POWER FACTOR TESTING
OF
ELECTRICAL INSULATION

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1. CONDUCTORS AND INSULATORS.

All electrical power system installations consist of conductors and insulators. The conductors are used to carry the electric current from the location where it is generated to the location where it is used. As most conductors exhibit resistance, the flow of current through such conductors generates heat that increases the temperature of the conductors as well as the insulation that surrounds it. Excessive heating of either conductor or insulation typically leads to depredation and eventual failure.

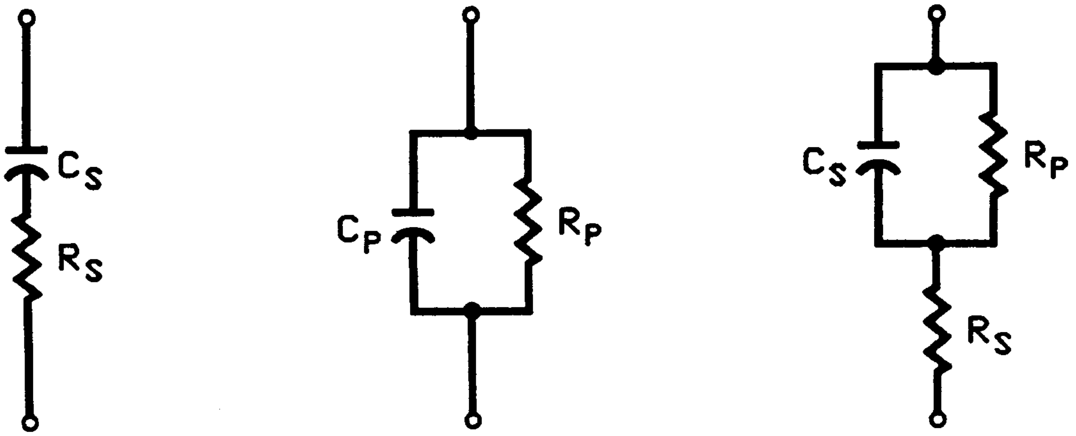
The insulators, on the other hand, are used to support the conductors as well as to separate them from each other and ground. Such insulators are required to withstand the continuous application of specified voltages and to exhibit low losses.

2. INSULATORS AND LOSSES

The primary requirement of insulation used on the power system is not only to withstand the continuous application of system voltage, but also to withstand over voltages and transients that may occur on the power system from time to time.

Another requirement of the insulation is to exhibit low losses. It should be remembered that, unlike losses in conductors that are generated ONLY when there is a current flowing in them. The losses in insulators, although typically quite small in magnitude, occur CONTINUOUSLY as long as there is voltage applied across them. As most utilities claim that their systems operate 24 hours a day, 365 days of the year, the insulator losses amount to a great deal of energy every year. The insulator losses can be considered on the same basis as no load losses (core losses) of transformers, as they need to be supplied continuously as long as the system is operating. The conductor losses can be related to load losses (copper losses) of power transformers, which occur only when there is a load current present.

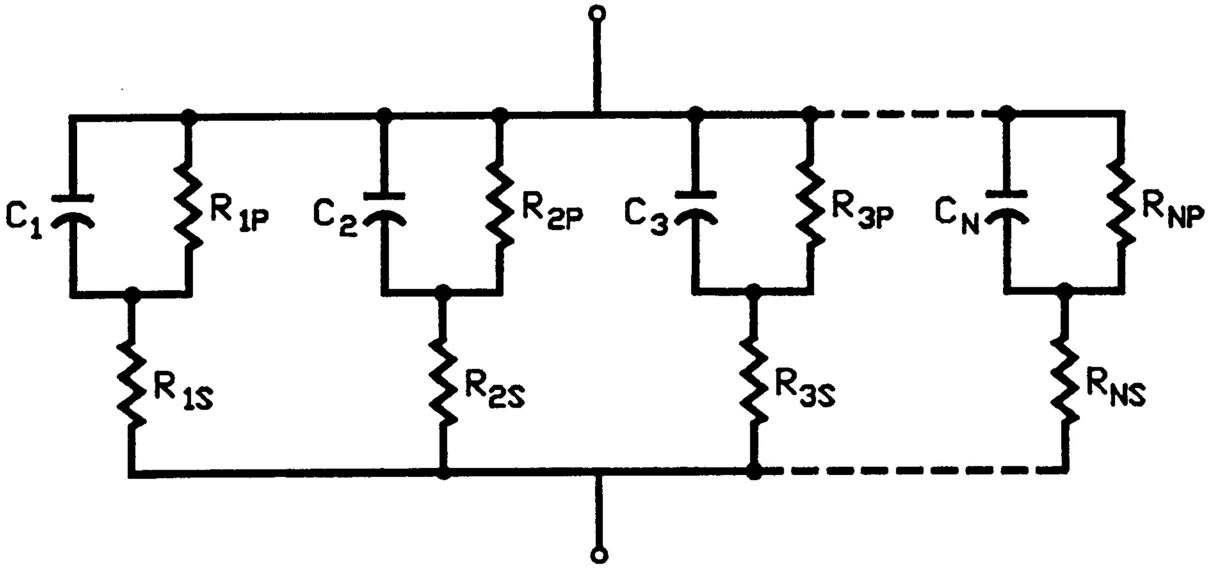
The simple equivalent circuit for an insulator consists of a capacitor in series with a resistor. Some prefer the parallel configuration, where the resistor is in parallel with the capacitor. Neither one of these circuits represents a "real" insulation. The equivalent circuit closest to the truth is that of many capacitors, each one with a resistance in series and parallel, and with each CR combination having a different time constant. These are illustrated in Figures 1A, 1B, 1C, 1D.



A. SERIES

B. PARALLEL

C. SERIES-PARALLEL



D. GENERAL

Figure 1
Capacitance Equivalent Circuits

3. QUALITY OF INSULATION

People in the electrical industry express the quality of insulating materials in terms of POWER FACTOR. This number is very small for good insulation and the smaller the number, the better the insulation. The POWER FACTOR is the ratio of active losses to volt-amperes. This term is not popular in Europe where the term DISSIPATION FACTOR or "tangent delta" is customarily used. It represents the ratio of active losses to reactive losses. For good insulation these numbers are almost equal and are typically smaller then 0.01 or 1%.

The reasons for this difference in customs is that the Europeans typically rely on the Schering Bridge as the means of measuring insulation characteristics. As the Schering bridge, as well as most other bridges, provide a direct readout of DISSIPATION FACTOR, this unit is preferred. On the North American continent, where test sets that measured the active losses in the insulation were devised, the POWER FACTOR was a more suitable unit.

3.1. BULK INSULATION CHARACTERISTICS

Every electrical insulator, be it solid, liquid or gas, possesses certain bulk characteristics. These are the DIELECTRIC CONSTANT, POWER FACTOR and RESISTIVITY.

The DIELECTRIC CONSTANT is the ratio of the capacitance of the electrode system with the insulation in place, to the capacitance of the electrode system with the insulation replaced with vacuum. The dielectric constant of typical insulating materials vary from 1 to about 5, but may be a hundred or more for exotic materials.

The POWER FACTOR of typical insulation varies from zero for insulating gases, to a few hundreds of one per cent for plastics and insulating oils, to a few tenths of one per cent for composite insulating systems.

The RESISTIVITY of insulating materials is typically very high. The resistivity should not be confused with insulation resistance which includes the leakage resistance of the insulation surfaces in addition to the bulk resistance of the material.

3.2. LEAKAGE COMPONENT

The LEAKAGE COMPONENT of insulation resistance is due to the various surfaces of the insulating material. This leakage component is typically much larger than that due to the bulk resistivity of typical insulating materials.

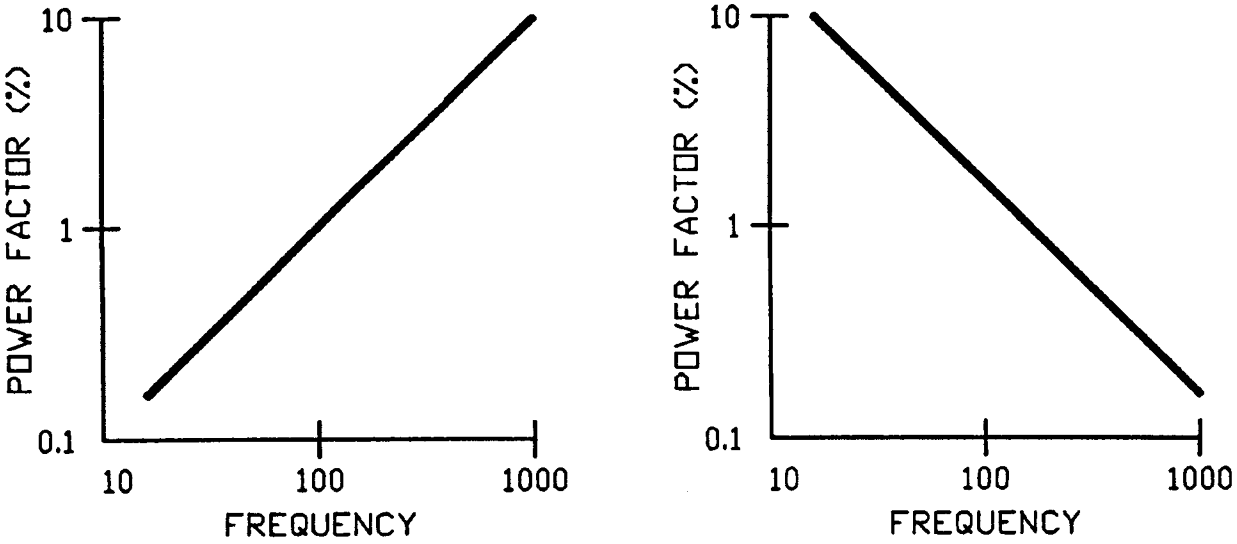
Leakage resistance depends a great deal on the condition and cleanliness of the surfaces involved as well as on prevailing atmospheric conditions. The leakage current of some surfaces can vary several orders of magnitude depending only on atmospheric conditions and the cleanliness of the involved surfaces.

3.3. FREQUENCY DEPENDENCY

The POWER FACTOR of a typical insulating system is not very dependent on the test frequency. Thus the power factor of typical insulation would be approximately the same at 16 ⅔ Hz, the lowest frequency used in power transmission, at 50 Hz, at 60 Hz, and at the low harmonics of these power frequencies. This is especially true of all the modern plastics and insulating oils.

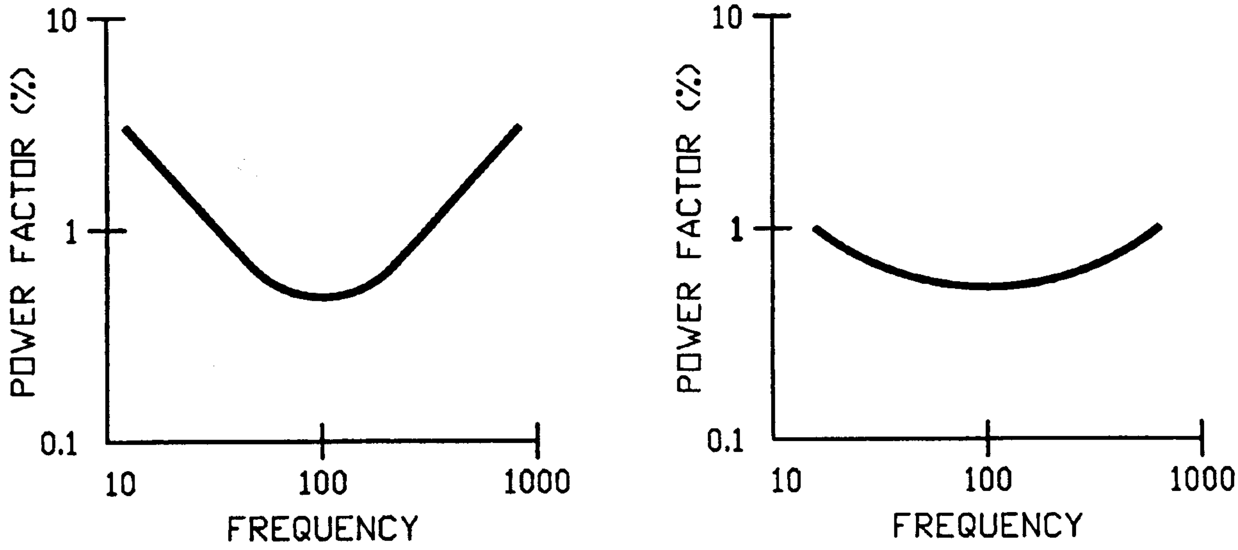
The frequency characteristics of the equivalent circuits shown in Figure 1 are shown in Figure 2. It is obvious from these curves that the simple equivalent circuits do not adequately represent the frequency characteristics of typical insulating materials. The only adequate representation would be that by Figure 1D, with its characteristics shown in Figure 2D.

The relatively flat frequency characteristics of most insulating materials indicate that it is acceptable to test insulation at frequencies other then the power frequency. The advantage of such tests is that it avoids power frequency interference in typical applications.



A. SERIES

B. PARALLEL



C. SERIES-PARALLEL

D. GENERAL

Figure 2
Frequency Characteristics of Equivalent Circuits

It should be pointed out that the frequency characteristics of some insulating systems, such as paper-oil insulation, changes with degradation. This phenomena can be used to assess the condition of such insulation.

3.4. TEMPERATURE DEPENDENCY

All types of insulation exhibit a temperature coefficient of capacitance and power factor. The temperature coefficient of capacitance is not very large and is typically not important. The exception may be the capacitance of CCVT components. Here, the accuracy performance of the CCVT depends on the capacitance remaining stable over the full temperature range of -40 to +140 degrees or more.

The temperature coefficient of the power factor of insulation is much larger than that for capacitance. Typical temperature coefficients of power factor are about 2% per degree (F). The coefficient varies considerably for different materials and may increase an order of magnitude between room temperature and the operating temperature for some materials. It is therefore important to take note of the temperature of insulation when it is being measured and to apply corrections if valid comparisons with previous readings are to be made.

4. INSULATION DEGRADATION

The primary reason for measuring the power factor of electrical insulation is to monitor its degradation and estimate its remaining service life. In this way maintenance on the equipment can be scheduled when required, thus extending the service life and avoiding costly failures and power interruptions. Discussed below are the typical measurements and quantities that are used to estimate or measure the condition of the insulation.

4.1. LEAKAGE

Whenever insulation becomes moist or dirty, it will indicate higher leakage current. This is especially true for equipment that has very little bulk insulation, such as small to medium size motors, dry type distribution transformers and lower voltage circuit breakers. Although often used on larger equipment, the leakage test is not capable of indicating the condition of insulation within high voltage power equipment.

An extension of the leakage test is the polarization index. Unlike the leakage test, the polarization index measures the characteristics of bulk insulation. To carry out a good polarization test will require minimizing the leakage component as the leakage component will reduce the sensitivity and usefulness of the test. The test is usually performed on larger, air cooled, equipment.

4.2. GAS ANALYSIS

As insulation deteriorates, it generates byproducts including gases. By sampling and analyzing these gases one can make a judgment on the condition of the insulation. Gases are typically sampled from gas or oil-paper insulated systems. In oil-paper systems the gases may be sampled from the gas blanket above the oil, or more often the gas is extracted from a sample of the insulating oil. The technique of gas extraction and analysis from insulating oils has advanced considerably since its introduction a few decades ago. Today, experienced individuals can not only detect the presence of insulation deterioration, but can also identify the type of problem that is causing the deterioration.

As do all things, gas analysis has its problems and limitations. As the analysis depends on the generation of gases, the generation of gases and their absorption in oil takes time. Being a cumulative method, it is very sensitive to slow and continuous deterioration of insulation. The method can not identify or locate deteriorating locations or detect serious faults that may destroy the equipment in a relatively short time. One of the main advantages of gas sampling is that the equipment need not be taken out of service.

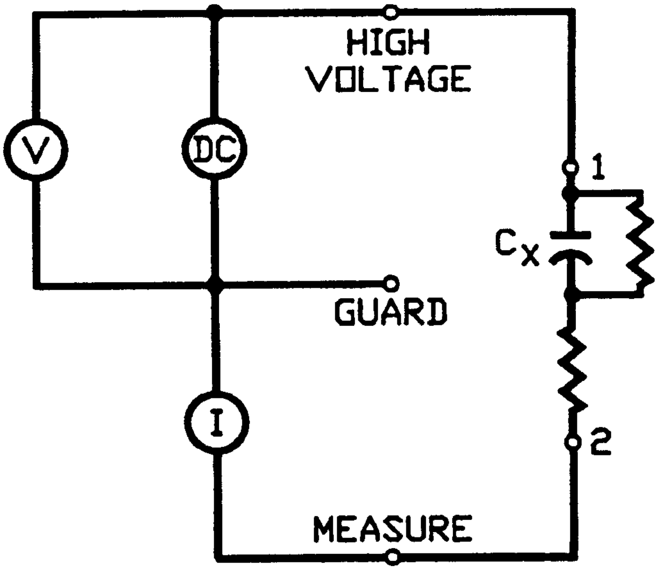


FIGURE 3A
DC MEASURING CIRCUIT

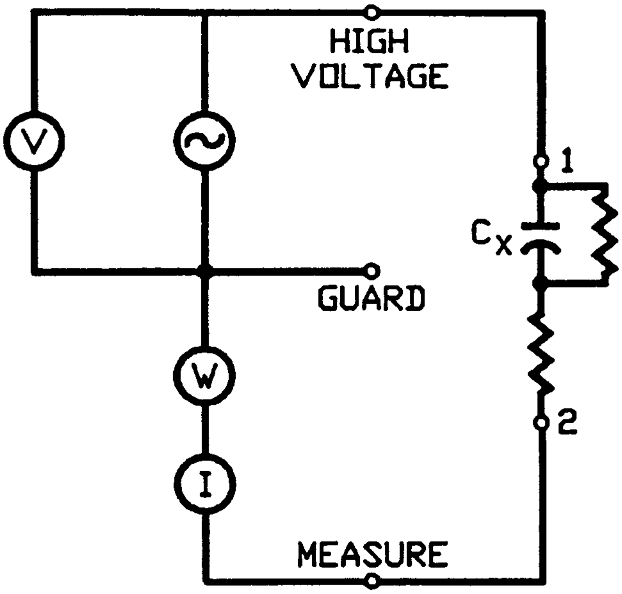


FIGURE 3B
AC MEASURING CIRCUIT

4.3. POWER FACTOR

Monitoring the power factor of the insulation is one of the oldest and most popular methods of assessing the condition of the insulation. One of the reasons for this popularity is its long history and good track record.

Power factor measurements can be carried out at the rated voltage, at the high pot voltage, at a "test voltage" or at more then one voltage to obtain additional information. As test at rated voltage usually require equipment that is not portable, the industry has standardized on "test voltages" of 10kV for equipment rated at higher voltages and 2.5kV for equipment rated at lower voltages.

The popularity of the method is so high that some utilities are continuously monitoring the power factor of some of their critical equipment.

Whenever monitoring power factor for insulation degradation it is important to compare readings taken under similar conditions. This implies the same connections, test voltage, and similar ambient conditions.

4.4. POWER FACTOR TIP-UP

As most insulation will exhibit a change in power factor at different test voltages, this characteristics is a good indicator of the conditions on the measured insulation. Power factor tip-up is referred to as the difference in power factor between a test conducted at rated voltage and a test conducted at half the rated voltage. Some prefer to use the difference between the rated voltage and one quarter of the rated voltage. The result of this test, although very informative, for practical reasons is limited to equipment rated at low voltages. Equipment rated at higher voltages can be tested only in factories, where high voltage and high capacity power sources are available.

The reason that tip-up is such a good indicator of insulation deterioration is that it is caused by partial breakdown of the insulation system. Break down of the voids within the insulation or the material itself will result in the power factor tip-up. As partial breakdown of insulation is occurring in insulation exhibiting tip-up, such tip-up can also be detected by means of partial discharge equipment that measures PD in pico coulombs or RIV in microvolts.

It should be pointed out that it is impossible to obtain a change (increase) in the power factor reading without obtaining a change in the capacitance reading at the same time. The change in capacitance may be very small, however, and not noticeable in the test set.

5. METHODS OF MEASUREMENT

5.1. DC METHODS

The DC methods are used to measure leakage, insulation resistance and polarization index of insulation. The test equipment is rather simple and consists of a power source of required voltage and an electro mechanical or electronic current meter. The power source for measurement of the polarization index must be well stabilized otherwise the results will not repetitive or trust worthy. Instruments for this application always have three terminals, one of them a guard terminal used for bypassing unwanted current from the measuring circuit. A simplified diagram of an instrument for this application is shown in Figure 3A.

5.2. PARTIAL DISCHARGE

Whenever the power factor changes due to the application of a higher voltage, it is very likely that such power factor changes are due to partial breakdown of the insulation. Partial breakdown is synonymous to partial discharges (PD) and can be measured or observed on a PD bridge or analyzer or measured with an RIV meter. The ideal insulation will have the same power factor at different voltages and no PD or RIV will be measured.

5.3. AC METHODS

5.3.1. MEASURING CIRCUITS

A simple circuit for measuring the power factor of insulation is shown in Figure 3B. It very much resembles the DC measuring circuit except for the AC test source and the wattmeter. The problems with such simple circuits is that they are not sufficiently sensitive or accurate for measuring insulation with power factors below a few per cent. It is shown here only for reference purposes. This circuit is very useful in explaining the operation of more complex measuring circuits.

5.3.2. BRIDGES

Bridges such as the Schering bridge have been specially devised for measuring the DISSIPATION FACTOR of electrical insulation. They work best when they are called upon to measure insulation (capacitance) with small losses (low power factors).

Most bridge circuits experience difficulties when called upon to make measurements outside of a laboratory or shop. These difficulties are related to non ideal field conditions. One of these difficulties is making measurements on samples that exhibit low capacitance but a high power factor. Lightning arrestors and cast bushings are examples of such test samples. The difficulty is due to the bridge configuration which has been optimized for measuring samples with relatively small losses. When used to measure samples with large losses, such bridges become insensitive and difficult to balance. In many instances, the bridges can not be balanced because of a finite limit on their dissipation factor range.

Another difficulty of most bridge circuits is their inability to measure negative power factors. Although negative power factors usually do not exist, negative power factor readings are consistently encountered in real measuring situations where some interference is present.

Still another difficulty is the bridge's ability to function correctly when exposed to power frequency interference. In many practical situations the interference can be an order of magnitude larger than the signal the bridge is trying to measure. These conditions make the good characteristics of the bridge circuit difficult to apply.

5.3.3. COMBINATION CIRCUITS

Most measuring circuits operate very adequately when the power factor of the circuit is high, but lack sensitivity and accuracy when the power factor of the measuring circuit is low. This is directly opposite to the situation that one experiences with bridge circuits.

For the above reasons, most power factor test sets use a combination of bridge and measuring circuits to provide the required performance at low power factors and at the same time capability of measuring high power factor samples. One type of test set uses a RL-CR bridge compensation circuitry to improve the performance of their metering arrangement. This circuit operates on voltage summation and is sensitive to power frequency harmonics. The simplified schematic of this test set is shown in Figure 4.

Another type of cancellation circuit operates on the current summation principle. This circuit is very similar to a Schering bridge but as it has the resistive arms replaced by windings of a summation current transformer, it is often called the transformer ratio arm bridge.

When the transformer ratio arm circuit is combined with a measuring circuit, it provides the accuracy and stability of the bridge circuit when measuring insulation exhibiting low power factor. When encountering high power factor conditions, the measuring circuitry is capable of its usual good accuracy.

This type of circuit is used in the **AVO** Multi-Amp ALFA- 10 power factor test set. The evolution of the test set from the AC measuring circuit and the transformer ratio arm bridge is shown in Figure 5.

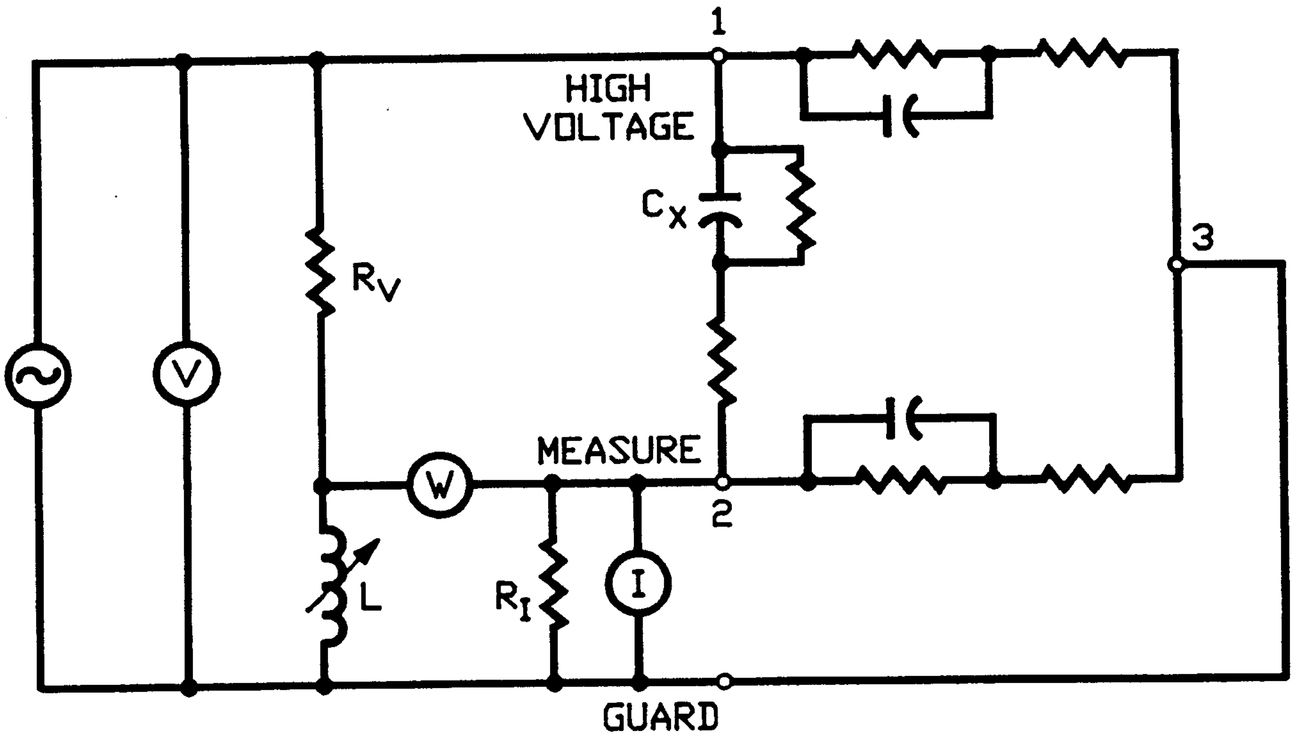


Figure 4
Power Factor Test Set with RC-CL Compensation

6. PRACTICAL DIFFICULTIES

So far we have been discussing the characteristics of electrical insulation and presenting some potential methods of measuring the power factor of such insulation. It is now time to discuss some of the practical difficulties of conducting power factor measurements in the field - the real world.

Unlike the shop or factory measurements, that can all be carried out using the ungrounded specimen test configuration (UST), most measurements in the field need to be carried out using the grounded specimen test configuration (GST). The reason for this is obvious, all equipment on the power system is grounded for safety and operating reasons.

The UST test configuration has two desirable features that should be mentioned. First, anything that is grounded is automatically guarded and therefore does not affect the measurement. Secondly, the configuration inherently possesses a certain amount of interference rejection. This makes the UST configuration the one to use whenever possible and whenever accurate and repeatable results are desired.

Reality will force us to use the GST configuration in majority of the cases and we will have to deal with the disadvantages of this connection. There are two major disadvantage of the GST connection, namely:

- the configuration is very susceptible to electrostatic pick up,
- the configuration requires double shielding construction and double shielded cabling to avoid residual errors.

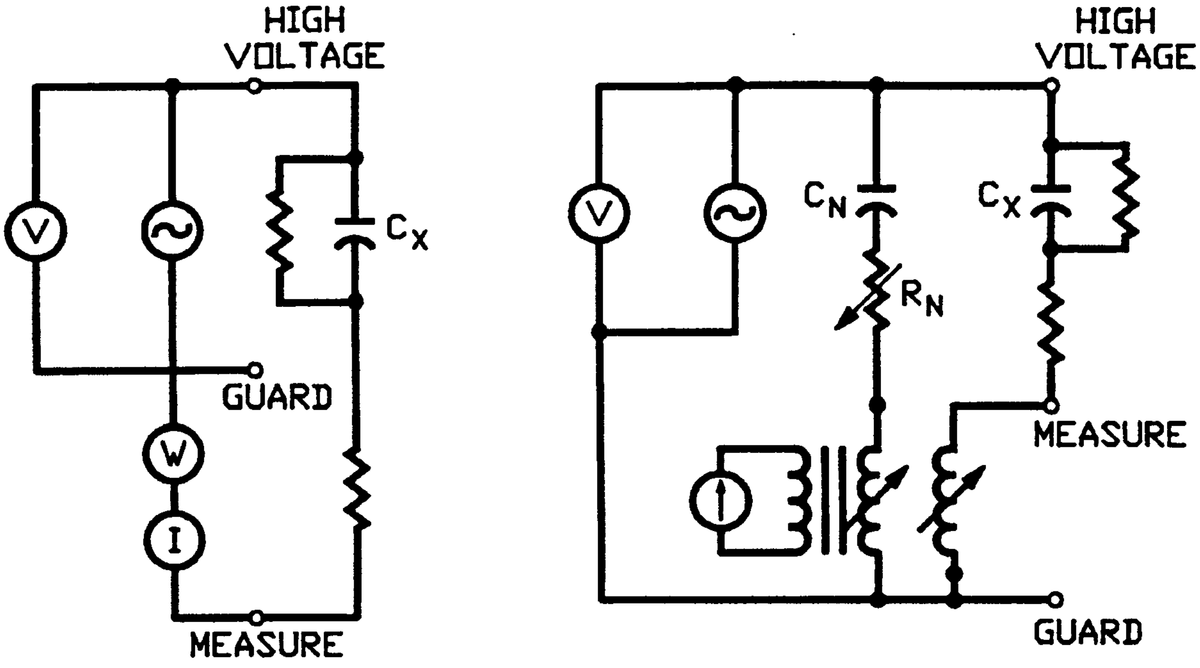
Equipping ourselves with a double shielded test set, we will have to deal with the problems with power frequency interference through electrostatic pick up when it occurs. There are several ways of dealing with interference which include:

- polarity reversal of the test voltage,
- interference suppression by cancelation,
- operating at a different frequency.

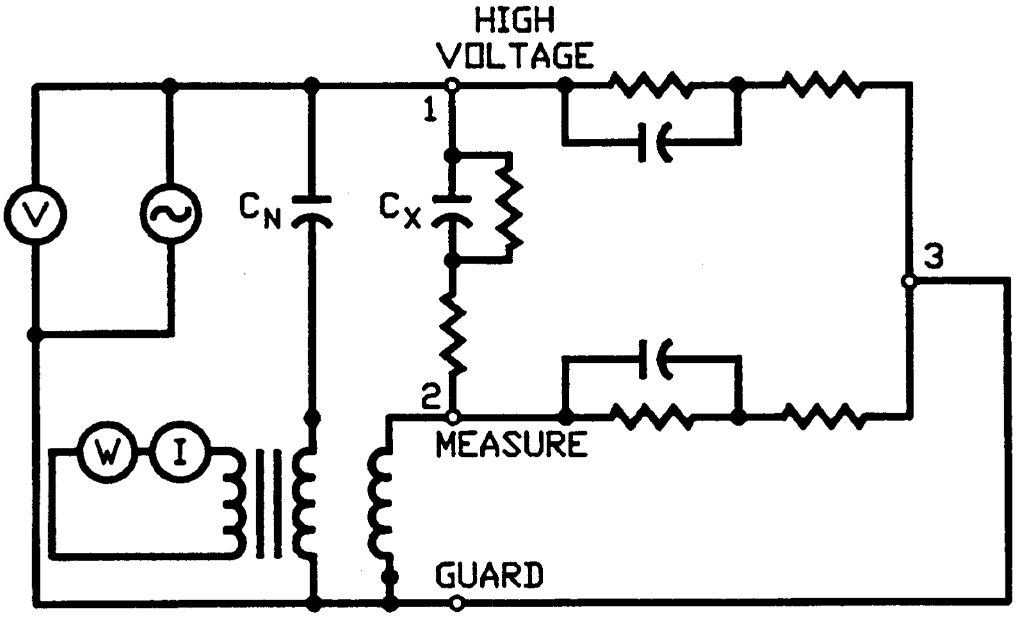
The polarity reversal of the test voltage and averaging of the two test results works quite well as long as the interference current is small when compared to the current the test set is trying to measure. Unfortunately, the interference current in some situations can exceed the current to be measured by a factor of 50 to 1. Under such conditions measurements are impossible to make relaying only on the polarity reversal principle.

Interference suppression by cancellation method relies on setting up a current source that will generate a current equal in magnitude, but opposite in polarity to the one being picked up. The cancellation need not be perfect as one can rely on the polarity reversal method to cancel the effect of the remainder. The additional problem that is encountered when measuring under severe interference conditions is the lack of stability in the interference. As interference is typically caused by energized overhead conductors, the variation of the voltage on these conductors will cause the interference to vary. Both, the interference suppression and the polarity reversal method rely on the interference remaining steady during the measurement period.

The only method that works well under all types of interference, steady or not, is the use of a test frequency that is different from the power frequency. Under such conditions, the effect of the interference can be totally removed from the measurement. **AVO** Multi-Amp has been the only company supplying power factor test equipment operating at a frequency different from the power frequency.



A. MEASURING CIRCUIT B. TRANSFORMER RATIO ARM BRIDGE



C. ALFA-10 POWER FACTOR TEST SET

FIGURE 5
DEVELOPMENT OF ALFA-10
POWER FACTOR TEST SET

7. ALFA-10 AUTOMATIC POWER FACTOR TEST SET

The ALFA-10 Automatic Power Factor Test set has been developed to help simplify the power factor testing of electrical insulation. The test set features many of the above discussed features. We feel that it is the "state of the art" test set and at this time we would like to overwhelm you with some of its characteristics and features.

The ALFA 10 POWER FACTOR TEST SET is an:

- automatic,
- microprocessor based instrument, for
- testing electrical insulation in the
- grounded specimen test, or the
- ungrounded specimen test configurations,
- using minimal operator intervention.

The ALFA 10 POWER FACTOR TEST SET was designed to:

- perform maintenance and diagnostic tests,in the shop, or in the field,
- offering automatic interference rejection and cancellation operation.

The ALFA 10 POWER FACTOR TEST SET features two measuring leads that provide:

- seven automatically conducted tests,
- three UST tests,
- one GST test,
- three GST tests with guard.

The ALFA 10 POWER FACTOR TEST SET was primarily designed to:

- make measurements at 10 kV, but it
- operates over a range of 1 to 12 kV, and will
- measure at a test voltage as low as 250 volts.

Some of the unique features of the ALFA 10 POWER FACTOR TEST SET include:

- measurement of interference,
- excitation current measurement complete with power factor,
- automatic digital correction to the 10 kV test voltage,
- measures with or without interference suppression,
- menu driven software,
- printer output for data recording,
- computer interface for automatic data logging and analysis.

In order to provide the users with the best measurements and most appropriate test results, the ALFA 10 POWER FACTOR TEST SET measures:

- **CAPACITANCE** with a transformer ratio arm bridge and standard capacitor,
- **POWER** with a time division multiplier wattmeter,
- **VOLTAGE** with an RMS responding voltmeter,
- **CURRENT** with an RMS responding ammeter,

The remainder of the required results are calculated from:

- **POWER FACTOR** = watts/volt amperes,
- **DISSIPATION FACTOR** = watts/vars.

The ALFA 10 POWER FACTOR TEST SET has available a full set of accessories which include:

- a guarded 10 kV oil cell,
- fixed inductors to extend charging current to measure capacitances of 0.26 microfarad,
- tunable inductor to allow tests up to 1 microfarad,
- multi lead selector to simplify test on complex equipment,
- calibrator that allows complete verification of the instrument.
- universal lead handling tool that allows measuring leads to be attached to high voltage equipment without the use of a bucket truck.