Fiber Optic Current Sensor Calibration

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Abstract: Fiber optic current sensors have been touted for their potential ability to measure currents with accuracy better than 0.1% over a dynamic range extending from literally milliamps to hundreds of kiloamps. Such claims have a good theoretical basis but it is quite difficult to verify such claims, especially at the two extremes of this range. At the lower end of the current range, white noise in the output compares to, or exceeds the signal level and thus interferes with the measurement process. At the upper end of the range, equipment limitations come into play.

In our laboratory we have undertaken a careful study of calibration techniques appropriate to manufacture fiber optic current sensors in the range from 1 to 3600 amps. The main results of our study are reported in this paper. Voltage techniques applied yielded errors of about 0.015% in the range from 1 to 100 amps, and 0.054% in the range from 100 to 3,600 amps. The current techniques applied can yield 0.001% errors in the range from 1 to 100 amps (though practically, this would be degraded to save time) and 0.054% in the range from 100 to 3,600 amps.

Keywords: Electric current measurement, optics, fiber optic current sensors, metrology.

I. INTRODUCTION

Devices utilizing optical means to measure current on high-voltage transmission networks have been in development for over 20 years. The development cycle has advanced to the point that products are now being introduced into the market by a variety of vendors [1]-[3]. One of the main advantages that optical current sensors offer over conventional current transformers is accuracy and bandwidth over a wide dynamic range. Optical current sensors that employ the Faraday effect contain no magnetic materials and are therefore not subject to saturation and hysteresis effects. As a consequence they are inherently linear and are fundamentally limited in time response only by the propagation time of the light through the sensor. The linearity and speed of optical sensors has naturally led to the vision that a single optical sensor could possibly cover all high-voltage CT applications, ranging from accurate metering of currents below 1 amp, to conventional metering of currents in the few hundred to few thousand amps range, to protection applications where the peak currents can approach 170 kA. In addition, some optical current sensors can sense DC currents and perform power quality monitoring up to (or even beyond) the 100th harmonic. Whether all these applications can be covered in a single optical current transducer (OCT) remains to be seen, but certainly the technology is close.

In this paper, the problem of calibrating optical current sensors over a wide dynamic range is addressed. The dynamic range chosen for study is ~1 amp to 3.6 kA. This particular range was chosen since it is the range of an OCT product now being introduced to the market by Nxtphase. As the sensor is claimed to maintain 0.2% accuracy over this entire range of currents, the calibration systems employed to verify these claims must be at least several times better than 0.2%.

OCT's, following the IEC standard (6044-8) [4], have three types of outputs: digital, low-energy-analog (LEA) (e.g., 4V represents rated current), and high-energy-analog (HEA) (e.g., 1 A represents rated current). Each of these signals requires different metrology. In addition, we have found that the metrology for each output is best divided into low current (<100 A) and high current (100 to 3,600 A) setups. Thus, for the analog outputs of the OCT, four setups are required to prove the accuracy claims. In the following sections these setups and an analysis of their main errors are described.

II. LEA CALIBRATION FOR <100 AMPS

Figure 1 shows the metrology setup for the low-voltage output of the OCT at low currents.

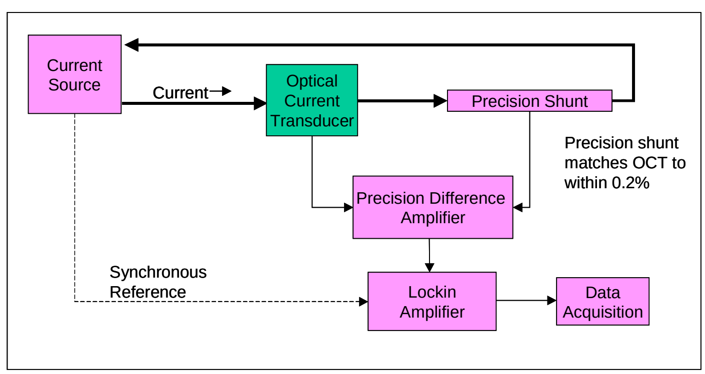

Figure 1. Low energy analog (LEA) metrology setup, applicable for < 100 amp turns.

Two key concepts influence this setup. The first is that a lockin type detection is needed. OCTs have white noise that must be rejected riding on top of the output. This noise arises primarily from shot noise at the photo-detector associated with the light itself. The noise is zero mean with a gaussian distribution, and causes the output of the sensor to look fuzzy at low primary currents. The amount of white noise that exists within the sensor depends on the details of the OCT design, but the lower end of the sensor's useful range can be reliably extended down into the noise since that noise is uncorrelated to the signal and can be removed to any desired level by filtering. The recording duration required to obtain a high quality measurement depends on the signal to noise ratio. As an example, the NxtPhase OCT being tested has a white noise level of 30 mA/√Hz at the output referenced to the primary input. To achieve 0.1% accuracy at 1 A primary current (1 mA resolution) requires that the data be collected and averaged over 450 seconds (a 1/900 Hz detection bandwidth is required to reduce the 30 mA/√Hz noise to 1 mA, and 1/900 Hz bandwidth is achieved by averaging for 450 seconds). Further reduction in the uncertainty of the scale factor measurement is possible with longer averaging, but at some point the wait is not worth the improvement. For energy transfer metering applications that typically have a minimum duration of 15 minutes, this level of noise would contribute a 0.07% error per measurement interval. This error is random and zero mean, so it accumulates to a vanishingly small percentage error for longer measurement intervals.

The second key concept employed in the calibration scheme is that the LEA of the OCT functions as a virtual shunt; a primary current is converted to a secondary voltage. Calibrating the OCT amounts to measuring the value of the virtual shunt. This is effectively accomplished by comparing the shunt value of the OCT to that of a standard reference. Thus, a reference current is made to pass through both the OCT and a calibrated shunt. The voltages produced by each are then taken to a difference amplifier, and the difference signal is then detected with a lockin amplifier and the data recorded. It is important to compare the LEA of the OCT to a shunt having a similar value. This approach removes the problem of having to accurately measure the difference between two large signals, each of which is measured independently.

Errors in this metrology arise from several sources. First is the accuracy of the precision shunt. For a 2000 amp rated OCT, at a 4V output, the virtual shunt value is 2 mΩ. Thus, for this sensor a real calibrated shunt of 2 mΩ should be used in the metrology. However, by passing the current through the OCT N times, the value of the shunt required becomes 2N mΩ. In our laboratory, we have standardized on N = 5, and we use a precision, actively cooled 10 mΩ precision reference shunt from Fluke calibrated to 150 ppm. The OCT is tuned to match the reference shunt to within 0.2% (i.e., the spec of the OCT). Then, the signal coming out of the difference amplifier is within 0.2% of each of the original signals entering. This matching of the signals allows us to avoid heavy dependence on the absolute accuracy of the lockin amplifier that is only specified to 1%. The 1% error made by the lockin amplifier, when applied to the <0.2% signal at the output of the difference amplifier, results in <20 ppm calibration error. This is insignificant when compared to the 150 ppm uncertainty of the precision shunt value.

A third error source that must be considered is the common-mode rejection of the difference amplifier. The technique presented here depends one-for-one on this rejection. Fortunately, high quality difference amplifiers are readily available with –100 dB CMRR (10 ppm error). Thus, in the final analysis, the quality of this technique depends primarily on the quality of the precision shunt used. Root-sum-squaring the three measurement errors mentioned leads to a 152 ppm calibration uncertainty.

III. LEA CALIBRATION FOR 100 - 3,600 AMPS

Extending the shunt technique to calibrations of the LEA of the OCT to high currents is difficult. The heating of the shunt limits its accuracy so that measurements of this type require the use of a very limited number of cycles [5]. Figure 2 shows our preferred technique.

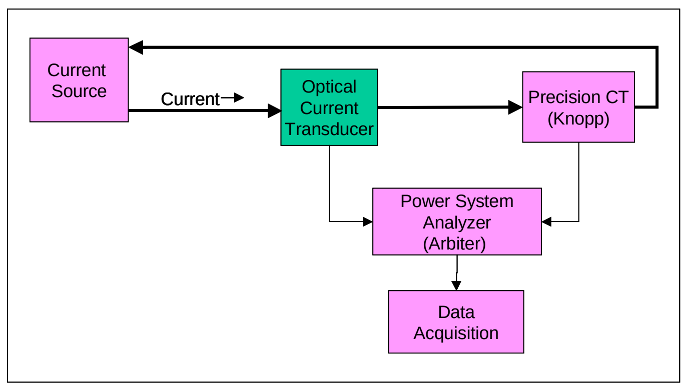

Figure 2. Low energy analog (LEA) metrology setup, applicable for 100 to 3600 amps.

A precision 1000:1 CT (200 ppm from 100 to 5,000 A; available from Knopp) is used to turn down the current, and this current is directly compared with the LEA output using a precision power system analyzer (Arbiter). The Arbiter has an accuracy specification of 500 ppm, which limits the quality of the calibration. Long integration times and precision lockin detection are not needed for these high currents because the noise is insignificant compared with these current levels. Some improvement could undoubtedly be obtained by combining a precision shunt with the output of the 1000:1 CT, but the improvement is not substantial, and the simplicity of the Arbiter power system analyzer weighs heavily in its favor. Root-sum-squaring the specified Arbiter and Knopp uncertainties leads to a calibration error of 538 ppm.

IV. HEA CALIBRATION FOR < 100 AMPS

Figure 3 shows the metrology setup for calibrating the OCT 1 amp current output for < 100 amps primary current.

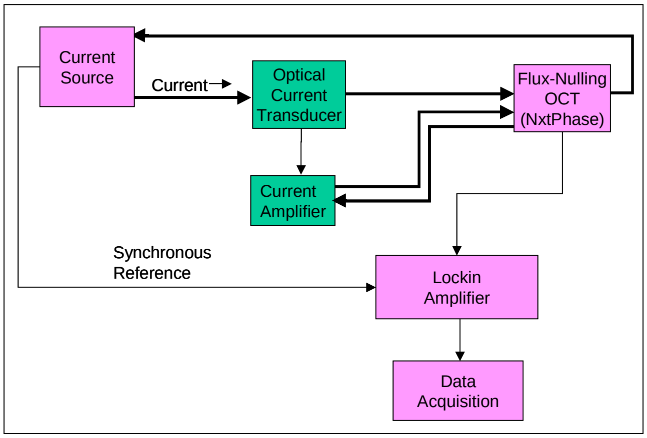

Figure 3. High energy analog (HEA) metrology setup, applicable for < 100 amps.

The key concept for this calibration technique is that the primary and secondary currents are cancelled in a flux-nulling transformer. The error signal is then recorded using a lockin detection method. Assuming the device under test is reasonably good, the accuracy of this technique depends primarily on the uniformity of the flux-nulling transformer sensitivity to magnetic fields around its perimeter. High quality magnetic core window CTs may be used for the flux nulling CT, however, we obtained our best performance using our own custom fiber optic current sensor. Our current sensor dedicated to this purpose uses the in-line configuration [6] with 500 turns of fiber wound to form a sensing coil, and achieves 10 ppm or better uniformity in sensitivity to magnetic field around its perimeter.

Figure 4 shows an experiment we have set up to test this calibration technique.

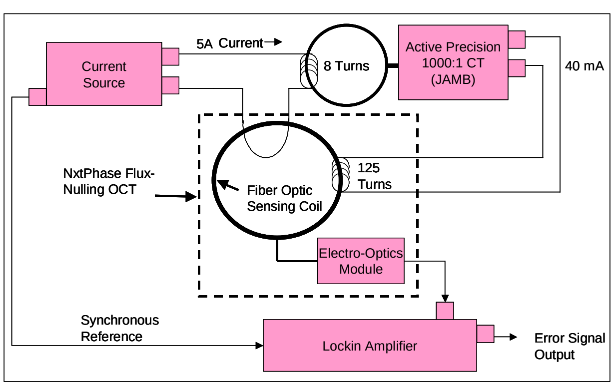

Figure 4. Test setup for proving HEA metrology.

The test CT to be calibrated is a 1000:1 active precision CT produced by JAMB Inc. (The JAMB CT itself uses a flux nulling technique to maintain its accuracy). The JAMB CT has been certified by NIST to maintain 100 ppm accuracy over a range of primary currents from 10 to 1000 amps. In our experiment, we used 8 turns of wire carrying ~5 amps as the primary current, (or ~40 amps primary current, within its certified range). The output of the JAMB CT is then ~40 mA, known to be accurate to 100 ppm. The 5 A primary current was simultaneously passed through the flux-nulling OCT while the 40 mA JAMB output was passed through 125 turns wrapped in the opposite direction around the OCT. Thus, if the JAMB CT were perfect, we should have 5 A primary canceling 5 A-turns secondary in the OCT, therefore the OCT should register a null. In fact, the OCT did not quite register a null, but showed a slight angular dependence on the 5 amp primary current loop orientation. (The 125 turns for the secondary were uniformly distributed around the OCT). To overcome the angular dependence of the primary turn, we physically rotated the OCT through eight 45 degree rotations and averaged the measurements. The results showed that the JAMB CT output was indeed 1000:1 to within 1 ppm ±10 ppm (2σ). The 10 ppm limitation in the measurement was primarily due to white noise in the flux-nulling OCT and was obtained using a total measurement time of 2 hours.

V. HEA CALIBRATION FOR 100 - 3600 AMPS

Because of the physical limitations of our hardware we have not yet attempted to extend the magnetic field nulling concept for characterizing the 1 amp output of the OCT to the high current range. Figure 5 shows our preferred setup for measuring currents > 100 amps.

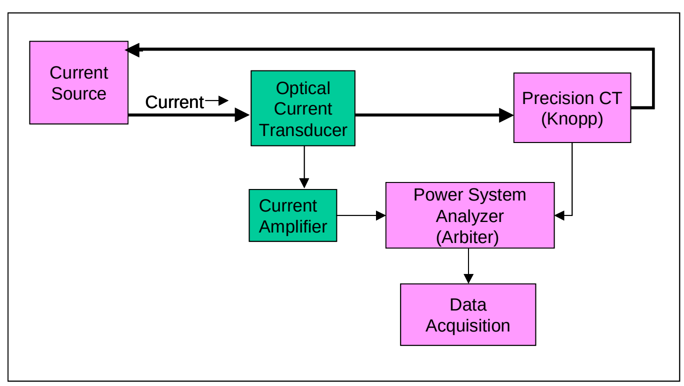

Figure 5. High energy analog (HEA) metrology setup, applicable for 100 to 3600 amps.

The setup shown is very similar to the calibration of the LEA at high currents. Again using the Knopp precision CT with the Arbiter power system analyzer, we achieve 538 ppm measurement accuracy.

VI. CONCLUSIONS

Laboratory techniques for accurately calibrating both the low energy (voltage) and high energy (current) analog outputs of optical current transducers in the range of 1 to 3,600 amps have been described. Greater accuracy has been obtained for primary currents at the low end of this range; in particular, 10 ppm calibration accuracy has been obtained for the analog current output using a novel OCT as a flux-nulling transformer. It is straightforward to extend the calibration techniques described to currents well below 1 amp, though the measurements will be time consuming owing to the need to integrate out the white noise. It is not so straightforward to extend the upper range of the calibration techniques beyond about 5000 amps because of equipment limitations. Future research at Nxtphase will address this issue.

VII. ACKNOWLEDGEMENTS

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VIII. REFERENCES

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IX. BIOGRAPHY

James Blake was born in Oakland, CA in 1959. He received his B.S.E.E. from U.C. Berkeley in 1981, and his Ph.D. in Electrical Engineering from Stanford University in 1988. He worked as a microwave antenna engineer at Ford Aerospace in Palo Alto, CA from 1981 to 1984. From 1988 to 1991 he was a Research Scientist at Honeywell in Phoenix, AZ working on fiber optic gyroscopes. From 1991 to 1999 Dr. Blake was a Professor of Electrical Engineering at Texas A&M University in College Station, TX. His research at Texas A&M concentrated on fiber optic gyros, flow sensors and current sensors. Since 1999, Dr. Blake has been Director of Research and Development at Nxtphase in Phoenix, AZ where he has concentrated on commercializing fiber optic current sensors for high-voltage applications.