOR A MEASUREMENT:

There are some individuals in the industry who are asking for a time of only 30 seconds to obtain a proper reading. Although this is readily possible for small or even medium

size transformers, this is very difficult to obtain for large power transformers. The cost for equipment for accomplishing this on large power transformer is rather large and those who are asking for it are not willing to pay the price.

Considering the measurement of winding resistance after a heat run is one of the most demanding application. The items that require time are as follows:

- a) Shutdown of heat run.
- b) Disconnection of heat run leads.
- c) Connection of TWRM-10 leads.
- d) Saturation of transformer and stabilisation of resistance reading.

ANSI C-57 specification allow 4 minutes of time between shut-down and the first resistance reading. This time is reasonable for medium size transformers but becomes unreasonable for the large transformers being manufactured today. The test people are pressed for time so much that they design and procure high current shorting and unshorting equipment for high current windings, as these typically take the longest to connect or disconnect.

Anyway, allowing half of the allowable time for tearing down the connections and connecting the Ohm Meter, the remaining 2 minutes is typically sufficient for saturating even the largest transformers and obtaining a reading with a TWRM-5.

The exception to the 2 minute time would be delta connected transformers. As was explained in section 6.3 there is a transient circulating current set up within the delta and this current must be allowed to decay before accurate resistance readings can be taken. The time constant of this circuit depends on transformer characteristics and is relatively independent of test conditions. It is this precise reason that some manufacturers of large power transformers are providing "a delta link" which can open the delta circuit to avoid the transient condition within the delta for resistance measurement.

## 8. TWRM-10

The Eltel TWRM-10 is a second generation instrument designed especially for measuring the winding resistance of transformers, inductors and other electrical equipment. The TWRM-10 uses current electronic technology to provide a regulated output current of upto 10A in a smaller size and lower weight than the TWRM-5. The TWRM-10 provides, many of the features asked by the users of TWRM-5.

### Some of its salient features are :

Test currents of 10, 1, 0.1, and 0,01 Amperes  
Resistance ranges of 1.9999 milli ohms to 1999.9 ohms

Resolution of 0.1 micro ohms

Two measuring inputs

Provides a safe shut-down system

Provides protection against inductive kickback

With the additional resolution, the TWRM-10 is ideal for measuring winding resistance during heat run in factory tests. Without additional weight the TWRM-10 is as portable as its predecessor the TWRM-5.

### 8.1 TAP CHANGER APPLICATION:

The design features of the TWRM-10 ATWRM-25 makes the instrument especially useful in checking the proper operation of on-load tap changers on power transformers. The protection circuit of the TWRM-10/ATWRM-25 automatically shuts down the instrument if the circuit is interrupted even for a few microseconds. This features is used for checking the proper, make-before-break, operation of the tap changer. The following procedure is used:

a) Connect the winding equipped with the on-load tap changer contacts to the TWRM-10 for measurement.

b) Energise the instrument and obtain a reading.

c) Operate the tap changer over its full range, up and down, while watching the indication of the instrument.

d) If the instrument continues to operate after the up-down cycle of the tap changer, the tap changer operation is proper.

e) The instrument will shut down immediately when a contact of the tap changer is operated incorrectly i.e. causes a break-before-make operation.

## 9. ATWRM-25

The Eltel ATWRM-25 is a high current, digital direct reading Automatic Transformer Winding Resistance Meter. It is designed to measure the DC resistance of circuits associated with large Inductances. It is specifically designed to measure the resistances of highly inductive transformer windings very quickly and accurately. The operation of the instrument is micro-processor controlled and is fully automatic.

The ATWRM-25 test set can measure the winding resistance of any transformer- small or very large, distribution or power, single or Three Phase, star, delta or zig-zag connected. There are four independent measuring channels which can be used to simultaneously measure the DC resistance of upto four windings at the same time.

### OTHER PRODUCTS

- Automatic Transformer Ratio Meters. ■ Automatic 12KV Capacitance & Tan Delta Test Set. ■ Automatic CT/VT Test Sets & Systems. ■ Automatic Tan Delta & Resistivity Test sets for Transformer Oil. ■ Digital Micro Ohm Meters with built in 100A. source
- Relaying Current Transformer Analyser. ■ Transformer Loss Measurement Systems.



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