THE DEVELOPMENT OF AN AUTOMATIC POWER FACTOR TEST SET FOR ELECTRICAL INSULATION

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ABSTRACT. An automatic insulation power factor test set was designed and developed. The paper presents the requirements for an instrument that would measure the power factor of electrical insulation under all shop and field conditions. A variety of available circuits for such a test set are discussed, and the selected circuitry, as well as the operating software for the test set, are described. Results of some typical measurements are presented.

KEY WORDS. Insulation, Power Factor, Dissipation Factor, Capacitance,Tangent Delta, Dielectric, Watts Loss.

INTRODUCTION

The preventative maintenance programs used by most electric utilities in North America, and elsewhere in the world, involves the periodic measurements of insulation quality of important components of the power system. Such periodic measurements are used to determine the condition of the insulation of the equipment, to assemble a history of the equipment, and to decide on any maintenance that may be indicated to keep the equipment in top working order.

The measurement of insulation quality is referred to by most individuals in the business as measuring the INSULATION POWER FACTOR. It is referred to as measuring the TANGENT DELTA by most Europeans. This work is carried out by means of dedicated test equipment specially designed for this application.

There are several pieces of equipment available in the market that can be used for the measurement of insulation power factor. This paper describes the development of an automatic test set especially designed for this application.

THE REQUIREMENTS

The requirements of a test set are:

* be able to measure the capacitance and the power factor of the insulation of interest, and
* provide the type of information that the test people are looking for.

Both of the above require further explanation.

To say that the equipment has to measure the capacitance and the power factor of the insulation is oversimplifying the task. As most of the equipment of interest is not configured as a simple capacitor, the test set has to be able to measure one component (capacitor) out of a network of components. This indicates a selective type of measurement usually associated with a guard circuit. In addition to this, as most of the equipment of interest is installed on the power system, meaning that it is grounded at the location where it is used, the test set must be capable of measuring both grounded as well as ungrounded specimen. Furthermore, as the measurements are typically conducted in a live station, or at least near some energized equipment, the test set must function properly in the presence of such interference as may be present.

Figure 1 shows the six different components of insulation associated with a three winding transformer. The components are interconnected between four terminals H, L, T and GROUND. The test person is interested in determining each of these components separately, as well as together, for checking purposes. The test set, therefore, must be selective in its measurements in order to accomplish this.

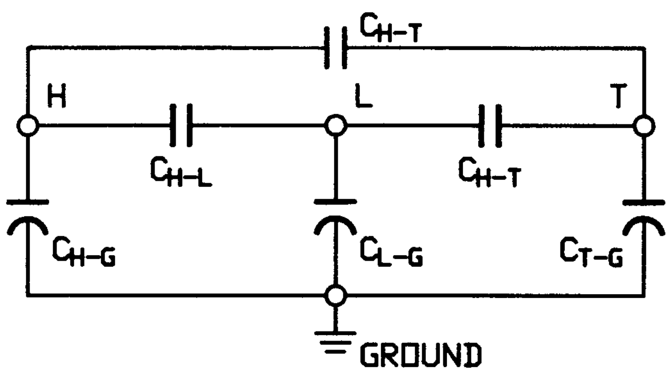

Figure 1. A typical sample to be tested, a three winding transformer.

In addition to the requirements of making the correct measurements, discussed above, the readings of the test set must be compatible with the current practices of the utilities. This means, for example, that even though the test set may measure the capacitance and tangent delta of the insulation, it should provide a reading of the power loss, as this is the quantity that has been traditionally used, and is easier to work with, then is the tangent delta. Furthermore, as most test people have been maintaining their records at a particular voltage, such as 10 kV, the requirement is to continue to provide them with readings of this type in order to maintain a continuity in their record base.

In order to meet most of the requirements of applicable standards and customer expectations, the test set would have to meet the following requirements:

* Test voltage	1 - 10 kV
* Test current	0 μA - 100 A
* Capacitance range	0 pF - 20 μF
* Power factor	0.00 - 100%
* Power loss	0.0 mW - 1 MW

A test set covering the above range would be capable of measuring anything between a small bushing and a sizeable power correction capacitor.

AVAILABLE TEST SET CIRCUITRY

The earliest test circuit used for this type of measurement was the Schering bridge. As the Schering bridge is not very useful for making measurements on grounded specimen, the Inverted Schering bridge was developed and used for this purpose. Another shortcoming of the Schering bridge is its relatively high impedances of the bridge arms, and the difficulty in providing a guard circuit for it.

A circuit more suitable for this application is the transformer ratio arm bridge circuit. This circuit was first used by Hartmann & Braun in Germany[1], and later developed by the National Research Council in Canada into a circuit called the Current Comparator[2]. This circuit was used also by Olman Instruments, the forerunner of MULTI-AMP Canada.

The operating principle of the transformer ratio arm bridge circuit can be described using Figure 2. The circuit consists of a three winding transformer T, a reference capacitor C_R, a power source to excite the test sample V, and an AC null detector ND. At balance, neglecting the loss component, the unknown capacitor is equal to $Cx = C_R \times N / M$.

It should be pointed out that the bridge circuit has tree terminals associated with it. These are labelled Hi, Lo and GUARD.

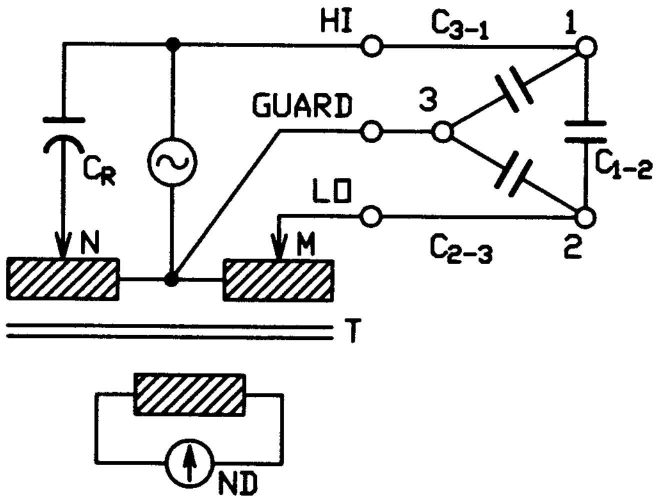

Figure 2. The transformer ratio arm bridge circuit.

With the connection shown, the bridge will measure capacitance C_{1-2}. The capacitor C_{1-3} appears across the power source and is not measured. The capacitor C_{2-3} appears across the N winding of transformer T, and is also eliminated from the measurement as long as the resistance of N is much smaller than the impedance of C_{2-3}.

In principle, the instrument can operate floating or connected to ground at any one of these three terminals. It is important to recognize these three different connections as they play a very important part in the measurement of electrical insulation.

Locating the ground on the Lo terminal configures the bridge into a "Grounded Specimen Test" configuration, or GST. It is identical to having terminal 2 of the test sample grounded. In this configuration any capacitance associated with the test specimen will be eliminated from the measurement as long as it is connected to the terminal labelled GUARD. This configuration is sometimes referred to as the "Cold Guard" configuration, because the voltage appearing on the guard is very low, typically less than 100 millivolts. This configuration is used to measure any capacitance (insulation) whose one terminal is grounded. This includes transformer windings to ground, generator windings, cables, CCVTs, lightning arrestors, and others.

To function properly and with only small residual (zero) errors, in the GST configuration, the bridge supply must be shielded. In our situation, where the supply is a transformer, the transformer must have two shields, one connected to ground, the other to GUARD.

Locating the ground on the GUARD terminal, configures the bridge in to an "Ungrounded Specimen Test" configuration, or UST. A very interesting, and very powerful, characteristic of this configuration is that any capacitance in this configuration that is connected to ground is automatically eliminated from measurement. This configuration is used to measure interwinding insulation in transformers, high voltage bushings with the aid of the capacitance tap, air blast circuit breaker grading capacitors, and other.

Locating the ground on the H terminal configures the bridge into a second "Grounded Specimen Test" configuration. This configuration is similar to the inverted Schering bridge. Although possessing many technical advantages, it suffers severely from practical disadvantages, and is seldom used in the industry. The advantage of this configuration is its ability to reject interference, and to be able to make accurate measurements under heavy interference conditions. The disadvantages of this configuration is the requirement of insulating the comparator transformer for the test voltage, and that the test voltage appears at the GUARD terminal. Because the guard potential is at the test voltage, this configuration is often referred to as the "Hot Guard" configuration. The appearance of high voltage on the guard terminal represents a severe safety hazard, and is the main reason for not using this configuration.

In addition to the Schering and transformer ratio arm bridges described above, there is a variety of other circuits available for this application. None of these, however, are bridge circuits and therefore suffer with respect to accuracy.

TEST SET SPECIFICATIONS

As it would have been very difficult to meet all of the above requirements in a single transportable test set, it was decided to limit the kVA rating of the set. Thus a conscious decision was made to reduce the weight and measuring range of the test set. This of course applies only to the test set proper, as the test set with available accessories will measure the full range of test specimen, as outlined under requirements.

The specifications for the test set include:

*	Test voltage	0.5 - 12 kV
	Accuracy	±1% of reading
*	Test current	0 μA - 0.2 A
	Accuracy	±1% of reading
*	Capacitance range	0 pF - 0.25 μF
	Accuracy	±1% of reading
*	Power factor	0.00 - 100%
	Accuracy	±5% of reading
*	Power loss	0 μW - 1 kW
	Accuracy	±3% of reading
*	Type of measurement	Guarded
*	No of measuring leads	two, Red, Blue
*	Configuration	UST
		GST
		GST with Guard

In order to allow for the measurement of larger values of capacitance, a range extension operating together with an external power supply can be used. The range extension increases the measuring range of the test set by a factor of up too 1000 on current, capacitance, and power.

AUTOMATING THE BRIDGE CIRCUIT

As the transformer ratio arm bridge circuit offered the most advantages, it was decided to automate this circuit for the test set to be described here. A block diagram of the test set is shown in Figure 3, and is discussed below.

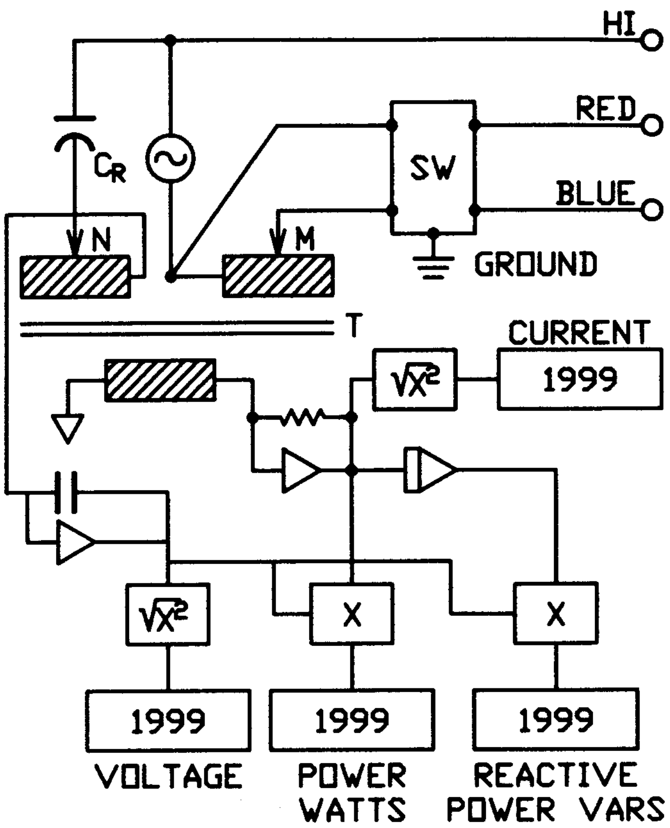

Figure 3. Block diagram of the insulation power factor test set.

Several decisions had to be made regarding the automation of the transformer ratio arm bridge circuit. After considering several alternatives, it was decided to partially balance the bridge, and to obtain the remaining significant digits by means of reading the in-phase, and the quadrature, current components appearing at the null detector.

Thus the bridge transformer is balanced by means of the multiplier (M), and a seven bit in-phase (capacitance) bridge reading (N). The remainder, which includes the rest of the in-phase component, and all of the quadrature component, is read out by means of A/D converters reading the output of multiplying null detectors. All of the required readings are calculated from a knowledge of the above values.

The above combination of part balance and part readout results in an algorithm that is fast and convenient for the variety of readings that have to be taken. It should be pointed out that, the in-phase component is proportional to residual capacitance and that, the quadrature component of the test current is equal to the power in the test circuit, if multiplied by the test voltage.

In addition to the above balance controls, the bridge circuit is automatically configured to the UST or GST configuration, as may be required. In order to allow for convenient measurements of complex specimen, such as the one shown in Figure 1, the bridge is provided with a second Lo, measuring lead, and a switching network that make the following test possible:

	Configuration	Measures	Guards	Grounds
1.	UST	Hi-Red	Ground, Blue	Blue
2.	UST	Hi-Blue	Ground, Red	Red
3.	UST	(Hi-Red)+ (Hi-Blue)	Ground —	
4.	GST	(Hi-Ground)+ (Hi-Red)+ (Hi+Blue)	—	Red, Blue
5.	GST-Guard	Hi-Ground	Red, Blue	—
6.	GST-Guard	(Hi-Ground)+ (Hi-Red)	Blue	Red
7.	GST-Guard	(Hi-Ground)+ (Hi-Blue)	Red	Blue

When considering the specimen shown in Figure 1, the seven test configurations allow for independent and combined measurement of each component. This allows for manual or automatic verification of readings and provides a high degree of confidence if all the readings check out.

BRIDGE READINGS

Perhaps more important than the bridge circuit configuration, users wish to know exactly what and how the various bridge readings are obtained. These are described below.

Voltage.
The test voltage is measured by means of an active capacitive divider and a true rms and A/D converters.

Current.
The test specimen current is measured by means of a true rms and A/D converters. The precision current comparator is used here as a current transformer over a range of microamperes to an ampere.

Capacitance.
The capacitance is calculated from a knowledge of the reference capacitor C_R, the multiplier turns M, the reference turns N, and the residual VARMETER reading.

Power.
The power loss in the specimen is measured by means of a WATTMETER. The wattmeter operates on the time division multiplier principle and works over the full range of instrument current (microamperes to an ampere) using the precision current comparator as a current transformer.

Power Factor.
The power factor of the test specimen is calculated by dividing the measured power by the voltage and current (voltamperes).

Dissipation Factor.
The dissipation factor is synonymous with the Tangent Delta, and is calculated by dividing the measured power by the measured reactive power.

Several items relating to the characteristics of the test set should be pointed out here. If the measurements are conducted on pure since wave voltage, then all of the above listed values can be double checked. That is, by knowing the frequency and the capacitance, one can check the test voltage and current. Under normal operating conditions, however, there are always harmonics present. These may be accentuated by the inductance of the test supply transformer or by the capacitive load. The result is that the measured test voltage and the measured test current NEED not correspond to the capacitance being measured. It must be stressed, however, that the values measured are the values desired by the test people. For example, the power loss is the CORRECT power loss regardless of any harmonic that may or may not be present. In this respect this test set differs from a conventional bridge circuit which can be nulled ONLY at the fundamental frequency.

INTERFERENCE SUPPRESSION

The in situ test conditions always results in some power frequency being coupled onto the measuring circuit, and interfering with the measurement. There are several ways of eliminating the effect of this interference, and include:

- using a test frequency other than the power frequency,

* using the average of two readings, one with forward and the other with reverse test voltage polarity,
* using some form of interference cancellation circuitry.

As the test set was to operate at a reasonably high voltage, and the power supply requirements are sizeable, the use of a dedicated test frequency was quickly eliminated. This left us with using either the averaging of readings, or interference suppression.

In many of the test situations the interference amounts to only a few percent of the signal current. Under these conditions, the effect of this interference can be easily eliminated by means of averaging two readings, one with a forward and the other with a reverse polarity of test voltage. This is one of the operating features of the developed test set.

There are situations where the interference is about the same order of magnitude as the test signal. This typically occurs when measuring the bushings on a high voltage transformer that is situated under a live bus or line. Interference levels in the order of 20 to 100% of signal level have been encountered in such situations. Under such operating conditions the averaging method, or the interference suppression circuitry, may be typically used with equal success.

There are other situations where the interference may reach 10 to 50 times the signal level. Such situations are encountered when measuring high voltage air blast circuit breakers, that are located under live sections of station bus. In such situations, the interference level ranges from about 10 times for the outside pole, if no bus is connected; to about 50 times for situations where there is a sizable length of bus connected to the outside pole. Under such conditions the averaging principle does not work as the result is the difference between two large numbers. The measurements would have to be taken with extremely high precision in order for the result be meaningful. The use of an interference suppression circuitry is necessary if acceptable results are to be obtained under interference conditions of this magnitude.

The interference suppression is accomplished by injecting a signal to the circuitry that is equal in magnitude, and opposite in polarity, to the interference that is encountered. To do this, the interference current is first measured, then a signal of the required magnitude, and opposite polarity, is set from a quadrature (sine-cosine) oscillator. The quadrature oscillator is highly stabilized, and synchronized to the power line.

It should be pointed out that this test set is the only test set known to be able to quantify the amount of interference experienced during a measurements. Using this test set, the maintenance personnel will be able to judge by themselves the accuracy of their measurements knowing the amount of interference experienced.

SAFETY CONSIDERATIONS

In addition to working in the proximity of high voltage equipment, the test set itself is generating a voltage that may be lethal to a person. Whenever working with the test set in a live yard, the operator must adhere to all applicable safety conditions, especially those that individual utilities have. I am going to concentrate only on the safety features of the test set.

The safety features of the test set include:

* double ground interlock
* zero start feature
* safety hand or foot switch
* safety interlock plug
* panel warning lights
* remote warning lights
* over temperature protection

Most of these features do not need explanation, except perhaps the double ground interlock and the zero start feature.

To assure the presence of a ground on the test set, it must be grounded through the power cord (U ground or twist lock) as well as by means of a separate ground conductor connected to the metal case of the instrument. A detector circuit measures the continuity of these two grounds, and will prevent the application of test voltage if there is no continuity.

The zero start feature works together with the safety switches to supervise the application of test voltage. The release of the safety switch not only removes the test voltage, but also drives down the control, and necessitates the re-starting of the test voltage from zero.

PHYSICAL CONSIDERATIONS

The handling and shipping characteristics of the test set can be argued to be as important as the electrical characteristics. This is because the test set must be taken from site-to-site, where it has to be set up and used. The ease of set up, and the packing and shipping of the test set, received much attention.

The final packaging decided upon was a metal cased instrument mounted inside a tough plastic case by means of shock absorbing spacers. In order to make the test set readily portable, the bridge portion and some of the leads are housed in one case that weighs about 80 lbs. The power supply portion and the high voltage lead are housed in an identical case weighing some 120 lbs. When assembled for use, the bridge portion is mounted on top of the power supply portion, and interconnects with it through a set of mating connectors. When thus mounted, the control portion of the bridge is elevated to a height that is convenient for the operator to use, and view the LCD display.

The test set can also be mounted in a vehicle for mobile use, or in a rack or test table for a stationary application. For such applications, the test set's portions need not be mounted on top of each other, but can be mounted in any convenient manner, and interconnected with an optional interconnecting cable system.

OPERATING SOFTWARE

The test set's software is menu driven and consists of several portions. The menu appears on a four line, eighty digit LCD display, and is activated by the operator with the aid of sixteen switches located about the display.

In the beginning the operating software warns the operator about out-of-limit conditions, such as:

* open ground
* open safety interlock
* voltage control not at zero
* over temperature

After satisfying the above, the software allows the operator to:

* select the desired tests for his application
* set the required test voltage
* conduct the test or series of tests
* check the results
* print the test results

The selected tests can be any one, or all seven tests listed earlier. These tests can be conducted with the interference suppression disabled or enabled, depending on requirements, and circumstances. For difficult situations, a continuous screen printout is available. This printout is useful in analyzing readings, measuring interference, and checking the functioning of the instrument.

The basic measurement consist of:

* reading the voltage
* reading the current
* determining approximate capacitance value
* setting multiplier M
* setting balancing turns N
* reading the power
* reading residual vars

* calculating the values for the forward polarity of test voltage
* reversing the polarity of the test voltage
* setting the same values for M and N as above
* reading the power
* reading the residual vars
* calculating the values for the reverse polarity of test voltage
* calculating the average, or final, results for the test

The same procedure is followed for any other connection that may be programmed.

If the interference suppression feature is enabled, then the instrument:

* measures the interference, and
* sets cancellation circuits;

prior to the actual measuring process. As different amounts of interference may be present on different connections, the interference is measured and cancelled prior to each connection.

In addition to conducting the actual measuring process, the software calculates the equivalent 10 kV readings, if required by operator, regardless of the test voltage during the test. The actual, or equivalent 10 kV readings, can be printed out or sent to a personal computer for analysis, logging, or report preparation.

The resident software is also used during the set up and calibration of the test set. This includes continuously looping routines that allow the calibration of the measuring circuits, as well as the adjustment of the interference rejection circuitry.

THE RANGE EXTENSION

Out of all the accessories available for the test set, the Range Extension Adaptor is the most interesting item, and is described below.

In principle, the range extension adaptor is a precision current transformer that scales the measured current. The scaling must be precise with respect to both ratio and phase, so that the accuracy of the measurement is not compromised.

The interesting characteristics of the range extension, is that it is insulated for a test voltage of 12 kV. When used, it transforms a grounded specimen test into a ungrounded specimen test. This is shown in Figure 4. It was pointed out earlier that to make an accurate grounded specimen test, the bridge supply transformer must be shielded. Double shielding reduces residual, or zero, errors by a large factor and is used on the supply transformer of the test set. When conducting tests on large grounded specimen, such as a generator windings, an external supply of high voltage must be used. The use of the range extension, which converts the GST into UST, allows one to use an ordinary supply transformer that is not shielded. This connection is therefore very convenient and greatly improves the accuracy of such measurements.

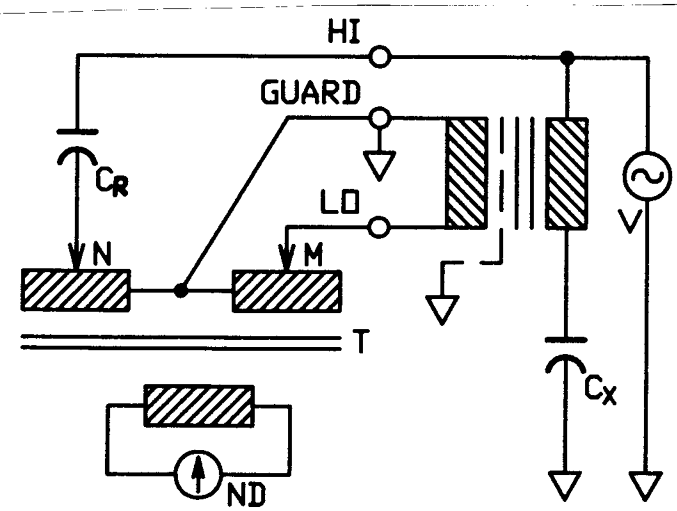

Figure 4. The use of external power source and extension transformer.

It should be stressed that the connection discussed here is available only for larger specimen, typically 0.05 microfarad and larger, as it is difficult to design and build accurate CTs for lower currents.

OPERATING EXPERIENCE

To date six instruments of the type described here have been built and extensively tested under field conditions. These were shipped by air and truck from test site to test site, and suffer little or no physical damage, or operating faults. This speaks well of the tough plastic case and the shock absorbing suspension for the instrument.

The measurements that were made were as varied as those normally encountered in the insulation power factor field. Some of the more interesting measurements involved a shielded high voltage power transformer and the measurement of the grading capacitors and support column of a 735 kV air blast circuit breaker.

The results, at 10 kV, on the shielded power transformer provided results of 963 pF and 90 mW for the high voltage winding to ground insulation, and 0 pF and 0.2 mW for the insulation between the windings that is shielded (or guarded). These values were very close to those expected from historic measurements.

The results on the outer pole of a 735 kV air blast circuit breaker were very interesting, as it was situated under a live bus, and subject to substantial interference. Both grading capacitors were measured at about 2300 pF and 600 mW loss in the UST configuration. These values were obtained with about 15% interference present, and the measurements conducted with, and without, interference suppression gave identical results.

The column of the circuit breaker was measured at 43 pF and 40 mW loss in the GST guarded configuration. It must be pointed out that the interference level in this connection was 1500% higher than the measured signal. This large increase (in percentage) in interference is due to the reduction of the test specimen (from 2300 to 43 pF) as well as the fact that some interference cancellation occurs inherently in the UST configuration of the test set.

The measured value of 43 pF was high by 15 pF. This higher reading was expected, as the test set has a residual (zero) capacitance of about this value in the GST configuration. It is planned to apply the residual value as a correction to the test set GST readings in software.

CONCLUSIONS

We set out to design and build an automatic insulation power factor test set that would be user friendly and capable of measuring electrical insulation under all field and shop situations.

We believe that we have accomplished our goal, as production prototypes of the test set have been used, with good results, under a variety of favourable and unfavourable field and shop conditions.

REFERENCES

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BIOGRAPHY

Oleh Iwanusiw was born in Ukraine. After emigrating with his parents to Canada he studied electrical engineering at the University of Alberta, obtaining his B.Sc. degree in 1957. Upon graduation he joined Ontario Hydro and worked at the W.P.Dobson Research Laboratory for 21 years. Working in the Instrumentation and Standards section, he was involved in the full range of electrical measurements, both in the laboratory and on the power system.

In 1979 he joined Olman Instruments as the President and Technical Director, and was in charge of the companies research and development activities. Upon the sale of the company to Multi-Amp in 1985, Oleh Iwanusiw became the Vice President of Multi-Amp Canada, and the Manager of the New Products Development Department.

Oleh Iwanusiw is a member of the Association of Professional Engineers of Ontario and IEEE.