THE APPLICATION OF CURRENT COMPARATORS IN INSTRUMENTATION FOR LOSS MEASUREMENTS

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ABSTRACT

A current comparator technique, applied to several auxiliary instruments, enables accurate power measurements to be made for measuring losses in medium and large transformers. The instruments include high voltage active dividers with nominal outputs of 120 volts, a current transformer with nominal output of 1A and precision wattmeters. Two stage compensated current transformer technology is used in each instrument to achieve uncertainties of < 10 PPM in magnitude and phase respectively. In the high voltage divider, the current comparator is used in a feedback loop to correct the magnitude and phase errors of the associated outputs. This paper discusses the technology used and the associated uncertainties of the instruments to achieve a full-scale system uncertainty of <50 PPM at all power factors.

INTRODUCTION

The measurement of electric power and energy at high voltages and low power factors is becoming increasingly important as a way to reduce costs in an ever-growing industrial economy. A more precise means for scaling these voltages and currents down to usable levels is required. For most practical purposes, medium and large transformers have adequately fulfilled this role and their technology is unlikely to change significantly. As a result, more precise measurements of power and energy will require more accurate measurement systems along with trace ability to SI Units of different national laboratories.

At unity power factor, accurate knowledge of the voltage and current magnitude is essential but considerable latitude in the phase angle between these two quantities is permissible. However, this phase angle tolerance decreases with decreasing power factor while a corresponding relaxation takes place in magnitude requirements.

For example, large high voltage shunt reactors are designed to operate at very low power factors, typically 0.001 to 0.004. For power measurements that are accurate to 1 percent of actual power at 0.001 power factor, a phase angle error of <10 μrad is required.

For accurate power measurements, in particular under these low power factor conditions current scaling is accomplished using special high accuracy current transformers such as a two stage compensated-current transformer. These high accuracy current transformers are used on the current input of the measurement system and in the current input for the precision wattmeter. Voltage scaling is accomplished using a current comparator based active voltage divider and high voltage standard capacitor.

For accurate current measurements, the secondary current of the current transformers should be accurate between 1 and 100 percent of its rated current. For accurate voltage measurements, the output voltage should also be accurate between 1 and 100 percent of its rated voltage on the voltage side.

CURRENT INPUT FOR THE LOSS MEASUREMENT SYSTEM

Two Stage Compensated Current Transformers

The current input to the AccuLoss™ System is provided using three high voltage two-stage compensated-current transformers. A two stage compensated current transformer is basically a four wire transformer with three windings and two magnetic cores.

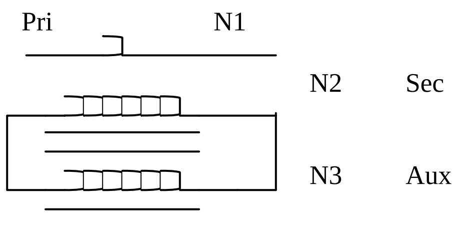

Fig 1: 2-stage current transformer

The inner core consists of a high permeability toroidal core with an auxiliary winding. The outer core is a magnetic shield placed around the first core and auxiliary windings. Such a composite transformer has the characteristics of a nearly ideal transformer when operated at zero burden. The primary current, which flows through the high voltage bushing bus bar, is supplied to the ratio winding. Deviation from turn's ratio in zero burden operation is in the order of a few parts per million in magnitude and phase.

A two stage compensated current transformer is similar to a three winding transformer, except that the auxiliary or compensation winding has the same number of turns as the ratio windings as the secondary. These two windings are connected with separate leads to the current input on the wattmeter, in order to minimize the impedance that would be common to both windings and leads. The current input to the wattmeter is also a two stage compensated current transformer. As a result, the input current transformers for the AccuLoss™ System are effectively operated at zero burden, which minimizes their errors to a few ppm. A lead length of up to 60 meters does not appear to contribute any errors to the measurement.

All current transformers are designed to maintain accuracy up to a one-ohm burden. This is sufficient to cover the burden placed on the current transformer by the ranges of the wattmeter.

Performance

The input transformers are calibrated over the full range of the current transformer from 2000A down to 1A and at the specified lead lengths for the installation of the system. A typical calibration report on the current transformer is indicated in Table 1 below. The length of the cables for this particular calibration was approximately 60 meters.

Test Amperes	Amplitude Error	Phase error
2000	0.0004%	-10 PPM
1000	0.0004%	-9 PPM
500	0.0004%	-9 PPM
200	0.0003%	-3 PPM
100	0.0002%	-3 PPM
50	0.0001%	-3 PPM
20	-0.0001%	-4 PPM
10	-0.0002%	-6 PPM
1	-0.0003%	-7 PPM

Table 1: Current Comparator Calibration

The calibration figures should not be considered as corrections as the uncertainty of the measurement maybe as large or larger than the errors. The current transformer is calibrated using a standard current transformer test set as shown in fig 2. The load for the wattmeter is provided by the wattmeter with compensated current input. A standard current transformer calibrated at the National Research Council of Canada provides trace ability for the calibration.

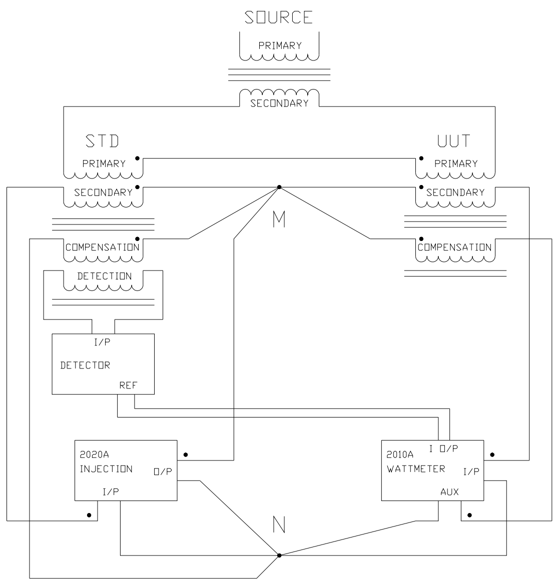

Fig 2: Current Transformer Calibration Using CT Test Set.

VOLTAGE INPUT FOR THE LOSS MEASUREMENT SYSTEM

The voltage input for the AccuLoss™ System is provided using a high voltage standard reference capacitor and a active voltage divider, with current comparator feedback referenced to a low voltage standard capacitor.

Current Comparator High Voltage Active Dividers

The active divider is basically the low-voltage arm of a capacitive divider consisting of a low-loss high-voltage standard capacitor and an operational amplifier with capacitive feedback. The capacitive feedback is a low-voltage standard capacitor.

In conventional high-voltage dividers, adjustments have to be provided for the phase errors due to the dissipation component in the polystyrene capacitor and amplifier circuitry and for the magnitude error due to changes in the capacitance caused by temperature variations of the capacitor and amplifier circuitry.

The output of a conventional voltage divider is given as

$$E_L = C_H / C_f * E_H \ [1 + (\alpha + j\beta)]$$

During Calibration, α andβ, the in-phase and quadrature errors of the divider, can be adjusted to zero. However, it is difficult to maintain magnitude and phase accuracy's due to the drift of the circuitry and more importantly, the drift of the polystyrene capacitor and related temperature coefficients of both the capacitor and amplifier circuitry. Due to these effects, calibration of a conventional high voltage divider is normally required twice a year. And depending on the calibration interval, the uncertainty equation must include the calibration uncertainty and drift uncertainties of the dissipation and magnitude components of the divider.

In the current comparator based high voltage divider, the current comparator provides a means to automatically correct the magnitude and phase errors without requiring adjustment controls.

A simplified schematic of the current comparator based voltage divider is shown in Figure 3. The current in the low-loss high-voltage capacitor (C_H) is compared, using the current comparator, with the current obtained by applying the output voltage V_L to a stable low-loss standard capacitor (C_L).

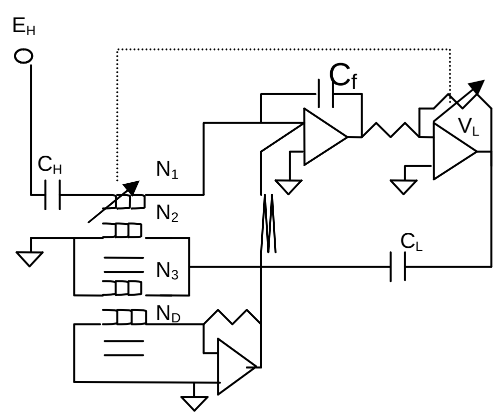

Fig 3: Current Comparator HV Active Divider

Due to the magnitude and phase errors of E_L, the current comparator will not be in ampere-turn-balance. The current difference derived from the output of the detection winding N_D is added through the feedback circuit to the current in the solid dielectric capacitor C_f resulting in a highly accurate and self balancing voltage at V_L. Thus the feedback circuit is used to provide an ampere-turn balance in the current comparator to correct the magnitude and phase errors of the output voltage V_L.

The output voltage V_L of the current comparator based divider is given by

$$V_L = \frac{C_H}{C_L * (N_2 / N_1)} * E_H$$

From the above equation, the capacitance ratio of C_H and C_L and the current comparator-winding ratio determine the divider output. Several gain stages are provided to insure that the output voltage is always operated at or near full scale. To change gain on the high voltage divider, a decrease in the current-comparator-winding ratio (N_2/N_1) is required to maintain ampere-turn balance. Relays, which are used to change the electronic gain and winding ratio are driven simultaneously to keep the winding ratio times the gain constant. The gain of the divider is set as 1, 2, 5, 10, 20, 50, and 100, where a gain of 1 corresponds to a voltage at V_H of 100kV and conversely a gain of 100 would represent an input voltage at V_H of 1kV.

The uncertainty of the high voltage divider is equal to the uncertainty associated with the two stage current transformer and the uncertainty of C_H and C_L.

Low Loss Capacitor and Feedback Capacitor

For the divider to have a zero temperature coefficient and loss-less high voltage capacitor C_H, the stability and accuracy of the divider are determined by the stability and accuracy of the low-loss standard capacitor and the gain of the feedback circuit. Capacitor C_L is a 1000 pF low-loss standard capacitor with dissipation and magnitude errors and a temperature coefficient of a few PPM. The feedback capacitor C_f is a 0.1 µF polystyrene capacitor, which has a temperature coefficient of ≈ 100 PPM/°C. The capacitance values of C_L and C_f have been chosen to provide a nominal output voltage of 100 volts for 100kV input.

Current Comparator

The current comparator in the high voltage divider is a two-stage current comparator toroidal transformer with one core inside the other. The ratio turns consists of N_1, which is variable, and N_2 equal turns. The compensation winding N_3 is connected in parallel with N_2, which has the same number of turns to reduce its leakage impedance. The detection winding N_D is connected to a current-to-voltage converter to obtain a voltage proportional to, and in phase with, the unbalanced ampere turns in the current comparator.

Feedback Circuit

The gain of the feedback circuit, approximately 100, is sufficient for the feedback circuit to correct for the dissipation factor and capacitance variation of the solid dielectric feedback capacitor (C_f). The feedback circuit is set to 100%.

Performance

The high voltage divider's ratio was checked using a set of loss-less gas-dielectric standard capacitors and a high voltage capacitance bridge. As this is a ratio calibration, only the short-term stability of the capacitor bank is important, and an uncertainty of <2 PPM has been assigned based on history and environmental conditions. The ratio accuracy of the high voltage Capacitance Bridge can be verified to <5 PPM.

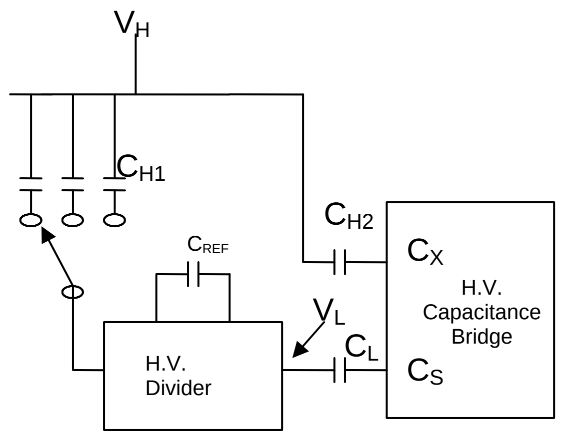

Fig 4: H.V. Divider Calibration

The ratio errors are calculated according to the following formula:

$$\text{Ratio Error} = \frac{\text{Measured Ratio} - \text{Calculated Ratio}}{\text{Calculated Ratio}}$$

Gain Setting	Feedback Pot Setting %	Ratio Error (PPM)
1	100	-8 +j6
2	100	-9 +j6
5	100	-9 + j6
10	100	-10 + j4
20	100	+6 + j2
50	100	+2 + j10
100	100	0 – j3

Table 2: Results of Ratio Error Calibrations

The errors of the divider at all ratios was found to be better than ± 10 PPM in magnitude and ± 10 µrad in quadrature. The calibration uncertainty was 5 PPM. However, the errors should not be treated as offsets or corrections but as an uncertainty.

Loop Gain Check

The high voltage divider has two conditions that it can be operated in, Open Loop and Closed Loop. To verify the loop gain and that the current comparator feedback is functioning properly an error can be introduced using the Gain Trim potentiometer. The Gain Trim potentiometer along with a Null Indicator is located on the front panel of the divider. In open loop condition, the gain trim potentiometer can be adjusted to introduce an error as indicated on the null indicator. For example, a 500 PPM error introduced in the Open Loop Mode should be reduced to 5 PPM when the loop is closed. In operation, the divider is always operated in closed loop.

POWER MEASUREMENTS

Power measurements for the AccuLoss™ System are provided using Time Division Multiplexing (TDM) wattmeters. The TDM Wattmeter has a two-stage compensated current transformer on the current input and a stable resistive divider on the voltage input. Current ranges are provided to allow all measurements to be performed at full or near full scale to maintain full-scale accuracy on the system. The linearity of the wattmeter has been verified to be less than 20 PPM from 100% to 10% on each range. The wattmeters are normally calibrated to an accuracy of less than 30 PPM.

Wattmeter Current Input

The current input of the wattmeter consist of two, two-stage current transformers to provide current inputs of 5, 2, 1, 0.5, 0.2, 0.1, 0.05, 0.02, 0.01 and 0.005 A. Both current transformers are compensated two-stage current transformers, which have an uncertainty of <10 PPM in magnitude and phase.

As indicated in Table 1, the linearity of the AccuLoss™ System input current transformer is <10 PPM over the range from 2000A down to 1A. Scaling of this current is provided using the current transformers in the wattmeter. For a system primary input current of 10A and the current transformer having a ratio of 2000:1, the wattmeter would be placed on the 0.005A input range. Due to the excellent linearity of the wattmeter, currents as low as 1 amp are possible.

Calibration of the wattmeter is performed using a power calibration system, which has an uncertainty of < 30 PPM as shown in Figure 5.

The AccuLoss™ System is completely automatic and wattmeters can be easily calibrated at 100% and 10% of full scale for each range. The wattmeter is normally calibrated over a 3-day period. The wattmeter, based on the TDM principle, with no feedback, requires yearly calibration to determine its one-year drift rate uncertainty, which will be added to the Wattmeter uncertainty equation.

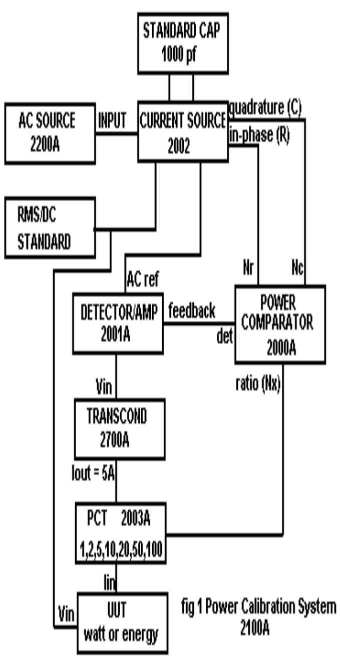

Fig 5: PCS Block Diagram

The wattmeter uncertainty is calculated from the RSS of the system uncertainty (PPM) and standard deviation of n readings (PPM) as follows:

$$\underset{(PPM)}{W_{UNC}} = \sqrt{\underset{(PPM)}{(SYS_{UNC})^2} + \underset{(PPM)}{(W_{SD})^2}}$$

$$W_{UNC} = \sqrt{(35)^2 + (5)^2}$$

$$W_{UNC} = 35.4 \text{ PPM}$$

AccuLoss™ SYSTEM UNCERTAINTY ANALYSIS

A Type A uncertainty for the system should be obtained by taking “n” readings from the wattmeters while performing the loss measurement test. The Type A uncertainty is the root sum square (RSS) of the system uncertainty. The Type A uncertainty will depend upon the quality of the source which supplies the voltage and current to the transformer under test and the AccuLoss™ System.

For the AccuLoss™ System, the following Type B components from the individual calibration reports contribute to the system uncertainty.

HV Standard Reference Capacitors	10 PPM
HV Dividers	10 PPM
HV Current Transformers	10 PPM
Wattmeters	35 PPM

Using the root sum square (RSS) method of calculating uncertainties, the Type B uncertainty of the AccuLoss™ System is calculated as follows:

$$Sys_{Unc} = \sqrt{(10)^2 + (10)^2 + (10)^2 + (35)^2} \quad PPM$$

Sys_{Unc} = 40 PPM of “full scale”.

To convert the 40 PPM to an equivalent uncertainty for different power factors, divide the 40 PPM uncertainty by the power factor.

Example:

The “full scale” system uncertainty (Sys_{Unc}) equals 40 PPM. To determine the equivalent uncertainty at a power factor of 0.01, divide 40 PPM by 0.01.

Sys_{Unc} (100% of scale) = 40 PPM /0.01 = 4000 PPM or 0.4%.

All uncertainties are stated as 2 Sigma (2s=95%).

CONCLUSION

A current comparator technique has been applied to several of the measuring instruments in the AccuLoss™ System to insure an accuracy of <50PPM. The current comparator technique is applied to the current transformers, the feedback of the high voltage divider and to the current input to the wattmeter. Through calibrations at Measurements International and NRC, the uncertainties of the current comparator technique have been verified to < 10 PPM.

The high voltage Current Transformers are passive in design and will not drift over time.

In the current comparator based high voltage Divider, the current transformer automatically corrects for drifts in magnitude and phase and does not require annual calibration.

The Wattmeter does utilize a current comparator at the current input, however it is recommended the wattmeter be calibrated on an annual basis to develop historical data on the drift of the electronics.

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