

Experimental Comparison of Conventional and Optical Current Transformers

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Abstract—Several manufacturers offer optical current transformers (OCTs) to replace the conventional magnetic current transformers (CTs). This paper compares the performances of some commercially available optical and conventional CTs. The steady state and transient responses of the two systems are compared in a laboratory. Field records are also obtained and evaluated to verify that the optical systems can replace conventional instrument transformers. In addition, OCT step response as well as the impact of ambient temperature on the OCT performance has been investigated. Results show that optical CTs are more than suitable for replacing conventional CTs. Further, the results also show that OCT has better frequency response than conventional CT. Differences found in the field and laboratory measurements are within experimental errors. Unlike the conventional CT, the OCT can have a digital output according to the IEC 61850 standard. The digital output of the OCT is tested for its frequency-amplitude characteristic. Results confirm that digital output has a narrower bandwidth than the low energy analog output of the OCT due to the limited sampling rate prescribed in a UCA guide to IEC-61850-9-2.

Index Terms—Current transformers (CTs), optical transducers, power system protection, transient response.

I. INTRODUCTION

OPTICAL current transformers (OCT) are becoming more commonly available for use in power systems. A number of suppliers have developed various kinds of OCTs in the last few decades. Most OCTs have the same basic operational principles, but they may be optimized for different sensor applications. An OCT can offer better accuracy compared to a conventional magnetic current transformer (CT), a better transient response due to the lack of an iron core, and a wider bandwidth for the Faraday effect-based measuring systems. Typically, OCTs are also safer, lighter, and smaller [1]–[4]. The interconnection of OCTs with power system monitoring and protection equipment is usually different from that of the magnetic CTs. OCTs offer three different output signals: digital, low-energy analog and high-energy analog outputs. All outputs represent the secondary output (5 A or 1 A) of conventional current transformers [5]–[7].

Manuscript received September 05, 2009; revised March 24, 2010. Date of publication August 23, 2010; date of current version September 22, 2010. This work was supported in part by the Power System Engineering Research Center (PSERC) under Grant NSF EEC-0001880 received under the Industry/University Cooperative Research Center program. Paper no. TPWRD-00671-2009.

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Digital Object Identifier 10.1109/TPWRD.2010.2050010

The literature shows several studies on OCT improvements [8]–[14]. Most papers aim to demonstrate that the developed OCTs have higher performance, are suitable for power system applications, and can replace the conventional CTs. Different comparison methods are used to show the comparability of OCTs with CTs [15]–[18]. Furthermore, a few OCTs have been installed together with conventional CTs at substations, allowing a comparison of the two devices' performances in practical power system conditions. Results are encouraging but have been limited. [19]–[23]. Literature reports only a few comprehensive laboratory studies on the comparison of these CTs [24], [25]. Specifically, there are only few studies to analyze the digital output characteristics of OCTs.

This paper compares both steady state and transient performances of conventional magnetic and optical current transformers. All laboratory tests were performed at ASU's high voltage laboratory. Actual field conditions (load current and fault current) were reproduced, and responses of both current transformers were compared. Transient performance of the OCT was measured by using a step-function. The impact of higher temperature on the OCT measurements was determined by increasing the sensor head temperature. Digital output signals of an OCT were captured from the process bus by a computer, and both steady state performance and frequency response were evaluated. Frequency characteristics of the OCT analog output were presented earlier in [26].

II. EXPERIMENTAL SETUP

The performance of optical and conventional magnetic CTs were measured and compared.

The specifications of the tested conventional magnetic CT are:

- voltage 69 kV, BIL 350 kV;
- rated frequency: 60 Hz;
- weight: 625 lbs.;
- current 800 A/400 A /5 A;
- ASA accuracy classification 0.3 B-0.1, B-0.2, B-0.5, B-2 at 60 Cycles (B-0.1 class 2.5 VA, PF = 0.9, Z = 0.1 Ω);
- 5 A high energy analog output.

The OCT specifications are:

- voltage: 145 kV, BIL: 650 kV;
- rated frequency: 60 Hz;
- weight: 152 lbs.;
- rated max thermal current: 3000 A;
- rated short-circuit current : 63 kA;
- 1 C accuracy (relaying): n/a;
- 2 C accuracy (metering): 0.15;
- rated delay time: 40 μ s.

It can be seen that the OCT, even though it is of a higher voltage class, is significantly lighter than the conventional magnetic CT.

Another characteristic that can be compared is the secondary outputs of the CTs. Magnetic CT has standard secondary output current of high energy analog 1 A or 5 A. On the other hand, optical CT output varies according to the manufacturer. Since OCT is based on electronics, output can be adjustable according to need in substation. The OCT under the test has three outputs:

- 1) digital;
- 2) low energy analog (LEA) output, rated at 4 V for metering and 200 mV for protection; in this case, the ratio was programmed to be 1 V output at 1000 A primary current; the accuracy in protection (relaying) mode is 0.3% and in metering mode, it is 0.15%;
- 3) high energy analog (HEA) (5 A rated output).

In this study, the LEA output was used. An OCT of this type can be configured for metering or for protection application. The physical design of the OCT is identical for both applications, but certain settings are optimized for each application. When configured for metering, the rated secondary output is typically 4 V with two times overcurrent measurement capability. For protection application, the rated output is typically 200 mV, allowing for 40 times fully-offset fault overcurrent (transient) measurement. Naturally, when using the protection rating, signal-to-noise ratio (SNR) on the output signal is lower at low currents (due to a fixed electronic noise) as compared to when the 4 V rated metering output is used.

When intended for metering applications with rated currents below 4000 A, typical OCTs of this type are built with 20 fiber turns. More fiber turns will result in higher SNR, which is of interest when metering low currents. For protection applications, on the other hand, OCTs of this type are typically built with 2 (or 3) fiber turns, to allow easy reproduction of current waveforms with peaks as high as 200 kA. Naturally, at an optical level, a 20-fiber-turn OCT is 10 times more sensitive than a 2-fiber-turn OCT. In this study, the OCT was specifically configured for ease of testing. Instead of using a 2000 A rated 2-fiber-turn OCT, a 200 A rated 20-fiber OCT was used. In this way, all of the tests could be performed at much lower currents, which were easily produced in a laboratory. The ratio of this 20-turn metering CT (3000 A: 4 V) was changed via software to 200 A:200 mV. Its performance would be equivalent to a typical 2-turn 2000 A:200 mV OCT while operating at one-tenth of the primary current.

The laboratory testing of the CTs requires high current. A switched current generator was developed and built similar to the one presented in [27]. This generator was suitable to test the CTs in steady state and in transient mode. Fig. 1 shows the one line diagram of the current generator. Since the rated primary current of the OCT was effectively reduced to 200 A, the OCT was easier to test.

The current generator that simulates the high current consisted of three ring type current transformers. The 5 A secondary coils of these three ring type current transformers were connected in parallel and supplied with a regulating transformer. This regulating transformer controlled the magnitude of the generated current. A heavy, insulated conductor formed a short-cir-

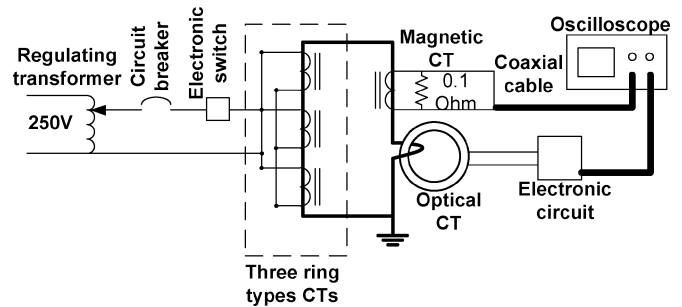


Fig. 1. Experimental test setup.

cuit loop as the primary conductor that carried the current thread through both current transformers under test.

A low voltage circuit breaker protected the system from overload and an electronic switch was used for current initiation between 0 and 180° on the source voltage wave. The maximum current of the system without the load was 1200 A. All tests were performed at room temperature. Fig. 2 shows the laboratory environment and the test setup.

The tested magnetic CT was configured to 800 A/5 A, and was loaded with a 0.1-ohm high precision resistor. The 0.1-ohm burden allowed metering accuracy. The voltage across this resistor was proportional with the current (1 V = 1600 A primary) and it was measured by a digital oscilloscope.

The optical CT was set in a protection mode with a ratio of 200 A:200 mV (i.e., 1 V secondary = 1000 A primary) and the LEA output was connected to the second input of the digital oscilloscope.

The voltage magnitude measurement accuracy of the oscilloscope is $\pm 2\%$. However, since only the difference between the two channels was considered in this study, the digital oscilloscope was calibrated by supplying the two input channels with the same signal and the difference of the two inputs was measured. The amplification of the channels was adjusted so that the difference between the two channel readings was less than 0.5%. This test was repeated for different settings of the input amplifier. The described calibration was repeatedly performed during the tests to ensure high accuracy.

A. Steady State Performance

The purpose of this test set was to compare the two CT operations rather than verifying their accuracies, and to examine the linearity of the CTs as opposed to their absolute calibration. The manufacturers use standardized methods [28], [29] to verify the rating and accuracy of both CTs.

For the steady state response measurements, both the circuit breaker and the electronic switch were closed and the current level was adjusted between 248 A-762 A in 8 steps, using the regulating transformer. Although the maximum-generated current in the setup was 1200 A, the impedance of the magnetic current transformer limited the generated current to 762 A. The waveforms began with a transient mode and gradually reached their steady state value. The tests were repeated by increasing and decreasing the current level. At each current level, the wave-shapes and rms values were recorded.

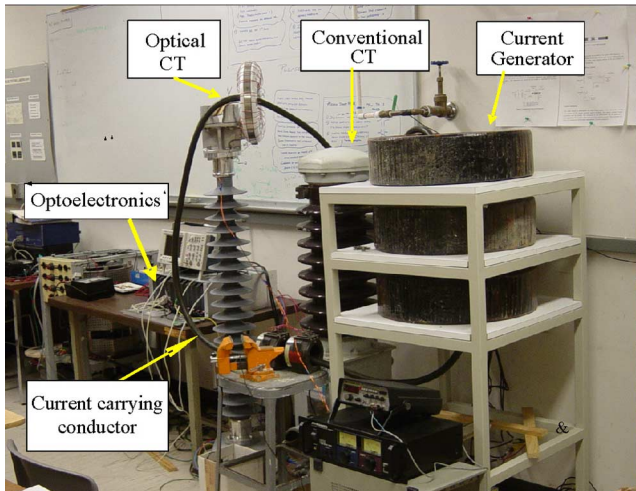


Fig. 2. Experimental test setup in the laboratory environment.

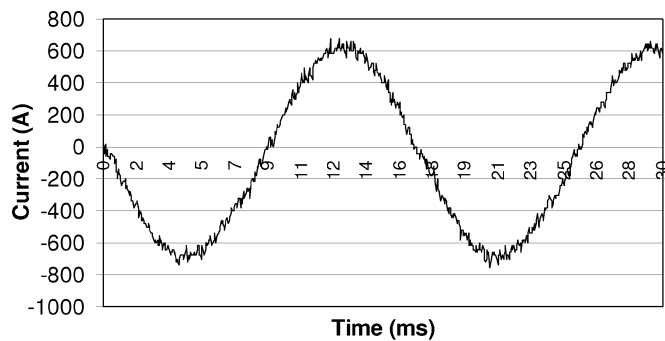


Fig. 3. OCT output signal.

The recorded waveshapes of the transformers were compared. It was noticed that the OCT output voltage had white noise. Fig. 3 shows the recorded OCT output signal when measuring 476 A. The measured rms value of the noise was 26 A rms (6.0% of the signal). The amplitude of the noise was independent from the load current, and it was easily observable at low primary current levels. The white noise of the conventional CT output was 0.48%, which was less than the white noise measured on the OCT's output. The majority of this noise may be attributed to the oscilloscope and the waveform capture circuit used in conjunction with the OCT electronics. The OCT LEA output consists of two floating conductors with common-mode electronic noise on them. When ground one side via oscilloscope, the common-mode noise appears as additional noise on the signal observed on the other conductor.

All optical and/or electronic systems have some inherent noise, and the amount of the noise depends on the sensor design. The measured white noise's average value is zero with Gaussian distribution. Filtering can remove this white noise [1]. Consequently, it does not affect metering accuracy or protection relay operation.

The CT measurements in steady state were compared by using the measuring technique recommended in [1] where it is used to calibrate the OCT with high accuracy of 152-ppm uncertainty. The tests included a high precision reference magnetic CT in which the output was compared with the tested CT

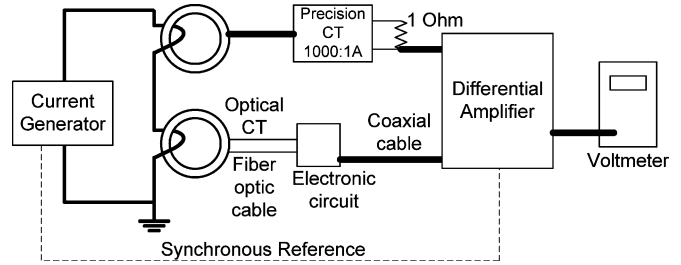


Fig. 4. OCT measurement test setup.

TABLE I
OCT LINEARITY TEST RESULTS

Applied Current (A)	Difference (A)	Difference (%)
248	0.4	0.16
313	0.7	0.22
390	0.8	0.20
466	0.8	0.17
543	0.6	0.11
619	0.6	0.09
688	0.4	0.05
762	0.2	0.02

output. The magnetic CT and optical CT were tested separately and the differences were compared.

The optical CT's output was compared with a 1000 A:1 A high-precision reference CT's output; Fig. 4 shows the test setup. The outputs of the CTs were connected to a precision difference amplifier, a lock-in amplifier, in order to make comparison and to find the difference between them. The lock-in amplifier has a frequency range of 0.5 Hz to 100 kHz. The precision CT output was connected to a 1-Ω calibrated resistor and the voltage across this resistor was used as the first input for the differential amplifier. In this case, 1 V across the 1-Ω resistor corresponded to 1000 A primary current.

The OCT LEA output was used as the second input for the differential amplifier. The OCT output of 1 V corresponded to 1000 A primary current, same ratio as the reference CT. The differential amplifier took these voltages and generated a voltage that represented the difference. This difference voltage was read with a true rms voltmeter.

Table I shows the test results for the experiment. The applied current was changed from 248 to 762 A. Eight different current values were tested and the corresponding voltmeter readings were recorded. Differences are presented in ampere and percentage. The test results show that the differences between the precision CT and optical CT are less than the specified 0.3% in all cases.

The magnetic CT (in 800/5 A mode) output was compared with the same 1000 A:1 A high-precision reference CT's output. Fig. 5 shows the test setup. The previous test setup was modified and did not include the differential amplifier since the outputs of the precision CT and magnetic CT were not at the same scale.

A 0.1-ohm calibrated resistor (0.04% accuracy) was connected to the secondary side of the magnetic CT under test and

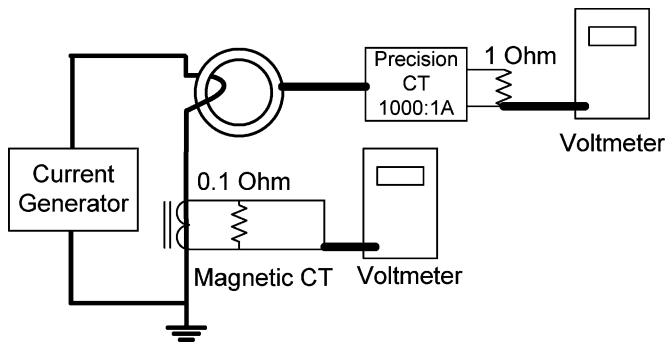


Fig. 5. Magnetic CT measurement test setup.

TABLE II
MAGNETIC CT AND OCT COMPARISON TEST RESULTS

Applied Current (A)	Precision CT Primary (A)	Mag. CT Primary (A)	Difference (A)	Difference (%)	OCT vs. Mag. CT difference (%)*
248	248.7	248	0.6	0.26	0.10
313	313.4	312	1.4	0.44	0.22
390	389.6	392	2.4	0.61	0.82
466	466.3	465.6	0.7	0.15	0.02
543	543.3	544	0.7	0.12	0.23
619	619.2	619.2	0.0	0.00	0.09
688	688.3	692.8	4.5	0.65	0.71
762	762.4	766.4	4.0	0.52	0.55

* The combination of the errors from two separate tests

the voltage across this resistor was connected to a voltmeter for the current readings. Consequently, 1 V corresponded to 1600 A primary current.

The 1-ohm resistor (0.05% accuracy) connected to the output of the reference CT was still in the circuit but connected to a voltmeter rather than differential amplifier. The 1 V still represented 1000 A primary current. The two outputs of the CTs were connected to two voltmeters and the applied current was changed from 248 to 762 A. Eight different current values were tested and the corresponding voltmeter readings were recorded.

Table II shows the test results and the voltmeter readings. The voltmeter readings were converted to primary current and presented with the differences. The differences of each CT with the precision CT are combined and presented in the last column of Table II.

The magnetic CT was switched to 400 A/5 A mode and the test was repeated. The objective of this test was to investigate the CT linearity and the effect of saturation on both CTs. A hand-held clamp-on current transformer measured the primary current. Test results show that the magnetic CT started to saturate after 400 A (as expected).

The magnetic CT was removed from the circuit in order to increase the generated current to be able to test the saturation of optical CT. The heavy, insulated conductor that carried the primary current was threaded 5 turns through the OCT sensor head.

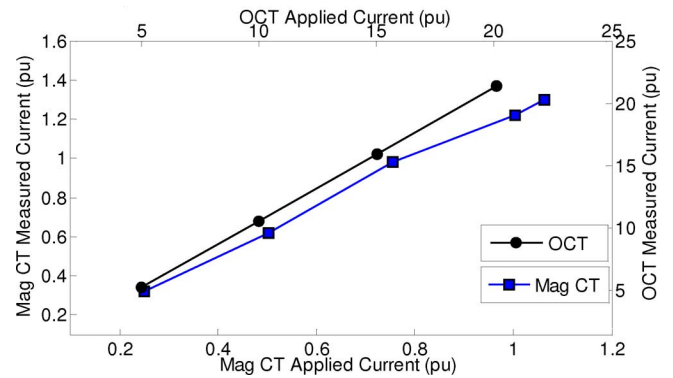


Fig. 6. Saturation effect (1 pu = 400 A for the conventional CT, and 1 pu = 200 A for the OCT).

This was equivalent to a five times increase in the primary current. The current was gradually increased to a maximum value of 4130 A, which is more than 20 times the rated current of the OCT. Results show that the OCT output is linear and no saturation effect was observed. The OCT output sine wave was not distorted. Fig. 6 shows the outputs of the two current transformers as functions of the primary current in per unit (p.u.) scales.

The magnetic CT was switched to the 800 A/5 A mode and 200 A max primary current was applied to both CTs. The current sine waves generated by the magnetic and optical CTs were recorded in a steady state condition, and the point-by-point differences of the two sine waves were calculated by subtracting one's measurement from the other. A digital oscilloscope noise filter was used during this measurement to reduce the inherent output noise of the signals. Fig. 7 shows the recorded one cycle current sine waves and the current level difference for this cycle. The figure shows that the current difference in this cycle is 5.3 A rms. A detailed investigation of this result shows that this difference is mostly due to the phase difference between the current transformers' output signals. The OCT output signal has a 40 μ s rated delay, which is less than one degree (0.86°) of equivalent phase offset. This delay is verified by recording the two signals using an oscilloscope. The time difference between the zero crossings of the two signals is found as 40 μ s. This rated time delay is due to the transit time of the light and the digital signal processing. These results are within specifications of devices under the test. For metering applications where a one degree phase offset is undesirable, this rated phase offset is reduced to zero for the power frequency signal (50 Hz or 60 Hz) using digital phase advancement algorithms in the OCT electronics.

B. Transient and Switching Performances

In this experiment, the basic transient performances of both current transformers were investigated, at a limited level, by applying a primary current that was above the rated current of each current transformer. The primary current was changed from zero to the maximum applied primary current level. The test was performed separately for both transformers because the magnetic CT limited the maximum value of the primary current. The closing of the electronic switch initiated the transient current.

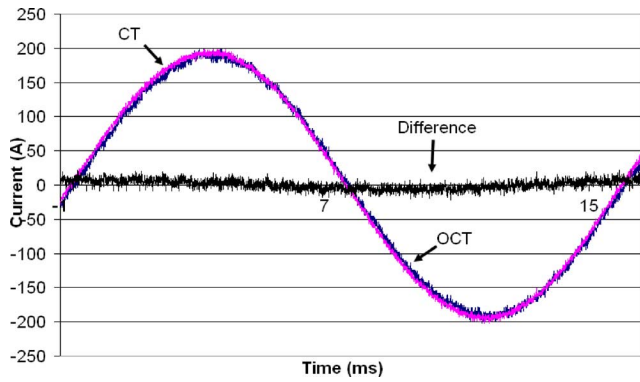


Fig. 7. Sine wave comparison.

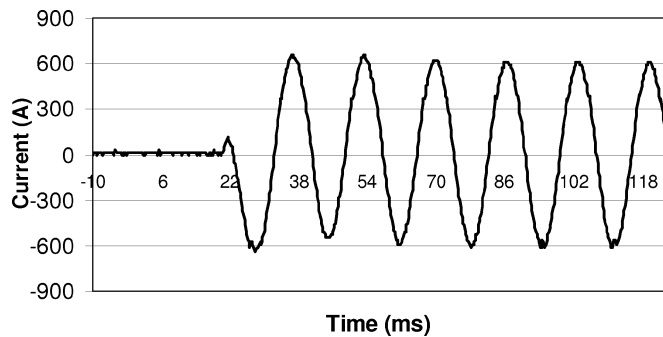


Fig. 8. Magnetic CT transient response.

The dc offset component and the peak value of the current depended on the switching time. The test set up available was not capable of producing a significant dc offset; nevertheless, the switching time was selected experimentally to produce maximum offset. The transient current attenuated very rapidly. The current was reduced to the steady state value after a few cycles. Previous studies [20] show the performance of the OCT in reproducing a fault current with a large and slowly decaying dc offset.

Fig. 8 shows the magnetic CT transient response. The magnetic CT was set to the 400 A/5 A mode, and the regulating transformer output voltage was adjusted to generate 425 A rms or 656 A peak primary current. Results show that the transient current reached the steady state value after three cycles. No distortion can be observed on the sine wave as the current is only slightly above the rated value. Since the Magnetic CT was not the main target of testing, no extra effort was made to produce higher currents necessary to properly test its transient performance at 20 times the rated current.

The magnetic CT was removed from the circuit in order to increase the generated current for testing the transient response of the optical CT. The heavy, insulated conductor that carried the primary current was threaded 5 turns through the OCT sensor head as it was done for the saturation test. A maximum 4130 A rms or 5840 A peak current, which is 20.65 times the rated current, was applied. Fig. 9 shows the optical CT transient response.

Results show that the transient current reached the steady state value after three cycles. The signal sine wave was not distorted.

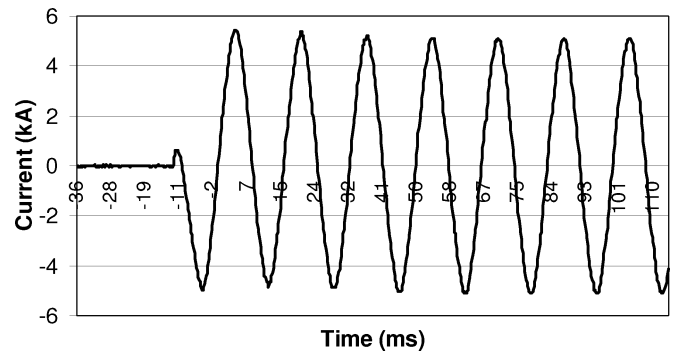


Fig. 9. Optical CT transient response.

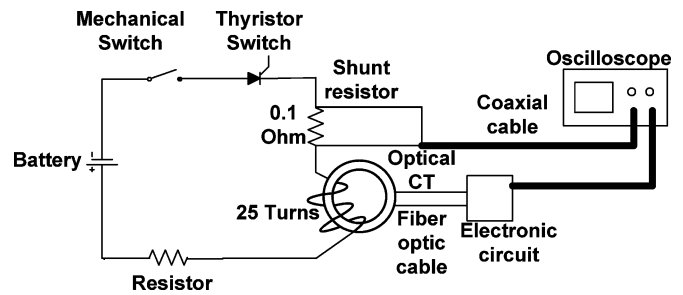


Fig. 10. Step response test setup.

C. Step Response Test

In order to test the step response of the systems, a dc bias circuit was built. The circuit contained a thyristor switch connected a 48 V dc source and 0.1 ohm shunt. The dc current in the circuit was measured and recorded by using a 0.1- Ω shunt resistance. This circuit generated a 2.75 A current pulse. Only the step response of the optical CT was investigated. The magnetic CT was not tested. Fig. 10 shows the test setup. In order to increase the effective current, 107 turns of conductor was threaded through the OCT sensor head. The equivalent OCT current was about 300 A. This current is sufficiently high to help compare the input step function and the output of OCT. The response of the OCT was analyzed. The test was repeated 5 times, for both polarities.

Fig. 11 shows one applied impulse signal and the OCT response. Results show that the OCT delays the current impulse by 40 μ s and increases the rise time of the pulse from 33 μ s to 160 μ s. The rise time here is defined as the time required for the pulse to increase from 10% to 90% of peak value. Results also showed that the OCT has the capability of measuring dc current without any saturation, unlike the magnetic CTs.

D. Temperature Performance of Optical CT

The Faraday effect is temperature sensitive. Accordingly, the manufacturers of OCTs compensate for the temperature dependency either optically or by using an electronic circuit (using an external temperature sensor). The OCT sensor head was heated with an electric heater in the experiment. The temperature was recorded using a thermocouple. The system was loaded with 392 A. The load current was maintained constant. The temperature of the OCT sensor head was increased and the output voltage of

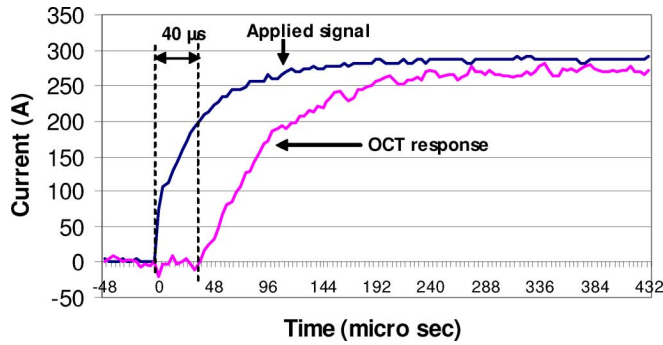


Fig. 11. Optical CT step response.

TABLE III
TEMPERATURE TEST RESULTS

Temp. (°C)	OCT (A)	Mag. CT (A)
23.5	392	392
27.5	392	392
30.0	391	391
39.8	393	393
43.5	393	393
47.3	390	390

the OCT and the unheated magnetic CT were recorded. Table III shows the results.

The results show that temperature does not affect the OCT output, indicating that the manufacturer has implemented an effective temperature compensation technique.

III. COMPARISON OF MAGNETIC CT AND OPTICAL CT BASED ON FIELD RECORDED DATA

A utility company in the country has installed both magnetic and optical CTs for protection studies at one of their substations. The OCTs' LEA outputs and the magnetic CTs' 5 A outputs were recorded by an event recorder and by digital protection relays when faults occurred on the associated HV line. Fig. 12 shows a recorded event. The recorded waveforms were expressed in primary current and plotted together. The difference of the waveforms was also plotted in the same figure. It can be seen that the difference is almost always dominated by a constant amount of noise and the transient fault does not affect the measurements. The maximum instantaneous difference seen in Fig. 12 is about 80 A peak (less than 3% of the 3000 A rated current) and is due to the noise in signals and the data acquisition system quantization noise. As expected, such low level of noise has had no adverse impact on the performance of the protection systems.

Among many recordings from the field records, 12 events, such as one phase fault and ground fault, were selected and analyzed like presented in Fig. 12. Protection equipment readings and signals and the CT readings were compared. The comparison shows that both CTs reproduced the primary current successfully and the protection system operated harmoniously with both CTs.

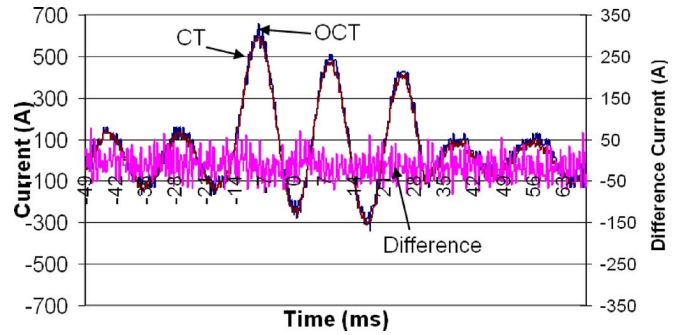


Fig. 12. Field recorded data.

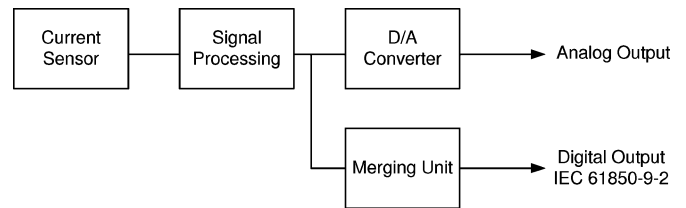


Fig. 13. OCT model block diagram.

IV. DIGITAL OUTPUT

One of the features of the OCT systems is having an optional digital output, which permits easy and safe transfer of the measured current values to protection devices. The purpose of the tests on the digital output was to understand the digital data acquisition capability when the IEC 61850 standard was used. Particularly important was the frequency bandwidth of the OCT's digital signal.

Fig. 13 shows the OCT block diagram based on IEC 60044-8 standard. The signal processing unit converts the light signal coming from current sensor to digital signal that is converted to analog signal by digital to analog converter. This is necessary because most of the digital protection relays require an analog signal. In order to provide digital input for relays according to the related standard [31], the same digitized signal is resampled to have a digital output from the merging unit.

The D/A converter produces the LEA signal output. The merging unit re-samples the signal and generates a digital output in Ethernet format. This signal is transmitted through an Ethernet network to protection and metering devices. The digital output protocol is described in IEC 61850-9-1 and 9-2 standards [30], [31].

Fig. 14 shows the test arrangement used for testing the digital output characteristics. Similar test setup was used earlier to investigate the analog output frequency response presented in [26]. A signal generator, with dc to 1 MHz frequency range, was used as a signal source. The variable frequency output voltage of the signal generator was amplified by a 1000 W stereo amplifier. The loop current was kept constant at 4 A while the frequency was varied from 60 Hz to 4.8 kHz in steps of five. The total current going through the OCT sensor head was $4 \text{ A} \times 55 = 220 \text{ A}$. The waveform of the output signal was captured and recorded at each frequency.

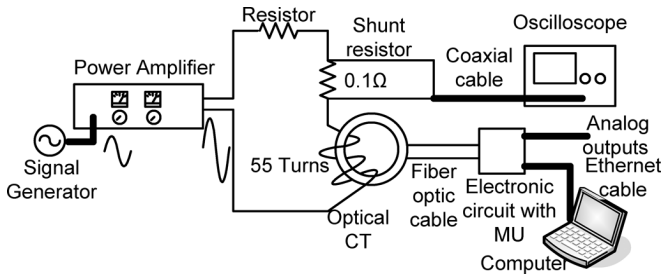


Fig. 14. Digital output test setup.

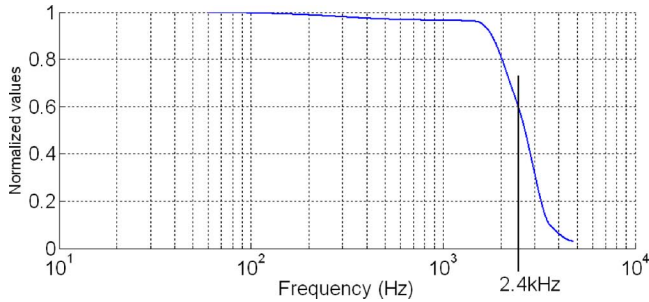


Fig. 15. Frequency-amplitude characteristics of the OCT digital output.

Fig. 15 shows the test results for frequency-amplitude characteristics of the OCT digital output.

The test results show that the 3-dB bandwidth of the OCT's 61850-9-2 digital output interface was about 2.4 kHz. On the other hand, as presented in [26], the analog output bandwidth was close to 20 kHz. The difference between the bandwidths of the analog and digital signals is mainly due to the sampling frequencies involved.

The test results and the merging unit specifications show that the merging unit has a sampling rate of 80 samples/cycle. At the power frequency of 60 Hz, this corresponds to 4800 samples in one second. Fig. 16 shows the 60 Hz signal recording of the digital output. The UCA guide [32] to implementing IEC 61850-9-2 defines two sampling rates: 80 samples and 256 samples per cycle. These rates in a 60 Hz system correspond to 4,800 and 15 360 samples per second (sps), respectively [33]. Any signal with a frequency higher than 2.4 kHz and 7.68 kHz, respectively, is aliased and can have incorrect outputs. Test records confirm that the signals up to 2.4 kHz have acceptable sine waves with correct sampling. Fig. 17 shows the 2.4 kHz signal recording of the digital output that has only two samples in one cycle corresponding to the 4800 sps rate. However, signals above 2.4 kHz are aliased and the waveforms have distortions. Fig. 18 shows the recorded signal for 4.8 kHz. It has four samples per cycle that are randomly distributed and aliased. Please note that in this case, to observe aliasing, the digital output of the OCT merging unit was not filtered by an anti-aliasing filter.

The test results show that the bandwidth of the OCT is limited to 2.4 kHz, as expected from the Nyquist theorem, due to the sampling rate of the merging unit. On the other hand, the analog signal has a higher bandwidth since the digital-to-analog converter for analog output processes the data at a much higher rate. In this case, the OCT D/A is supplied at 333 000 samples

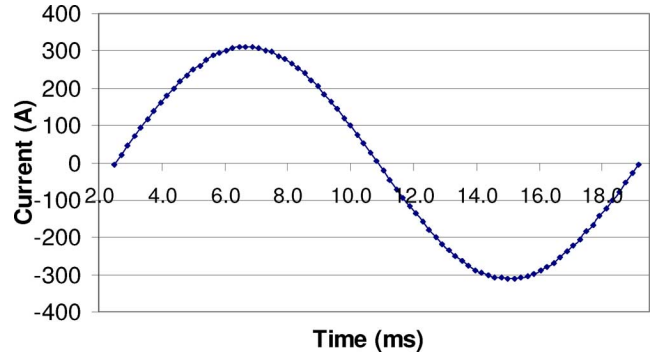


Fig. 16. Digital output for 60 Hz with 80 sampled value.

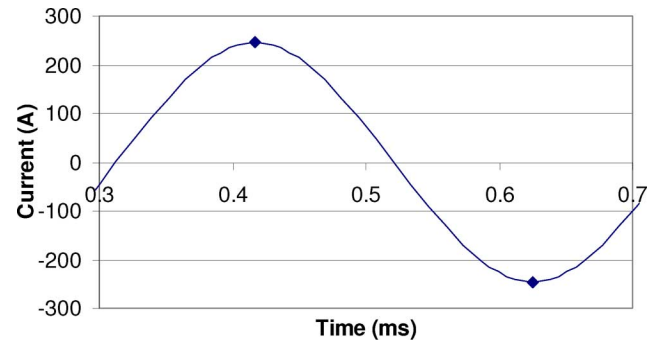


Fig. 17. Digital output for 2.4 kHz with two-sampled value.

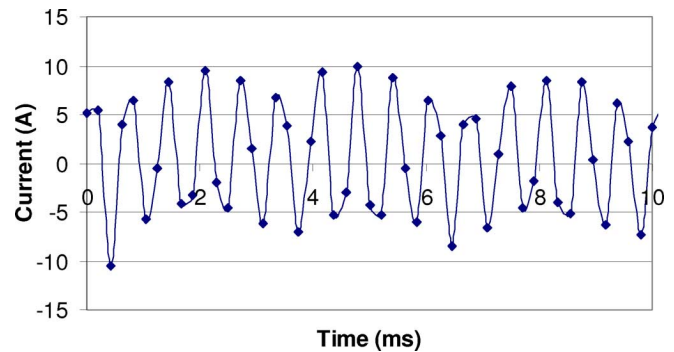


Fig. 18. Digital output for 4.8 kHz (aliased).

per second with digital data that were filtered (anti-aliasing) at an effective 3-dB bandwidth of 20 kHz.

The choice of the sampling/communication rate depends on the application as well as the total capacity of the communication system. The best choice is a compromise: high data rates (large bandwidth) may enable more applications, but it also loads (or overloads) the communication system. For example, 80 and 256 samples per cycle prescribed in [32] load a 100 MB/s Ethernet network to about 5 to 12% [33], respectively. Considering that most common relays and meters use internal sampling rates less than 128 samples per cycle, the prescribed values in the UCA guide [32] appear to be sufficient for most applications, without unnecessarily overburdening the communication network with excessive data.

The fact that the internal and LEA output bandwidth of an OCT can be much higher than these prescribed rates may be useful in some special applications, including testing. Also,

please note that these bandwidths are limited by the electronic circuits used, not the optical sensor head. It is quite possible (with relative ease and low cost) to upgrade the electronic circuit associated with an already-installed OCT of this type to provide higher-bandwidth measurements if and when the interest in higher speed applications grow. This shows the adaptability feature of OCTs of this type.

V. CONCLUSION

We have provided an experimental comparison of the performance of the optical current transformers with conventional magnetic current transformers. The results have confirmed that the OCTs are suitable for power system protection and can replace the magnetic CTs. Similar comparison can be performed with other technologies of optical CTs, like magneto-optic and FOG based fiber optic current sensors.

The results are as follows.

- 1) The optical CT analog output has significantly higher bandwidths than the magnetic CT.
- 2) The OCT reproduces the simulated short circuit currents correctly, and the dc offset current does not saturate the OCT.
- 3) The OCT analog output may have significant white noise, but the white noise does not affect accuracy or protection performance.
- 4) Temperatures up to 50 °C do not adversely affect the performance of the OCT.
- 5) The OCT output signal has a 40 ~ 60 μ s time delay, but this is typically less than the equivalent phase difference permitted by the IEEE and IEC standards for protection applications.
- 6) The digital output signal bandwidth (2.4 kHz) is significantly lower than the analogue signal bandwidth (20 kHz) due to the sampling rates involved.
- 7) The lower digital signal bandwidth is due to the choice of sampling rate (80 times/60 Hz period) prescribed by the relevant standards and guides [32].
- 8) The OCT is much easier to test with the real primary current since it does not load the current supply circuit and its window-type head can accommodate multiple primary wire turns.

ACKNOWLEDGMENT

The authors would like to thank Dr. F. Rahmatian for his guidance in preparation of this work.

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