THE MEASUREMENT OF TRANSFORMER CHARACTERISTICS AND POWER LOSS

by

Oleh W. Iwanusiw, P. Eng.

OLMAN INSTRUMENTS LIMITED
445 Finchdene Square
Scarborough, Ontario
CANADA M1X 1B7

Presented at the

IEEE Transformers Committee Meeting

Los Angeles, March 30, 1982

ABSTRACT

The classical voltmeter-ammeter-wattmeter method, using traditional instruments and instrument transformers, is reviewed and its shortcomings outlined. This is followed by an outline of an electronic metering system capable of accurately measuring the characteristics and power loss of power transformers over a wide range of current and voltage. Appended to the paper are descriptions and specifications for a polyphase metering system operating over the range of 0-5000 amperes and 0-250kV.

INTRODUCTION

The method of power transformer characteristics and loss measurement to be described here is rather ancient and should be well known. It is the classical voltmeter-ammeter -wattmeter method. The equipment that is described however, is very up to date and capable of high accuracy over a wide range of voltage, current and power factor.

THE VOLTMETER-AMMETER-WATTMETER METHOD

This method is probably the oldest and most widely used method used to measure the characteristics of electrical equipment including transformers. Two possible connections for the method are shown in Figure 1 and Figure 2. When used on equipment with linear characteristics, and testing with a source of low distortion, only the voltage, current, and power need be measured. When used on transformers, the method typically consists of measuring at least four quantities. These are the rms voltage, the flux voltage, the rms current and power. Additional quantities of interest are peak voltage and peak current.

Both the rms and the flux voltages are measured so that the magnitude of harmonic distortion in the test voltage can be appreciated and applicable corrections made. The measurement of peak voltage helps to determine the harmonic distortion more accurately. A knowledge of the peak current and flux voltage during open circuit tests allows the manufacturer to determine the exact operating point of the core material.

Traditionally, the rms voltage and current is measured using either a dynamometer or a moving iron instrument with their characteristic square-law scales. The flux voltage is measured with a moving-coil-permanent magnet movement associated with a copper oxide rectifier. The wattmeter for power measurement typically uses a dynamometer movement. The peak values were traditionally not measured due to the lack of peak responding instruments.

The limitations or drawbacks of the voltmeter-ammeter-wattmeter method using traditional instruments are many. These included in the dynamic limitations of the ammeters and voltmeters, due to their square-law scale. This necessitates the use of many ratios of instrument voltage and instrument current transformers. It would not be uncommon to have available ten different ratios on the current transformers, and ten different voltage transformers to cover the current up to 5000 amperes and voltage up to 120kV. To change ratios it would be necessary to change connections on a multi-ratio transformer, or actually substitute one instrument transformer for another.

The measurement of transformer core loss presented few limitations. The power factor of this test circuit being in the range of 0.1 to 0.4 allowed the use of conventional, unity power factor, or the low power factor (20%) wattmeters. The most serious limitations of this test circuit was a possibility of a low wattmeter indication. This would be due to the unavailability of a suitable voltage or current range to match the test circuit.

The measurement of copper losses presented many problems. This would be especially true when testing large power transformers where the test circuit power factor may be 0.01 or even lower. This would result in an indication of only a few divisions even on the most sensitive (low power factor) instrument.

To be accurate, the test results have to be corrected for the errors of the instruments and instrument transformers used. The voltmeters and ammeters must be corrected for the scale errors of the instruments as well as for the ratio correction factor (RCF) of the associated instrument transformer. The correction of the wattmeter is much more complex and needs to be corrected for:

- scale error of wattmeter,
- phase error of wattmeter,
- ratio error of current transformer,
- phase error of current transformer,
- ratio error of voltage transformer,
- phase error of voltage transformer.

The corrections due to the phase angle errors are more important than those due to the ratio errors at the low power factor under consideration here. To complicate the situation the ratio and phase errors of the instrument transformers are load and current or voltage sensitive, and have to be accurately determined from tables or graphs. The correction can be a good fraction of the wattmeter indication if instrument transformers of commercial, instead of precision, accuracy class are used in the measurement. If the instrument transformers of ANSI 0.3 accuracy class are used then the total phase angle correction due to their allowed phase angle defect could be as much as ±33 minutes. This results in an uncertainty of ±100% of measured power at 0.01 power factor. One can see that the scale errors of .25% accuracy class wattmeter are rather small when compared to the possible phase angle errors of instrument transformers in low power factor circuits.

To be able to make accurate power measurement at low power factors one must have available accurate and clibrated instruments and instrument transformers. A phase angle uncertainty of only 1 minute on the CT, PT and wattmeter may result in a total error of ±9 percent when measuring power at, a power factor of 0.01.

In addition to the errors of the instruments and instrument transformers, one must examine and correct for the power losses in the measuring equipment. This can be readily seen in Figure 1, where the power reading should be corrected for the I^2R losses in the current transformer and the current circuit of the instruments. The losses measured in Figure 2 should be corrected for the V^2/R losses in the voltage circuit of the instruments. These corrections, although appear small and trivial, can amount to a percent or two in very low power factor test circuits.

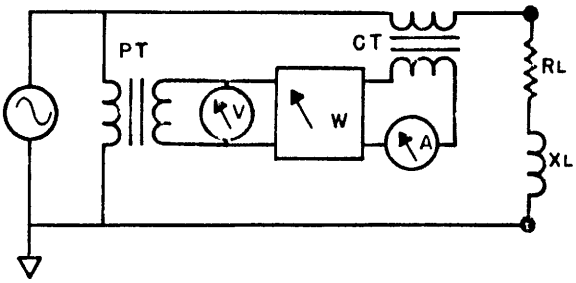


FIGURE 1

VOLTMETER-AMMETER-WATTMETER CONNECTION 1

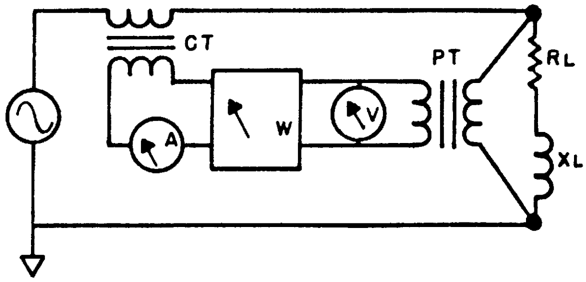


FIGURE 2

VOLTMETER-AMMETER-WATTMETER CONNECTION 2

The circuit shown in Figure 2 is usually preferred because the voltage measurement can be performed directly at the terminals of the test specimen eliminating all lead-drop errors from the measurement. The lead-drop errors are usually larger than the losses in the voltage or current transformers discussed above.

In summary, one can say that the accurate measurement of losses using conventional instruments and instrument transformers require numerous corrections. Many of these corrections are voltage, current, and burden sensitive and therefore vary from set-up to set-up. Needless to say, the instruments and the instrument transformers need to be calibrated on all ranges and possible burdens so that tables of corrections can be prepared.

THE MODERN VOLTMETER-AMMETER-WATTMETER METHOD

With the advent of solid state technology and a judicious choice of current and voltage sensors, it is possible to improve the voltmeter-ammeter-wattmeter method substantially. By using electronic rather than electro-mechanical meters, the burdens on the instrument transformers can be reduced dramatically, typically from watts to milliwatts or even microwatts. This automatically reduces the error and improves the linearity of the primary voltage and current sensing equipment.

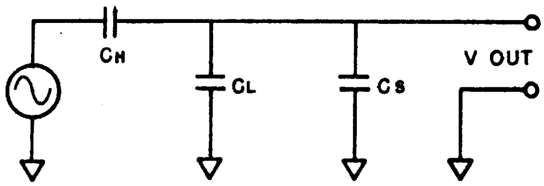
Instead of an electrodynamometer ammeter or voltmeter cunsuming about 5 volt amperes at full scale deflection it is possible to use a solid-state, rms responding, voltmeter or ammeter that requires only milliwatts of signal power. In addition to the power reduction, the solid state instrument can offer improved accuracy and precision due to digital presentation.

Similarly, for power measurement, the electrodynamometer wattmeter which consumes typically 2 volt amperes in both current and voltage inputs, can be replaced with an up to date time-division multiplier wattmeter. This type of instrument not only reduces the power consumption from the sensors but will substantially improve the accuracy of power measurement.

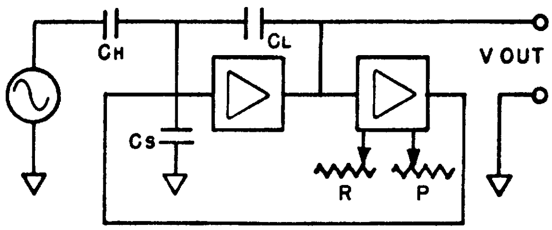
The choice of primary sensors is also very important. Practical voltage sensors include:

- magnetic voltage transformer,
- capacitive voltage transformer,
- capacitive voltage divider,
- amplifier aided capacitive divider.

The first two of these are capable of supplying substantial power to the load, but are rather limited in linearity when operated outside their range. The second two offer improved linearity and accuracy but are limited in their output capacities. Of special interest is the amplifier aided dividers shown in Figure 3. One of its desirable characteristics is that it is not sensitive to stray capacitance and that its ratio and phase errors can be easily adjusted to zero.



A. CONVENTIONAL



B. AMPLIFIER AIDED

FIGURE 3

CAPACIVE DIVIDERS

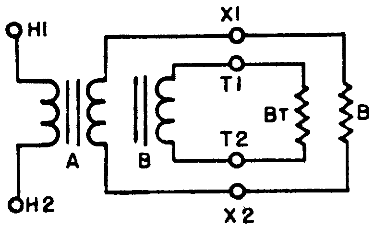
Practical current sensors include:
- shunts,
- current transformers,
- compensated current transformers.

Shunts are useful only for single phase measurements where they can be located at or near ground potential. Current transformers are the most acceptable sensors for current and can be designed to meet very stringent accuracy and load requirements. Even the best of these, however, are limited in their dynamic range to about 100 to 1.

The compensated current transformers do offer improved linearity and accuracy. The type of compensation used, makes them more suitable for one or another applications. Some of the more suitable configurations include:
- two stage design,
- zero flux design,
- amplifier compensated design.

The two stage design of Brooks and Holts /1./ is the oldest, but for some reason has been forgotten by the industry until about twenty year ago. A properly designed two stage CT is capable of extremely high accuracy and very wide dynamic range. In addition, the error curves of a two stage CT are very flat and change very little with the load current. The CT is illustrated in Figure 4. The operation of the two-stage current transformer can be explained as follows. The transformer is wound in such a way that the difference in ampere-turns between primary (H_1 - H_2) and secondary (X_1 - X_2) is applied to core B and results in a current in the tertiary winding (T_1 - T_2).

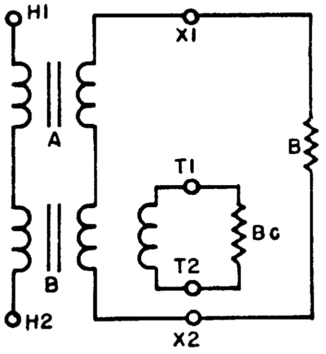
FIGURE 4



TWO-STAGE CURRENT TRANSFORMER

When properly burdened, and assuming and error of 1 percent for each stage of the transformer, the secondary current will be 99% of ideal. If the tertiary now supplies 99% of the remainder, the overall accuracy of the transformer will be in the vicinity of 0.01 percent. The above operation is maintained provided that the windings are burdened individually.

FIGURE 5



ZERO-FLUX CURRENT TRANSFORMER

The zero flux current transformer of Hobson /2/ is capable of high accuracy. Its error compensation depends on the adjustment of a compensating burden, the similarity of core characteristics, and the tracking of the service and compensating burdens. It is shown in Figure 5. When properly adjusted, the voltage developed across the compensating burden Bc is equal and opposite to the voltage drops in the secondary circuit. This results in a low flux density in core A and therefore a high accuracy.

There are several arrangements of the amplifier aided CT possible. The most accurate would appear to be the combination of a two-stage current transformer and amplifier according to Saunders /3./ as shown in Figure 6. Its main advantage is that it does not require special burden arrangements and can be loaded with one common burden. It provides the same accuracy as a two-stage transformer.

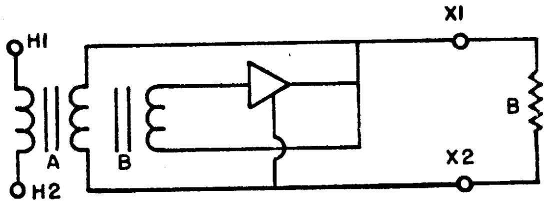


FIGURE 6

AMPLIFIER AIDED, TWO-STAGE CURRENT TRANSFORMER

METERING CONNECTIONS

The loads to be considered here are:
- two-wire, single-phase,
- three-wire, three-phase,
- four-wire, three-pahse.

According to theory, one requires only one set of instruments for the single-phase circuit, two sets of instruments for the three-phase circuit, and three sets of instruments between the required metering connections.

According to practice, however, one should never use the two-element connection (two sets of instruments) for metering the three-wire, three-phase circuit under low power factor conditions. The reason for this is that in the two element metering scheme, each line current is associated with a line-to-line voltage. This voltage is shifted by +30 degrees for the other element. The resulting net reading is the difference between two large numbers. The net reading can be in error by a very large amount when one of the large numbers is in error by only a small percentage.

The example indicates that it is very important to use only the three-element connection (three sets of instruments) for metering both the three, and the four-wire, three-phase circuits.

Example:

Line current	- 1000 amperes.
Line-line voltage	- 14,400 volts.
Power factor	- 0.01
True power	- 250 kW.
Rdg. of Wattmeter #1	- +7325 kW.
Rdg. of Wattmeter #2	- -7075 kW.
Difference	- 250 kW.

It can be readily seen that even a small error in individual wattmeter readings will result in a substantial error in power measurement. An error of 1 percent in either wattmeter will cause an error of approximately 30% in power determination.

THE MODERN POLYPHASE METERING SYSTEM

The polyphase metering system to be discussed here is designed to operate over the current range of 0 to 5000 amperes and voltages of 0 to 250 kV. The system is also designed to avoid the shortcomings of the traditional voltmeter-ammeter-wattmeter method. The major improvements are as follows:

- current and voltage ranges switched from front panel.
- linear voltage and current sensors requiring no corrections over the designed range of voltage and current.
- accurate power measurement with full-scale values at power factors down to 0.01.
- digital presentation of readings.
- frequent updating of all readings (½ second).
- provision for obtaining all three-phase readings simultaneously.

The major components of this system shall be described below as will the reasons for their selection.

CURRENT SENSORS

The current sensors in the system are two stage current transformers. They were selected because of their wide dynamic range and small errors. The current sensors are accurate to a few parts per million on the highest range (5000A) reducing to 0.02 percent on the lowest range (5A). The two-stage CT is capable of this high accuracy over this wide dynamic range because one of the cores is used to supply power (internal losses, lead losses, burden), while the other core supplies the required precision. The two stage CT is rather insensitive to loads on individual windings. For this reason the load common to both windings is maintained low and constant.

Each CT is also equipped with a test winding. This winding is used during the calibration of the equipment as well as during routine accuracy tests.

VOLTAGE SENSORS

The voltage sensors selected for the system are amplifier aided capacitive dividers. The high-voltage capacitor uses a concentric geometry. This construction is used because of its stability of capacitance with respect to time and temperature. This geometry also results in a very small capacitance voltage coefficient. The capacitors are filled with SF_6 gas to give them the required insualtion strength, to be loss-free,and to be corona free up to the specified voltage. Each voltage range has its own amplifier, low voltage capacitor arm and necessary adjustments.

THE METERING UNIT

The concentric measuring capacitor and the two stage current transformer are combined together into one assembly - the high voltage metering unit. The unit is SF_6 gas pressurized with the gas providing insulation both for the capacitor and the CT. The design of the units is such that they will withstand the specified voltage even if the insulating gas pressure is reduced to atmospheric. Three metering units are used in a polyphase metering system.

ANALOG CONDITIONING EQUIPMENT

Electronic analog computing circuitry is used to process the signals from the two stage current transformer and the measuring capacitor to provide the required outputs. The required outputs are:

- voltage - rms reading.
- voltage - average responding (flux voltage).
- current - rms responding.
- power.

A block diagram of the analog computing circuitry is shown in Figure 7. The first stage in the signal processing chain is to normalize the signal levels. The voltage and current signals are normalized at 5 volts at full scale of each available range. These normalized signals are available to the user for waveform monitoring purposes. The rms voltage and current measurement are performed by means of monolothic integrated circuit rms converters. These convert the 5 volt normalized signals to DC by computing the true root-mean-square value of the applied waveform. In the configuration used, the converters operate correctly up to a crest value of 2.6 at full scale. The crest value increases at lower signal levels.

The flux voltage is measured by means of a precision rectifier. The configuration used eliminates non-linearities due to rectifier characteristics by means of feedback.

The power is measured with the aid of a time division multiplier circuit. In this circuit the signal from one of the inputs is chopped according to a pulse-width modulated signal proportional to the other input. The average output for each cycle of the carrier frequency is proportional to the area under the curve. This is proportional to the instantaneous product V;I, which is the power in the circuit.

The time-division multiplier circuitry, used as part of the equipment, is an improvement over circuitry normally used in commercial time-division multipliers. The improvement consists of double-pole, double-throw (DPDT) chopping rather than single-pole, double-throw (SPDT). This arrangement cancels many of the residuals and results in improved and stability. The carrier frequency used in the multiplier is in the order of 3600 Hz, which is sufficiently high to accurately account for the harmonics in the voltage or current circuits.

The output of each of the converters is applied to a three pole Bessel filter which results in quick response, no overshoot, and low ripple. The filtering in the output of the multiplier is heavier than the others, so that low ripple is obtained even at low power factor power measurements. It should be pointed out that the ripple of the multiplier is proportional to volt-amperes. This results in the ripple being ten times higher at 0.1 power factor, and hundred times higher at 0.01 power factor, than the ripple at 1.0 power factor.

The accuracy of all the converters is 0.1 percent.

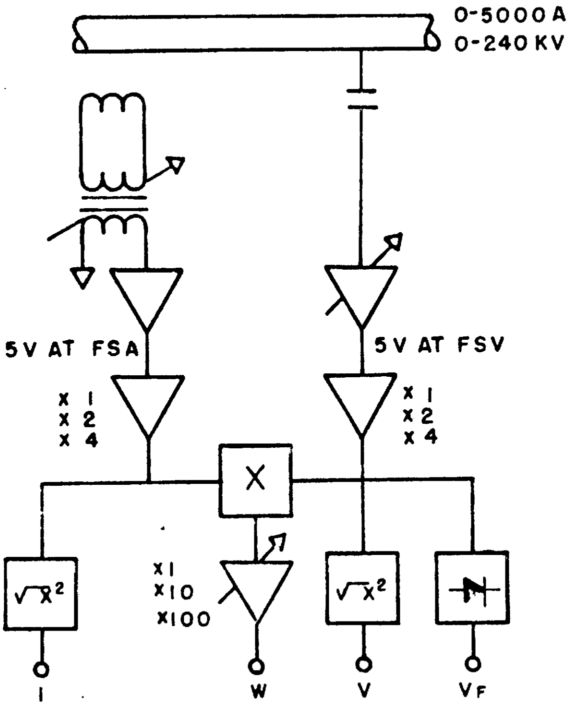


FIGURE 7

ANALOG CIRCUITRY BLOCK DIAGRAM

DIGITAL COMPUTING CIRCUITRY

The heart of the digital equipment is a micro-processor computing system. This computer performs the following tasks:

- controls A/D converters,
- drives the displays,
- communicates with the keyboard,
- performs required scaling and other arithmetic functions,
- optimizes the voltage, current and power ranges,
- communicates with the printer.

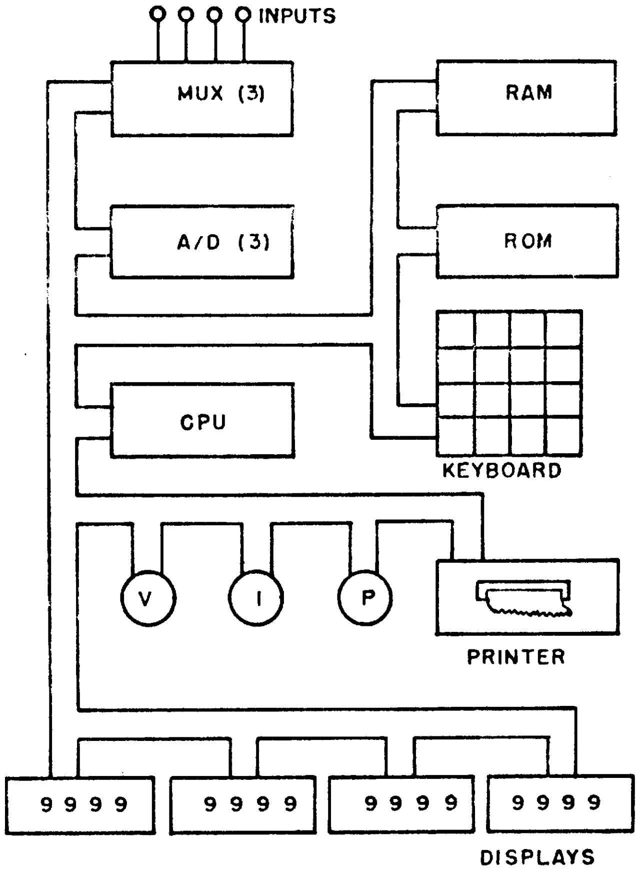


FIGURE 8

DIGITAL CIRCUITRY BLOCK DIAGRAM

Under normal operating conditions the readings are updated twice every second. The operator can monitor the quantities for one phase, or the average of the three-phase values, and at the same time have the opportunity to printout the monitored, or all three-phase quantities. When commanded to print, the quantities stored in the memory are printed. All of these are accessed within a half second of each other even though it takes the printer about 20 seconds for a complete printout.

ADJUSTMENT, CALIBRATION and CHECKOUT

The provision of test windings on the measuring current transformers greatly simplifies the adjustment and calibration of the circuitry associated with current. This is not possible for the voltage circuit, however, each voltage range must be individually adjusted against a calibrated reference standard voltage transformer. Routine checks on the accuracy of the equipment can be performed by applying 100 volts and 5 amperes to external input terminals. This checks out all the electronic equipment except for the amplifier-aided voltage dividers.

Once adjusted, the equipment can be tested out on low power factor loads of known characteristics. In the past, power factor correction capacitors have been used for this purpose. A number of these can be tested with a transformer-ratio-arm bridge, and then used in series, parallel, or series-parallel configuration to check the accuracy of the system on several voltage and current ranges.

PERFORMANCE

When properly adjusted, and in good operating condition, the equipment is capable of measuring the voltage, current, and power in a single-phase, or three-phase circuit with an accuracy of 0.3 percent. The accuracy of the power measurement reduces to 4 percent at 0.01 power factor.

DISCUSSION

The metering system has the following advantages over conventional CT's, PT's, and instruments:

- the ratio and phase errors of the current sensors are very small and can be neglected.
- the ratio and phase error of the capacitive dividers are linear and can be adjusted to be very small or zero.
- the current and voltage measuring ranges can be changed easily by means of a switch on the control panel.
- the measuring instruments provide high accuracy from 10 to 90% of range.
- one operator can obtain a simultaneous set of all single or three-phase readings.

REFERENCES

1. H.B. Brooks and F.C. Holtz "The Two-stage Current Transformer". AIEE Transactions, Vol. 41, June 1922, p. 382.

2. T.M. Sauders "Wide-band Two-stage Current Transformer of High Accuracy". AIEE Tran Transactions, Vol. IM-21, No. 4, November 1972.

3. A. Hobson "Instrument Transformers". Journal IEE, April 1944, Part II.

AUTHOR

Oleh W. Iwanusiw was born in Ukraine in 1935. He received most of his education in Edmonton, Alberta, where he graduated from the University of Alberta with a B.Sc. degree in electrical engineering in 1957.

Since graduation he held the position of instrumentation engineer at the W.P. Dobson Research Laboratory of Ontario Hydro. In that position he has been involved in most aspects of electrical measurements. This included the maintenance of electrical standards, calibration of electrical instruments and instrument transformers, and the measurements of characteristics of electrical power system equipment and components.

Since 1978 he holds the position of president and chief engineer of OLMAN INSTRUMENTS LTD. In this position he directs the research and development efforts of the company in the field of instrumentation for the electric power industry.

APPENDIX

HIGH VOLTAGE METERING EQUIPMENT

GENERAL DESCRIPTION

The high voltage metering equipment is suitable for conducting factory tests on electrical equipment, especially single-phase and polyphase transformers.

The equipment consists of three basic components:

1. High voltage metering units (3).
2. Electronic processing unit.
3. Data acquisition and display unit.

The high voltage metering units, one for each phase, consists of a gas insulated capacitor and a current transformer. Gas, rather than other dielectric, is used in the voltage measuring capacitor because of its stability and low loss. The vessel containing the concentric capacitor is also used for insulating a two stage current transformer. The two stage current transformer makes accurate current measurement possible over a very wide dynamic range.

The electronic processing units converts the signals from the capacitors and CT's into direct current signals proportional to:

Voltage (RMS)
Current (RMS)
Power
Voltage (average)

The DC outputs drive analogue panel meters and supply signals to micro-processor controlled data acquisition and display (DAD) system. The DAD system:

- scans and digitizes the DC signals.
- drives the four digital displays.
- drives the printer.
- provides automatic auxiliary ranging.

The displays are controlled by means of a front panel switch and can display the per phase values (A, B, C) or the three-phase average values. The three-phase values are computed from the individual phase readings.

The printer can print-out the values indicated on the displays or it can print-out all sixteen values.
In addition to the above functions, the micro-processor modifies the gain of the replica signals so that the converters operate at their optimum signal levels. The automatic gains for voltage and current are a factor of 1, 2, and 4, for power they are 1, 10, and 100.

The automatic gain settings are indicated by means of pront panel LED indicators.

SPECIFICATIONS

1. High Voltage Metering Units

High voltage metering units are available for maximum operating voltages of 70, 140 and 250 kV and currents up to 5000 amperes. The metering units are designed to operate corona free up to the rated voltage, (coronal less than 10 pC), and to withstand a high-pot test equal to the rated line-to-line voltage.

Approximate dimensions of the metering units are as follows:

	70 kV	140 kV	250 kV
Length	64	96	132 in
Diameter (max)	16	28	42 in
Mounting Centres (min)	48	72	96 in

2. Electronic Processing Unit

The electronic processing unit contains:

- buffers to provide 4 voltage ranges (3 ranges plus external input) on each phas phase.
- buffers to provide 5 current ranges (4 ranges plus external input) on each phase.
- RMS converters for voltage and current.
- average (flux) converters for voltage.
- power converters.

The unit also provides replica outputs of the voltage and current signals for viewing on an oscilloscope.

3. Data Acquisition and Display Unit

The data acquisition and display unit performs the following:

- scans the 4 values on each phase.
- updates four digit displays twice every second.
- provides data for printer.
- provides automatic sub-ranging for voltage, current and power.
- accepts keyboard input relating to date and serial number.

The controls on this unit include:

- power ON-OFF.
- current range switch.
- voltage range switch.
- line-to-line: line-to-ground voltage measurements selector,
- keyboard - 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, .,
  - print 1 phase readings
  - print 3 phase readings
  - date
  - serial number
  - clear

The printer requires about 20 seconds to print-out complete three-phase data on 2¼" heat sensitive paper. The data printed out is that residing in the computer memory at the time of print command.

4. Accuracy

The accuracy of the metering equipment is:

- ±0.3% on current measurement.
- ±0.3% on voltage measurement.
- ±0.3% on power at 1.0 power factor.
- ±0.6% on power at 0.1 power factor.
- ±4% on power at 0.01 power factor.

The accuracy of the replica signals are within ±0.1% in magnitude error and less than 1 minute in phase error.