POWER FACTOR TESTING OF POWER TRANSFORMERS

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GENERAL

Power factor testing of electrical insulation is one of the recognized and highly-regarded procedures in the preventive maintenance process of electrical power aparatus. The power factor of electrical insulation, the ratio of the power loss to the volt-amperes, is a measure of the quality of the insulation. The lower the power factor, the better the condition of the insulation. With this in mind, the electrical power industry is monitoring the power factor of their major system components to avert unwanted failures and outages.

This paper will consider the requirements for equipment to be used for power factor testing, comment on available equipment, discuss problems of interference and outlines procedure and readings to be taken on two-and-three winding transformers.

TEST EQUIPMENT REQUIREMENTS

To say that the test equipment has to measure the power factor of electrical insulation would be greatly oversimplifying the problem. To put the problem in a better prospective one should list and discuss the requirements of the test equipment for this application.

- The test equipment must measure capacitance and power factor of electrical insulation. A measurement of the dissipation factor or power loss is also acceptable, as the power factor can be readily calculated from these values.
- The test equipment must measure insulation that is grounded (GST test) or ungrounded (UST test). This is a real necessity, as practical applications demand such measurements.
- The test equipment must be equipped with an effective guard circuit. As most practical applications involve several interconnected capacitors, it is necessary to separate these into individual sections for analysis. The only practical method of doing this is to be able to eliminate them from the measurement by suitable guarding.

It should be pointed out that there are two types of guard circuits possible. In the HOT GUARD configuration the guard is at the test potential of the test set. In the COLD GUARD configuration the guard is at, or near, ground potential. As the HOT GUARD configuration requires more diligence on the part of the operator, with respect to safety, the COLD GUARD circuit is usually preferred.

- The test equipment must reject or cancel interference. Most practical situations involve measurements near live lines or other power equipment. Such live apparatus invariably interfere with measurements by injecting power frequency interference into the measuring circuit. To allow measurements in the presence of interference, the equipment must have provisions for rejecting or cancelling interference.
- The test equipment must be capable of conducting measurements at the traditional stress levels. As most people in the industry have been making measurements typically at 10 or 2.5 kV, the test equipment must be capable of duplicating these measurements so as not to disturb trend analysis.

AVAILABLE TEST EQUIPMENT

The equipment available for conducting power factor testing is varied. Most of the traditional test equipment were bridges such as the Shering Bridge and the Transformer Ratio Arm Bridge. These are shown in Figure 1 and 2, respectively. Both of these measure the dissipation factor of the insulation being measured, rather then the power factor. The difference between the power factor and the dissipation factor, however, is very small, especially for insulation of good quality, that is for power factors less than 5%. The Transformer Ratio Arm Bridge circuit is more suitable for this application as it offers guard connection that is inherent to the circuit and passive in nature.

To use the above bridge circuits for the measurement of grounded specimen (GST test) such measuring equipment must use double shielded power sources, as well as double shielded high-voltage cables. Only in this way can power line interference and internal residuals be reduced to a value that permits a meaningful measurement.

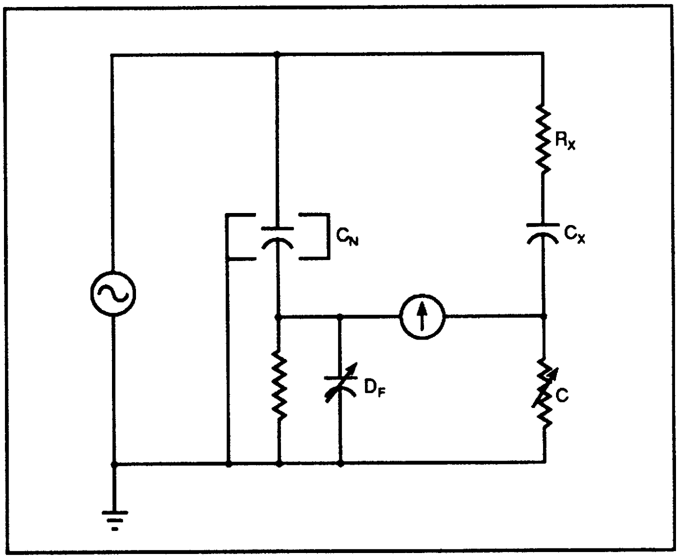

Figure 1. Schematic of a Shering Bridge

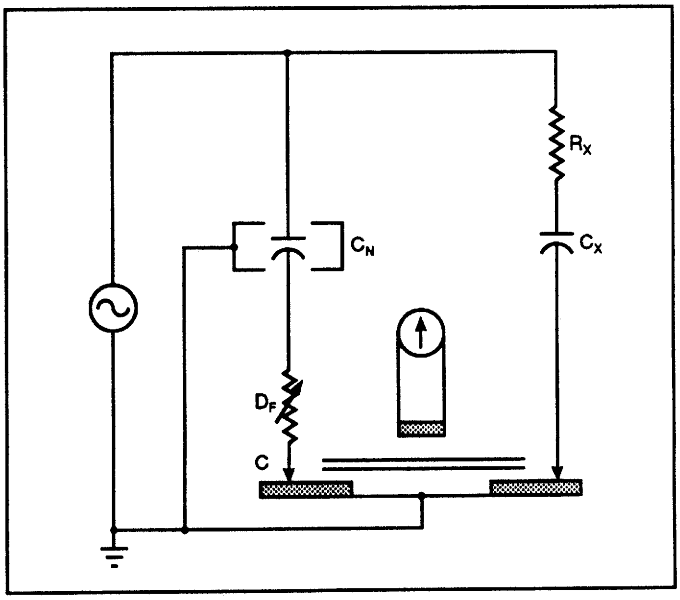

Figure 2. Schematic of a Transformer Ratio Arm Bridge

Over the years many pieces of test equipment were developed and used for this application. Perhaps the most famous of these is the Doble Power Factor Test Set. A simplified diagram of this test set is shown in Figure 3. In reality, this piece of test equipment does not measure power factor, but it does allow the user to calculate the power factor from two measurements. The first measurement is the total current in the measuring circuit. The second measurement is the residual current, after all the quadrature current is subtracted, or cancelled, from the measuring circuit.

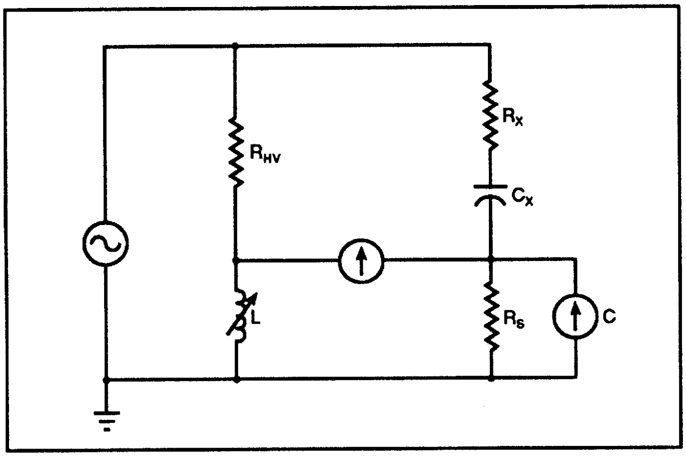

Figure 3. Schematic of a Doble Power Factor Test Set

It is noteworthy to point out that if such a test set is operated at a reference voltage, say 10,000 volts, then the total current in the measuring circuit is proportional to the capacitance of the insulation and the residual current in the measuring circuit is proportional to the power loss. The ratio of the residual to the total current is the power factor of the insulation being measured. Being a readout type instrument, this test set has few controls and is simple to operate.

The Doble set is not without its shortcomings. Consisting of resistances, inductance and capacitance, the test set is sensitive to frequency and accentuates harmonics in the measuring circuit. It must rely on filtering to provide the desired reading.

There are a variety of other developments, each with its advantages and disadvantages. There is the "Cameron Hot Box" shown in Figure 4. This is an Inverted Shering Bridge, where parts of the instrument are at high voltage and the controls are operated with the aid of insulating shafts. Its uniqueness is the use of the internal capacitance between the internal bridge components and the outside case for the reference capacitor. Its shortcomings are its inability to measure ungrounded specimen and the absence of a guard connection.

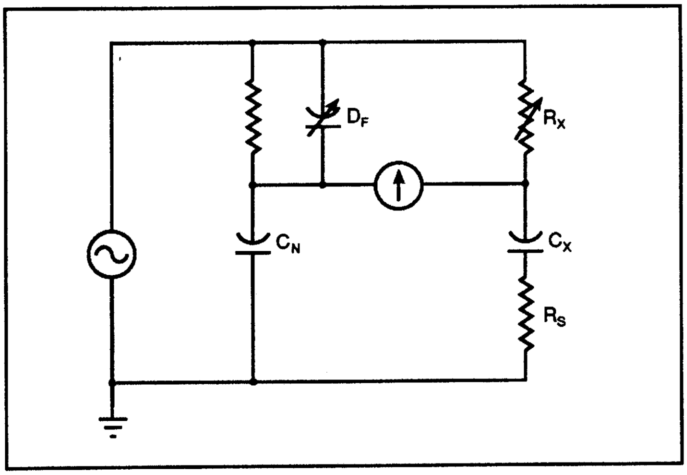

Figure 4. The Inverted Shering Bridge - The Cameron Hot Box

There is the Olman Instruments CB60. This is a transformer ratio arm bridge circuit, of the HOT guard configuration, which could be operated in UST and the GST connections. To operate in the GST connection, the instrument is insulated from ground and the controls are operated by means of insulated shafts, similar to the inverted Shering bridge. This instrument has impressive features such as an effective guard for both UST and GST connections and interference suppression circuitry. Its downfall was the HOT GUARD circuit whose voltage was 10,000 volts when the instrument was operated at 10,000 volts in the GST connection. Figure 5 shows the CB60 in the GST connection. This characteristic made the instrument rather unsafe.

There are other transformer ratio arm bridge circuits introduced by Olman Instruments and Tettex Instruments. All of these feature the COLD GUARD circuit, where the potential of the guard is at or very near ground potential. These instruments are considered to be safer then the HOT GUARD, and therefore readily accepted by the industry. The problem with most of these test sets is that they are full ac bridges, and as such require balancing of the in phase and quadrature components. Under usual field conditions, which may require an adjustment to suppress power frequency interference, the balancing procedure gets to be rather involved. These operating complications are responsible for these instruments not being widely accepted by the industry.

One very desirable characteristic of the transformer ratio arm bridge is that it can be easily configured to cancel or suppress interference. The interference could be reduced, or even eliminated, by injecting current from an internal or external source to one of the windings on the transformer.

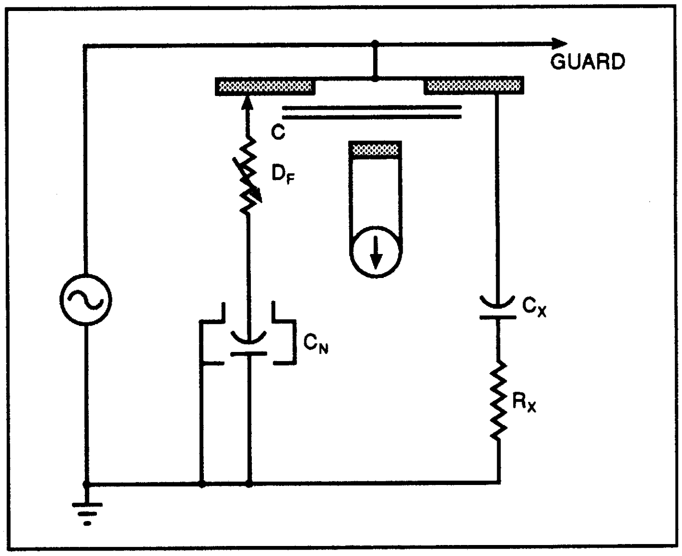

Figure 5. A HOT GUARD Transformer Ratio Arm Bridge

A general characteristic of all bridges is that they are designed to test insulation of relatively low power factors, say below 10%. They are not designed for the measurement of equipment exhibiting high power factors. Lightning arresters, for example, are typically very difficult if not impossible to measure on some bridges, as they may fall outside of the dissipation factor range. This is a definite drawback not only for the transformer ratio arm bridge, but for all capacitance bridge circuit in general.

AUTOMATIC POWER FACTOR TEST SETS

Lately several automated bridges or test sets have become available on the market. All of these make the measurement of insulation power factor easier as the operator no longer needs to be an expert in balancing a two component ac bridge circuit. The automation is even more helpful when interference is encountered.

It should be remembered that the automatic instrument will still suffer from the limitations of the circuitry used. Therefore, the bridge circuit, transformer ratio arm or other configuration, will be limited by its dissipation factor range as was explained above.

At this time I wish to introduce a new instrument configuration. This configuration is very powerful in that it is a combination of a transformer ratio arm bridge circuit and a readout instrument. In its simplest form the instrument can be presented as a measuring system consisting of a voltmeter, ammeter, wattmeter and varmeter. If these instruments were very precise, then the capacitance and the power factor of the measured insulation could be calculated with sufficient accuracy. The accuracy of such a system is very adequate at high power factors, say above 10%, but it becomes progressively less accurate as the power factor is reduced. At typical power factors of good insulation, say 0.5%, the accuracy would be no better than ±100%. Such accuracy is not acceptable for insulation measurement. The disadvantage of such a circuit is that the wattmeter becomes progressively less accurate as it is required to measure power in a low power factor circuit. By combining this readout instrument with a bridge circuit, which inherently is very accurate at low power factor, results in a measuring system that is accurate at any power factor.

The function of the bridge circuit is to effectively increase the power factor at which the wattmeter operates. This is accomplished by cancelling the bulk of the capacitive charging current. The cancellation is accomplished by using current from the loss free standard capacitor which is a part of the bridge circuit. In this way the power factor, and therefore the accuracy of the power measurement, is greatly improved. When taken to the limit of zero power factor, the accuracy of such a configuration is limited only by the power factor of the standard capacitor.

The operation of this type of test set can be also explained as a bridge circuit with part ratio arm balance and part residual readout capability. The capacitance is determined from the settings of the ratio arms and a knowledge of the value of the standard capacitor. The readings of the varmeter are used as corrections to the capacitance determination. The reading of the wattmeter is the true power in the test circuit. This power reading is used to calculate the power factor.

This instrument configuration allows itself to be easily automated. It does not require a complete null balancing procedure involving the in phase and quadrature components. A good portion of the reading can be obtained by simple readout instrumentation. A simplified schematic of the test set discussed above is shown in Figure 6.

INTERFERENCE

The problem of interference has been with us since the time when technicians first tried to make a measurement on a piece of equipment in a live switch yard. Due to its nature, interference is most severe on specimen that are grounded and must be measured using the GST configuration. Interference levels involving the UST configuration are usually an order of magnitude smaller then those encountered during GST tests.

It is interesting to note that the interference that has been affecting everybody's measurements has not been the subject of a study of its own. There are very few people today that can tell you the amount of interference that you should be expecting in a particular situation. As a matter of interest, everyone expects that the highest interference will be present in the highest voltage switch yard. This may not be true. Interference is the product of voltage and stray capacitance. As the stray capacitance is usually lower in a higher voltage switch yard due to the larger spacings, the interference in a 500 kV yard could be the same as the interference in a 345 kV yard. The largest interference is expected to be encountered in low profile stations. Here the spacing has been reduced to a minimum, resulting in high stray capacitance and therefore high interference levels.

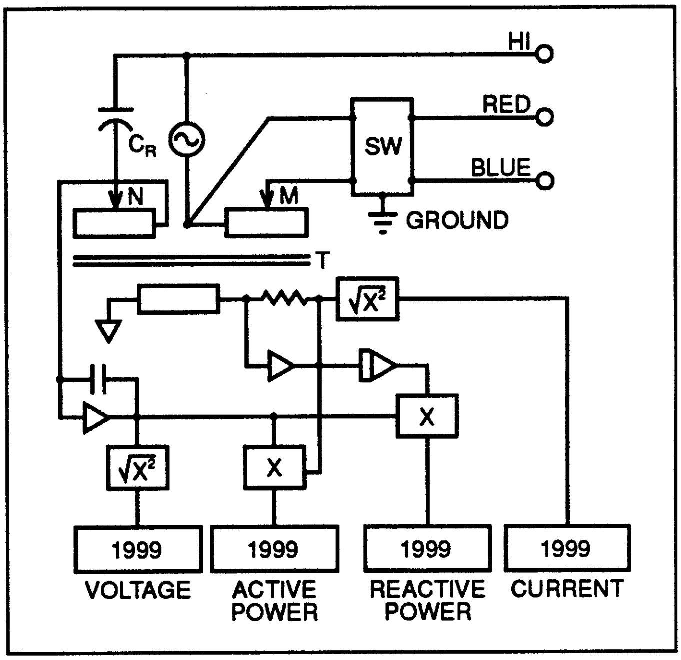

Figure 6.
The Multi-Amp® ALFA-10™ Automatic Power Factor Test Set

It is appropriate to point out that the volt/amp/watt/varmeter measuring system discussed earlier is very suitable for measuring the interference levels in a test situation. To measure the interference, one only requires to shut of the test set's power source. This, for the first time, makes it possible for technicians to measure and keep some statistics on the levels of interference they encounter. This feature is typically not present in bridge type measuring circuits.

INTERFERENCE CANCELLATION AND REJECTION

As indicated earlier, most measurements do involve at least some interference. Depending on the amount of interference encountered, one might use different techniques to suppress their effect on the measurement.

Two available techniques of overcoming the effect of the interference are rejecting the interference or cancelling it. These two methods will be described below.

Interference Rejection.

By choosing a test frequency different from the power frequency, one would be in a position to suppress or even eliminate its effect on the measurement. Depending on the frequency selected, one may find the task easier or harder to accomplish. Thus, if one selects 100 Hz for the test frequency, then the task of eliminating 60 Hz interference signal from the measurement is not very difficult. The 100 Hz test frequency, however, may not be an acceptable frequency for power system applications.

A better selection may be 55 Hz. This frequency is between the two major frequencies used for power applications, 60 and 50 Hz, and would therefore be quite acceptable. The task of rejecting either the 50 or the 60 Hz interference signals would normally be difficult, due to their proximity to the test frequency. Today, however, with the advent of digital signal processing, DS, this task may not be very difficult to accomplish.

The suppression technique is typically limited to a signal to interference ratio of 1 in the measuring set up. Above this level precise correlation techniques and circuits with extreme linearity must be employed. The ratio of signal to interference ratio that can be tolerated will depend on the linearity of the measuring circuitry.

Interference Cancelation.

There are at least two ways of applying cancellation techniques to reduce the effect of interference on the measurement. One of these is to make two measurements, one with forward and one with reverse polarity of the test voltage, and then to average the results to obtain the final reading. As a result of this simple procedure the effect of the interference signal will be greatly reduced or even completely eliminated. This arrangement is simple, convenient, and is applicable to situations where the interference is small, say less than 10% of the total current. Good readings can be obtained even at higher interference levels, provided that the interference is very steady and that the measuring circuit is very linear.

For situations where the interference is higher, say more then 10%, other techniques must be used. One of these is interference reduction by cancellation. As was mentioned earlier, the transformer ratio arm bridge circuit is very convenient for this as it allows the application of a current to any of the windings on the bridge transformer.

In practice, the interference current is measured and a current of the same magnitude but of opposite polarity is injected into the bridge transformer. If accurately done, the interference will be substantially reduced. Some complications with this principle arise due to the stability of the interference and the stability of the cancelling current.

It is not the intention of typical cancellation circuits to eliminate the interference completely. A measurement with forward and reverse test voltage polarity still must be done to obtain a good reading. Interference cancellation principles, together with reading averaging, make it possible to make measurements in situations where the interference is thousands of percent higher then the signal to be measured.

SPECIMEN TO BE MEASURED

As this presentation is focused mainly on the maintenance of transformers, we will consider the measurement of a two winding transformer, the measurement of a three winding transformer and the measurement of bushings.

To facilitate the measurement of insulation power factor, most transformers have all of their windings terminated on bushings even if one of them may be directly grounded. To measure the bushings, these are typically equipped with "Test Taps" that allow the bushings to be measured without disconnecting them from the transformer.

Two Winding Transformers.

The simplified schematic diagram of a two winding transformer is shown in Figure 7. It consist of three components, namely:

- the high-voltage winding to ground capacitance (Ch-g),
- the high-to-low voltage winding capacitance (Ch-l),
- the low-voltage winding to ground capacitance (Cl-g).

The capacitances listed above include the capacitance of the bushings. As the bushings are connected to ground, the high-voltage winding to ground measurement will include the capacitance of the high-voltage bushings. Similarly, the low voltage to ground measurement will include the capacitance of the low-voltage bushings.

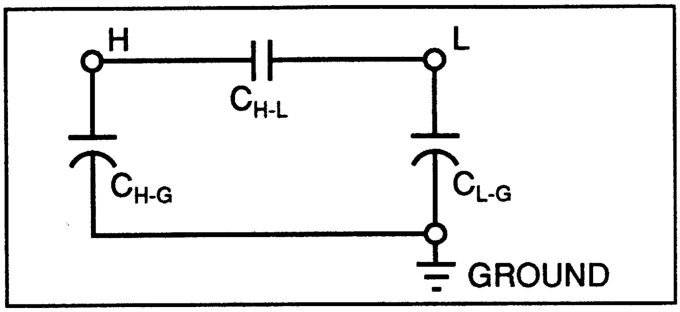

Figure 7. Schematic of a Two Winding Transformer

Three Winding Transformers.

The simplified schematic diagram of a three-winding transformer is shown in Figure 8. Labelling the windings in this transformer as high voltage, low voltage and tertiary, the schematic consists of six components, namely:

- the high-to-low voltage winding capacitance (Ch-l),
- the high-voltage to tertiary winding capacitance (Ch-t),
- the low-voltage to tertiary winding capacitance (Cl-t),
- the high-voltage winding to ground capacitance (Ch-g),
- the low-voltage winding to ground capacitance (Cl-g), and
- the tertiary-winding to ground capacitance (Ct-g).

Similarly to the two-winding example, all the capacitances between the windings and ground include the capacitances of the appropriate bushings.

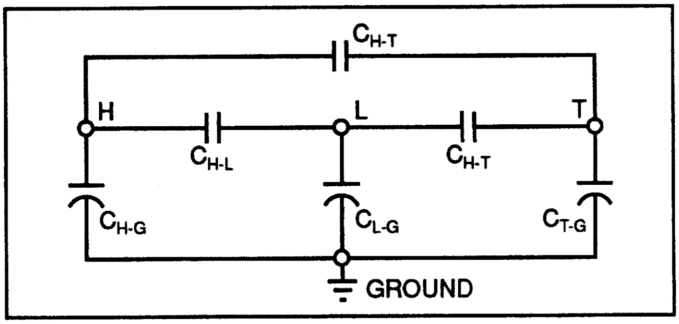

Figure 8. Schematic of a Three-Winding Transformer

Bushings.

The measurement of bushings is a particular connection of the ungrounded specimen test (UST) connection. The schematic of a typical high-voltage bushing is shown in Figure 9. It consists of:

- high-voltage terminal to Test Tap capacitance (Ch-t), and
- Test Tap to ground capacitance (Ct-g).

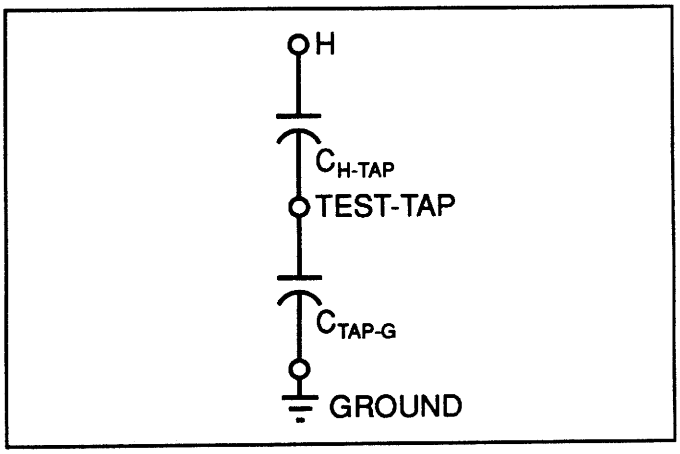

Figure 9. Schematic of a Transformer Bushing

MAKING THE MEASUREMENTS

Whenever making the measurements, it is important to make ALL the possible measurements. This allows one to double-check all the results on the spot and avoid repeats.

To allow for convenient measurement with the fewest possible set-ups, many commercial test sets provide two measuring leads and a variety of test configurations. With two measuring leads, and calling the instrument connections as High Voltage (HV), Red measuring lead (R), Blue measuring lead (B) and Ground (G), it is possible to make the following measurements:

1. HV - R
2. HV - B
3. HV - (R+B)
4. HV - (G+R+B)
5. HV - G
6. HV - (G+R)
7. HV - (G+B)

The listed measurements offer duplication and allow one to check the results. It is suggested that all of these, plus even additional duplicate readings be taken to ascertain good results.

Two Winding Transformer.

It is recommended that, typically, fourteen measurements be done on a single-phase two-winding transformer. These measurements would include the following capacitances:

1. H - L (1)
2. H - G (5)
3. H - (L+G) (6)
4. L - H (1)
5. L - G (5)
6. L - (L+G) (6)
7. TapH1 - H1 (1)
8. TapH1 - G (5)
9. TapH2 - H2 (1)
10. TapH2 - G (5)
11. TapL1 - L1 (1)
12. TapL1 - G (5)
13. TapL2 - L2 (1)
14. TapL2 - G (5)

The above sequence assumes that the high-voltage and the low-voltage bushings have test taps. The sequence, although rather long, is not difficult to conduct. The first three measurements are carried out with one connection, the next three with another connection, and the bushing measurements are done two measurements per connection. Therefore six different connections are required to complete the recommended sequence of fourteen measurements.

It is important to point out the intentional duplication of readings that are taken:

- The H-L capacitance is measured twice independently, and another two times together with H-G and L-G.
- The H-G capacitance is measured twice, once alone and once with H-L.
- The L-G capacitance is measured twice, once alone and once with H-L.

The above duplication allows the operator to quickly double-check any reading on the spot. Some of this checking will soon be done by of personal computers attached to the test sets.

No double checking of the bushing capacitances are possible. The results of the bushing tests should be very similar and this serves as a check in itself.

As noted above, the capacitance measurements of winding to ground include the capacitance of the associated bushings. If the power factor of the bushings is substantially different from the power factor of the total measurement, then one may wish to subtract the readings of the bushings from the total in order to obtain the reading of only the winding. One must not forget that there are two bushings per winding on a single-phase transformer, and three or four of them on a three-phase transformer. Again, this calculation is not difficult to do and can be done by the operator on site.

Three-Winding Transformer

For those who considered the two-winding transformer example to be rather tedious, they will be thrilled by all the readings that are suggested for a three-winding single phase transformer.

Provided that there are bushings to be tested on all three windings of the transformer, then there are 33 tests suggested. These tests measure the following capacitances:

1. H - L (1)
2. H - T (2)
3. H - (L+T) (3)
4. H - (G+L+T) (4)
5. H - G (5)
6. H - (G+L) (6)
7. H - (G+T) (7)
8. L - H (1)
9. L - T (2)
10. L - (H+T) (3)
11. L - (G+H+T) (4)
12. L - G (5)
13. L - (G+H) (6)
14. L - (G+T) (7)
15. T - H (1)
16. T - L (2)
17. T - (H+L) (3)
18. T - (G+H+L) (4)
19. T - G (5)
20. T - (G+H) (6)
21. T - (G+L) (7)
22. TapH1 - H1 (1)
23. TapH1 - G (5)
24. TapH2 - H2 (1)
25. TapH2 - G (5)
26. TapL1 - L1 (1)
27. TapL1 - G (5)
28. TapL2 - L2 (1)
29. TapL2 - G (5)
30. TapT1 - T1 (1)
31. TapT1 - G (5)
32. TapT2 - T2 (1)
33. TapT2 - G (5)

Again, similarly to the two-winding transformer, there are fewer test set-ups as there are readings to be taken. It takes only nine set- ups to do all the 33 tests listed above.

Thus, the first seven readings are taken with the HV lead connected to the H bushing, the next seven with the HV lead connected to the L bushing and the next seven with the HV lead connected to the T bushing. The bushing readings require a different connection for each set of readings for each bushing.

Again one will note the numerous duplications that are suggested. These, together with calculations, will assure that you have a valid set of readings. Each of the main six capacitances are measured twice alone and another six times in combination with other capacitances. This allows for a complete verification of the test results.

Identically to the two-winding transformer situation, if the power factors of the bushings are different from the power factor of the total reading, then the readings of the bushings should be subtracted from the total to obtain the readings of only the winding.

Bushings

The measurement of the bushings is rather simple as there are only two capacitances involved in the measurement. The HV lead is a lied to the test tap which is especially provided on all high-voltage bushings for this reason. The important result here is the Tap-to-conductor capacitance. When in service, it has the system voltage applied to it. The Tap-to-ground capacitance is shorted out during normal operation of the equipment.

One must not forget that if the capacitance of only the winding is required, it is to be calculated by subtracting the capacitance of the bushing from the total capacitance that is measured.

SUMMATION

With the number of readings that need to taken on the two winding transformer and especially on the three-winding transformer, there is ample opportunity for the test person to make errors in connection, reading or transcription. In order to reduce these to a minimum and to ascertain a good set of test results, first time, every time, some degree of automation is desirable.

The modern automated power factor test sets come to the rescue of the test technician. Such test sets are capable of conducting series of measurements, provide printed records of test results, and when combined with personal computers will double-check every reading that was taken and save it in a database for future reference.