# 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 the current transformers of 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 of the associated outputs. This paper discusses the technology used and the associated uncertainties of the instruments to achieve a system uncertainty of <50-PPM.

## 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 current 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 traceability 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 a current transformer should be accurate between 1 and 100 percent of its rated current. On the voltage side, for accurate voltage measurements, the output voltage should also be accurate between 1 and 100 percent of its rated voltage.

## LMS CURRENT INPUT

### Two Stage Compensated Current Transformers

The current input to the LMS 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.

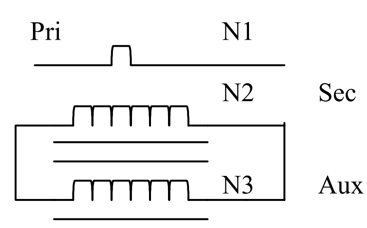



Fig 1: 2-stage current transformer

The extra core is normally 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 flowing through the bus bar is supplied to the ratio winding. Deviation from turns ratio in zero burden operation are 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 winding has the same number of turns as the ratio windings with the most turns. 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. The current input to the wattmeter is also a two stage compensated current transformer. As a result, the input current transformers for the LMS system are effectively operated at zero burden to minimize their errors. Below 60 meters, the length of the leads does not appear to contribute any errors to the measurement.

All current transformers are designed to maintain accuracy up to a 1 ohm burden. This is sufficient to cover the burden placed on the current transformer by the ranges of the wattmeter

Performance:

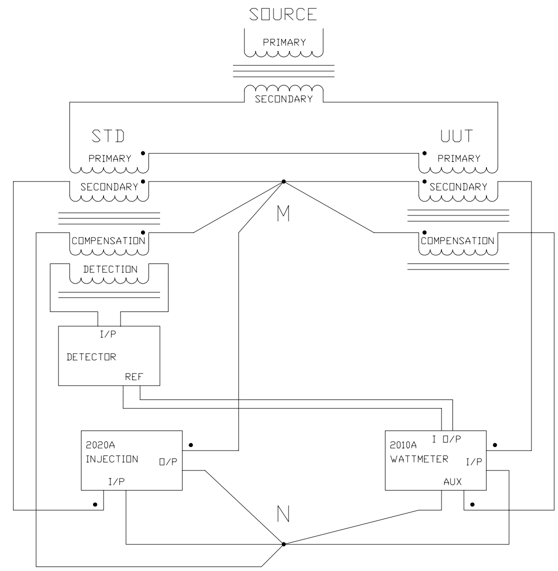
The input transformers are calibrated over the full range of the current transformer from 2000A down to 1 A. The transformers are calibrated using specified lead lengths for the installation of the system with the load being the wattmeter. A typical calibration report on the current transformer is indicated in table 1 below. The length of the cables for this particular calibration was approximately 90 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 is as large as the errors. The current transformer was calibrated using a standard current transformer test set as shown in fig 2.

Fig 2: Current Transformer Calibration Using CT Test Set.




LMS VOLTAGE INPUT

The voltage input for the LMS is provided using a high voltage standard capacitor and 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 a 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 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

$$E_L = \frac{C_H}{C_f} * E_H \; [1 + (\alpha + j\beta)]$$

During Calibration, $\alpha$ and $\beta$, 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 solid dielectric capacitor caused by temperature variations. 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 high 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 ($C_L$).

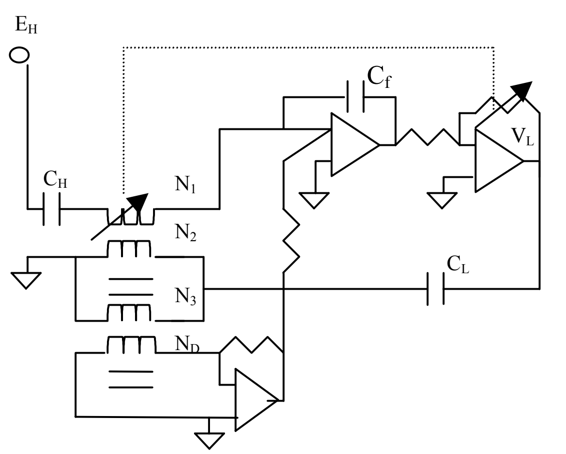



Fig 3: Current Comparator HV Active Divider

Due to the magnitude and phase errors of $E_L$, the current comparator will not be in ampere-turn-balance. The difference current 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 $V_L$. The magnitude and phase errors of the output voltage $V_L$ are corrected by the feedback circuit to provide an ampere turn balance in the current comparator.

The output voltage $V_L$ of the 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. 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. The relays changing the winding ratio and the gain of the amplifier are driven simultaneously to keep the winding ratio times the gain constant. The gain of the divider is set as 1,2,5,10,20,50,100 where 1 corresponds to a voltage at $V_H$ of 100kV and a gain of 100 would represent an input voltage at $V_H$ of 1kV.

Thus the uncertainty of the high voltage divider is equal to the uncertainty associated to a 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 uF 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 $N_2$ has 1000 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. A 400-turn 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.

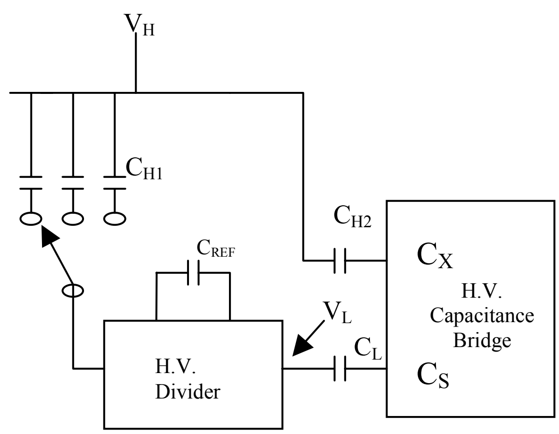



Fig 4: H.V. Divider Calibration

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 urad 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 LMS are provided using TDM wattmeters. The TDM Wattmeter has a two-stage compensated current transformer on the current input and a 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 wattmeters has been verified to be <20 PPM from 100% to 10% on each range. The wattmeters are calibrated to an accuracy of less than 50 PPM.

Wattmeter Current Input

The current input of the wattmeter is made up from 2, 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 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 input of 10A and the current transformer having a ratio of 2000:1, the wattmeter would be placed on the 0.005A input range.

Calibration of the wattmeter is performed using a power calibration system with an uncertainty of <35 PPM as shown in Figure 5.

The system is completely automatic and wattmeters can easily calibrated at 100% and 10% of full scale for each range. The wattmeter is normally calibrated over a 3-day period. Because electronics with no feedback is used in the wattmeter, it will be necessary to determine a one-year drift rate uncertainty, which will be added to the Wattmeter uncertainty equation.

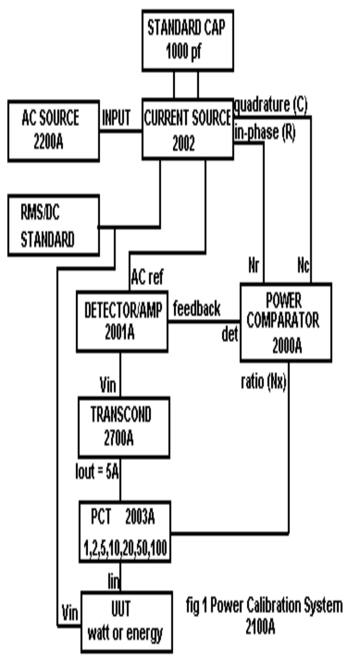



Fig 5: PCS Block Diagram

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

$$W_{UNC}\Big|_{PPM} = \sqrt{SYS_{UNC}^2\Big|_{PPM} + W_{SD}^2\Big|_{PPM}}$$

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

$$= 35.4 \text{ PPM}$$

LMS SYSTEM UNCERTAINTY ANALYSIS

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

| | |
|---|---|
| HV Capacitors | 10 PPM |
| HV Dividers | 10 PPM |
| Current Transformers | 10 PPM |
| Wattmeters | 35 PPM |

A type A uncertainty for the system should be obtained by taking n readings from the wattmeters during loss measurements and RSS the uncertainty to the system uncertainty. The type A uncertainty will depend upon the quality of the source, which supplies the voltage and currents to the transformer under test and the LMS System.

Using the root sum square (RSS) method of calculating uncertainties, the uncertainty of the LMS system is calculated as follows.

$$\text{Unc} = \sqrt{10^2 + 10^2 + 10^2 + 35^2}$$

$$= 40 \text{ PPM of full scale}$$

To convert the 40 PPM to of reading for different power factors, the 40 is divided by the power factor.

E.g. 40 PPM of FS = 40 /0.01 = 4000 PPM or 0.4%
100 PPM of FS = 100 / 0.01 = 10000 PPM or 1%
All uncertainties are stated as 2s ( 95%).

CONCLUSION

A current comparator technique has been applied to several of the measuring instruments in the loss measurement 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 on the current input to the wattmeter. Through calibrations at MIL and NRC, the uncertainties of the current comparator technique have been verified to < 10 PPM. The current transformers are passive in design and will not drift over time. In the high voltage divider, the current transformer automatically corrects for drifts in magnitude and phase and does not require yearly calibration. Although the wattmeter uses a current comparator for its current input, it should be calibrated on a yearly level to gain history on the drift of the electronics.

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