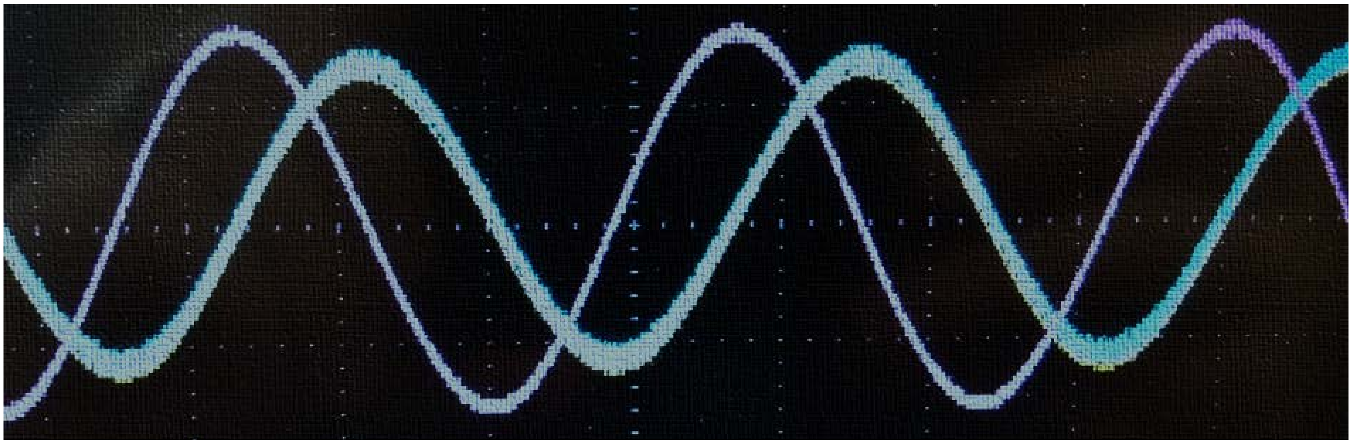
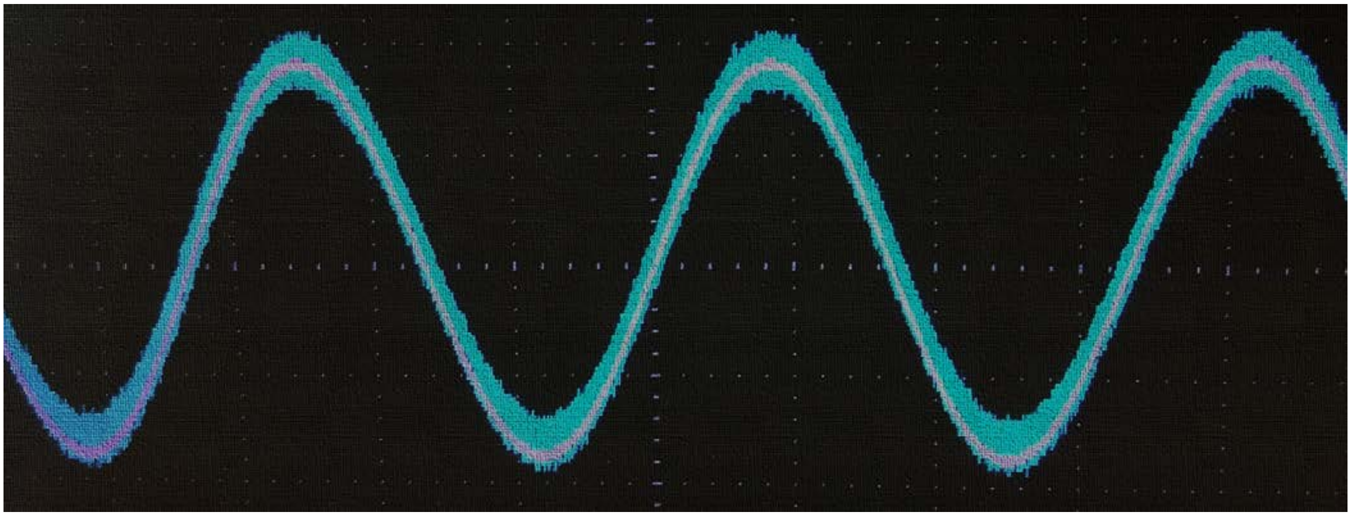
BUREAU OF
RECLAMATION

Feasibility of Utilizing Optical Instrument Transformers

Science and Technology Program
Research and Development Office
Final Report No. ST-2020-19219-01





U.S. Department of the Interior

September 30, 2020

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 30-09-2020	2. REPORT TYPE Research	3. DATES COVERED *(From - To)* 01/10/2018 – 30/09/2020

4. TITLE AND SUBTITLE Feasibility of Utilizing Optical Instrument Transformers	5a. CONTRACT NUMBER 19XR0680A1-RY15412019PE19219/X9219
	5b. GRANT NUMBER Not applicable
	5c. PROGRAM ELEMENT NUMBER 1541 (S&T)
6. AUTHOR(S) Ryan Hogg	5d. PROJECT NUMBER Final Report ST-2020-19219-01
	5e. TASK NUMBER Not applicable
	5f. WORK UNIT NUMBER Not applicable
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Bureau of Reclamation Technical Service Center Electrical & Mechanical Engineering Division Power Systems Analysis & Controls Group (86-68440)	8. PERFORMING ORGANIZATION REPORT NUMBER Not applicable
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Science and Technology Program Research and Development Office Bureau of Reclamation U.S. Department of the Interior Denver Federal Center PO Box 25007, Denver, CO 80225-0007	10. SPONSOR/MONITOR'S ACRONYM(S) Reclamation
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) Final Report ST-2020-19219-01

12. DISTRIBUTION/AVAILABILITY STATEMENT
Final Report may be downloaded from https://www.usbr.gov/research/projects/index.html

13. SUPPLEMENTARY NOTES
None

14. ABSTRACT

Conventional instrument transformers constructed with copper and iron are an integral component of the modern power grid. These conventional devices have well known accuracy and safety drawbacks. These drawbacks are accounted for in system design. Optical instrument transformers utilizing the interaction of light with electromagnetic fields are an alternative to conventional instrument transformers. However, these optical instrument transformers are not a one-to-one replacement for conventional instrument transformers. The optical versions are more complex but can provide real benefits. This report examines the properties of optical instrument transformers, reviews the use of one in a lab environment, and discusses the use of them in the power grid.

15. SUBJECT TERMS
Current Transformer, Faraday Effect, Optical Current Transformer, Optical Voltage Transformer, Optical Instrument Transformer, Pockels Effect, Potential Transformer, Voltage Transformer

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
				47	Ryan Hogg
a. REPORT U	b. ABSTRACT U	THIS PAGE U			19b. TELEPHONE NUMBER *(Include area code)* 303-445-2528

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Mission Statements

The Department of the Interior (DOI) conserves and manages the Nation's natural resources and cultural heritage for the benefit and enjoyment of the American people, provides scientific and other information about natural resources and natural hazards to address societal challenges and create opportunities for the American people, and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities to help them prosper.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Disclaimer

Information in this report may not be used for advertising or promotional purposes. The data and findings should not be construed as an endorsement of any product or firm by the Bureau of Reclamation, Department of Interior, or Federal Government. The products evaluated in the report were evaluated for purposes specific to the Bureau of Reclamation mission. Reclamation gives no warranties or guarantees, expressed or implied, for the products evaluated in this report, including merchantability or fitness for a particular purpose.

Acknowledgements

The Science and Technology Program, Bureau of Reclamation, sponsored this research.

Feasibility of Utilizing Optical Instrument Transformers

Final Report No. ST-2020-19219-01

prepared by

Ryan Hogg, Electrical Engineer
Power Systems Analysis & Controls Group (86-68440)
Electrical & Mechanical Engineering Division
Technical Service Center
Bureau of Reclamation

Peer Review

Bureau of Reclamation
Research and Development Office
Science and Technology Program

Final Report ST-2020-19219-01

Feasibility of Utilizing Optical Instrument Transformers

RYAN HOGG Digitally signed by RYAN HOGG
Date: 2020.09.15 11:54:23
-06'00'

Prepared by: Ryan Hogg
Electrical Engineer
Power Systems Analysis & Controls Group (86-68440)
Electrical & Mechanical Engineering Division
Technical Service Center
Bureau of Reclamation

JAMES
DEHAAN
Digitally signed by JAMES
DEHAAN
Date: 2020.09.16 10:10:34
-06'00'

Peer Review by: James DeHaan, P.E.
Electrical Engineer
Hydropower Diagnostics & SCADA Group (86-68450)
Electrical & Mechanical Engineering Division
Technical Service Center
Bureau of Reclamation

"This information is distributed solely for the purpose of pre-dissemination peer review under applicable information quality guidelines. It has not been formally disseminated by the Bureau of Reclamation. It does not represent and should not be construed to represent Reclamation's determination or policy."

Acronyms and Abbreviations

9-2LE	UCA implementation guide, "Implementation Guideline for Digital Interface to Instrument Transformers using IEC 61850-9-2"
ABB	Asea Brown Boveri (the OEM)
BIL	Basic Impulse Insulation Level
CT	Current Transformer
CCVT	Coupling Capacitive Voltage Transformer
COSI-CT	Compact Sensor Intelligence Optical Current Transformer (product by GE)
COSI-CT F3	Compact Sensor Intelligence Flexible Optical Current Transformer (product by GE)
COTS	Commercially Available Off-the-Shelf
CPC 100	Omicron CPC 100 universal primary injection test set
CVT	Capacitive Voltage Transformer
EFOCT	Electronic Fiber-Optic Current Transformer (product by CONDIS)
EMC	Electromagnetic Compatibility
EOVT	Electro-Optical Voltage Transformer (product by ABB)
F-EFOCT	Flexible Electronic Fiber-Optic Current Transformer (product by CONDIS)
FOCS	Fiber-Optic Current Sensor (product by ABB)
FOCS-FS	Fiber-Optic Current Sensor – Free Standing (product by Hitachi ABB)
GE	General Electric (the OEM)
HEA	High Energy Analog
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
IEEE	Institute of Electrical and Electronics Engineers
IT	Instrument Transformer
LEA	Low Energy Analog
LED	Light Emitting Diode
MU	Merging Unit
NCIT	Non-conventional Instrument Transformer
OCT	Optical Current Transformer
OEM	Original Equipment Manufacturer
OIT	Optical Instrument Transformer
OVT	Optical Voltage Transformer
PT	Potential Transformer (see VT)
Reclamation	Bureau of Reclamation
SEL	Schweitzer Engineering Laboratories, Inc (the OEM)
Std	Standard
TOCT	Trench Optical Current Transformer (product by Trench)
VT	Voltage Transformer

Measurements

°	Degrees (e.g., 180° phase shift)
A	Ampere (electric current)
ft	Feet
Hz	Hertz (frequency)
V	Volt (voltage, electric potential difference)

Table of Contents

Executive Summary

Instrument transformers (ITs) are an integral component of the electrical grid. These devices transform the primary current and voltage waveforms on the power grid to levels usable by controllers, meters, and relays. Most of the ITs in the power grid are conventional ITs, constructed with copper and iron. [1]

Optical instrument transformers (OITs) perform the same function as conventional ITs. In an OIT, light passes through a sensor head and is affected by the electromagnetic field. The resulting change to the light signal is measured by the OIT sensor electronics and output to controllers, meters, and relays.

While conventional ITs experience widespread use and market domination, conventional ITs have several drawbacks that can lead to inaccurate secondary waveforms (e.g., magnetic saturation) and safety concerns (e.g., shock hazards). OITs are marketed as a solution to the drawbacks of conventional ITs.

Compared to conventional ITs, OITs are more complex and have additional installation, operational, and maintenance requirements. The benefits of OITs include increased linearity and safety. The digital nature of OITs can provide flexibility to electrical system design. While OITs can be used in place of conventional ITs, OITs are not a one-for-one replacement for conventional ITs. A cost benefit analysis should be conducted prior to retrofits and new installations of OITs .

OITs have the potential to provide measurable benefits at the cost of increased complexity. OITs are not a silver bullet for the drawbacks of conventional ITs. Rather, OITs introduce their own set of drawbacks and complications that need to be considered. The continued use of conventional ITs throughout the power grid is both rational and justified.

1.0 Introduction

Modern electrical systems rely on control, measurement, and protection secondary devices[1] to operate. These secondary devices are not designed to directly receive the primary current and voltage waveforms of the systems they operate on. Instead, instrument transformers (ITs) are used to provide reproductions of the primary currents and voltages. The two basic functions of an IT are to (1) reduce the primary current or voltage to an acceptable secondary input level and (2) provide electrical isolation from the primary electrical system.

Conventional ITs provide analog reproductions of the primary current and voltage waveforms. The secondary analog currents and voltages are reduced in magnitude (e.g., 5 amperes (A), 120 volts (V)). The secondary analog waveforms are also galvanically isolated from the primary system via a magnetic circuit. For the purposes of this review, these electromagnetic devices will be referred to as conventional ITs. Conventional ITs include current transformers (CTs), voltage transformers (VTs)[2], capacitive voltage transformers (CVTs), and coupling capacitive voltage transformers (CCVTs). Conventional ITs have a long history of operation in the electric system. The reliability, benefits, drawbacks, and operation of conventional ITs are well known. The drawbacks are accounted for in system design, compensating for their undesirable traits.

Non-conventional instrument transformers (NCITs) are an alternate solution to provide current and voltage information to secondary devices. NCITs provide various types of analog and digital outputs. NCITs used to reproduce current include hall effect current sensors, optical current transformers (OCTs), resistive shunts, and Rogowski coils. NCITs used to reproduce voltage include capacitive dividers, optical voltage transformers (OVTs), and resistive dividers.

Optical instrument transformers (OITs) include both OCTs and OVTs. Commercial OITs are available for use on the electric grid for generation, transmission, and distribution applications. This report takes an in depth view of the application of OITs based on their purported benefits over conventional ITs. The application and use of the other NCITs are beyond the scope of this review.

OITs are marketed as a safer, more accurate, and more environmentally safe alternatives to conventional ITs. This review:

- Describes the benefits and drawbacks of conventional ITs and OITs
- Describes the basic operation and qualities of OITs
- Identifies commercially available OITs
- Discusses the “digital substation”
- Identifies related industry standards
- Describes an experience procuring, setting up, and testing an OCT in a laboratory
- Discusses potential future work

---

[1] I.e., controllers, meters, and relays

[2] Also called potential transformers (PTs).

2.0 Conventional ITs

Conventional ITs replicate the analog primary current and voltage waveforms as analog secondary waveforms of reduced magnitude. These analog secondary waveforms are then provided to secondary devices such as controllers, meters, and relays.

Conventional CTs are used to replicate currents waveforms. A conventional CT is constructed with an iron core and copper secondary windings. A primary current waveform (e.g., 5,000 A) is converted to a smaller, proportional secondary current (e.g., 5 A).

Conventional VTs, CVTs, and CCVTs are used to reproduce voltage waveforms. CVTs and CCVTs use a combination of a capacitive divider and VT to reproduce the primary waveform at a lower magnitude. VTs are constructed with an iron core and copper secondary windings. A typical secondary voltage magnitude is on the order of 69 V or 120 V.

Ideally, the only difference between the primary and secondary current/voltage is the magnitude of the waveform. For an ideal IT, the angle and frequency of the secondary is equal to the primary. Due to the use of iron cores and copper wiring, the secondary waveforms of convention ITs are not ideal replications of the primary waveforms.

By its nature, iron can magnetically saturate. When a conventional IT magnetically saturates, the secondary waveform will not be a perfect reproduction of the primary waveform. The burden, or load, placed on a conventional IT can overburden the IT. Overburdened ITs do not accurately reproduce the primary waveform. CVTs and CCVTs can also misrepresent voltage transients by nature of their capacitive design.

The known error sources of conventional ITs need to be considered during design for both continuous operation and faults (see section 2.2 for more discussion of these errors).

2.1 Benefits

The benefits of conventional ITs explain the market domination of these devices. The benefits include their familiarity, reliability, long use history, consistent maintenance procedures, secondary devices compensating for drawbacks, high market competition, and high data security.

An extremely important benefit of conventional ITs is their familiarity and reliability. [2] These devices have been in use for many decades before the advent of NCITs. Their use in the electric industry is prolific and modern versions of conventional ITs remain dominant in the market.

Personnel are extremely comfortable with the use and implementation of conventional ITs. Engineers know their uses and implement them in their designs. With their prolific implementation, electricians and relay test personnel are highly familiar with these devices. Therefore, there is no need for specialized training when new conventional ITs are installed in a facility.[3]

---

[3] Some training may be needed if a new insulating gas is brought into a facility.

Conventional ITs also have well established standard maintenance and testing procedures (e.g., found in sections 5, 6, and 7 of Reclamation's Facilities Instructions, Standards, and Techniques Volume 3-8, "Operation, Maintenance, and Field Test Procedures for Protective Relays and Associated Circuits", May 2011). [3] These procedures are implemented across almost all conventional ITs from any manufacturer. While failures of conventional ITs are known to occur, in general conventional ITs are highly reliable and have a long service life.

As conventional ITs are so prolific, the limitations and proper usage of conventional ITs is well known and understood. For example, relay systems commonly consider the nature of conventional CTs in their design. Percentage differential elements in protective relays include compensation to ensure secure differential protection during severe though faults which can saturate the iron in conventional CTs (e.g., "High Security Mode" within a SEL-300G Multifunction Generator Relay). [4]

As conventional ITs are prolific in the market, there are an abundant number of choices for conventional ITs from reputable vendors. This competition has led to competitive pricing, driving down costs for end users.

Finally, from a security of data perspective, conventional ITs present little concern. Conventional ITs are like a local area network with no external access points. The analog signals from conventional ITs are wired point to point. Devices needing input from a conventional IT have copper wiring attaching the IT to the secondary devices. This configuration does not readily allow for the signals to secondary devices to be manipulated to provide false indicators to secondary devices.

In summary, the benefits of conventional ITs are:

- Familiarity and reliability
- Long history of use
- Consistent maintenance procedures across manufacturers
- Secondary devices designed to compensate for their drawbacks
- High level of market competition among vendors
- Highly secure from a data perspective

This list of benefits explains not only the continued usage, but also why new designs implement conventional ITs.

2.2 Drawbacks

The usage of conventional ITs also include many drawbacks based on the nature of the devices. This includes magnetic saturation, voltage transient misrepresentation, safety hazards, and the need for multiple conventional ITs at one electrical node.

All conventional ITs can magnetically saturate due to the inclusion of an iron core. Conventional CTs can magnetically saturate during power system faults or if the CT is overburdened. A magnetically saturated CT will misrepresent the primary waveform. [5] Conventional CTs can also experience magnetic saturation due to external magnetic fields. [6] If a conventional VT (as well as CVT and CCVT with an internal conventional VT) is overburdened, the VT will also misrepresent the primary voltage waveform. During voltage transients, CVTs and CCVTs can misrepresent the primary voltage. This can lead to relay misoperation. [5]

In general, for all conventional ITs, the secondary waveform does not necessarily perfectly represent the primary waveform.

If the secondary of a conventional CT is opened and there is current in the primary winding, the voltage at the open circuit will increase to complete the secondary circuit. The shock hazard is highly hazardous to personnel proximate to the open circuit. Additionally, there are known cases of conventional ITs exploding under fault conditions. [5]

Another drawback is the need to utilize separate conventional CTs for metering and protection at the same electrical location. The accuracy demands of metering versus protection applications under normal operating conditions and faults leads to the need for separate conventional CTs.

In summary, the drawbacks of conventional ITs are:

- Possible misrepresentations of primary values
- Safety concerns (shock and explosion hazard)
- Separate CTs for metering and protection

While there are many benefits to the use of conventional ITs, there are also drawbacks. OITs are marketed as a solution to mitigate the drawbacks of conventional ITs.

3.0 OITs

The focus of the remainder of this review is OITs. OITs utilize the principles of light in electromagnetic fields to measure and reproduce the primary currents and voltages. This section first reviews the various types of NCITs. From there, this section reviews OITs in relation to their principles, construction, benefits, drawbacks, performance, market penetration/adoption, and failure modes.

3.1 NCIT Types

NCITs include more than just OITs. NCITs include:

- Current measurement:
    - Hall effect current sensors
    - OCTs (Optical current transformers)
    - Resistive shunts
    - Rogowski coils
- Voltage measurement:
    - Capacitive dividers
    - OVTs (Optical voltage transformers)
    - Resistive dividers

The outputs from NCITs are analog and/or digital. This report only reviews the characteristics and operation of OITs (OCTs and OVTs). The remainder of the types of NCITs are beyond the scope of this review.

3.2 OCTs

3.2.1 Principles of Operation

Most OCTs operate on the Faraday Effect. The Faraday Effect is also known as the Magneto-optic effect and was discovered by British scientist Michael Faraday in 1845. The Faraday Effect is described as, "For a plane-polarized light wave propagating through the optical medium in a direction parallel to the applied magnetic field, the polarization plane of the light rotates." [7]

Modern day designs of OCTs utilize multiple wraps of optical fibers around the primary conductor. More wraps of optical fiber are used to meet applications that require more accuracy. [7]

3.2.2 Configurations

As found in Institute of Electrical and Electronics Engineers (IEEE) Standard (Std) C37.241-2017, optical current measuring devices are separated into four basic types: [2]

- "Type 1 – conventional CT with optical readout"
- "Type 2 – magnetic concentrator"
- "Type 3 – bulk optics"
- "Type 4 – optical fiber"

Type 1 and 2 devices are considered "hybrid optical" solutions while type 3 and 4 devices are "purely optical CTs." [2] Type 1 and 2 devices do not utilize the Faraday Effect, while type 3 and 4 devices do utilize the Faraday Effect.

Type 1 devices utilize a conventional CT to perform the conversion from primary to secondary current. The analog secondary current signal is then converted to an optical, digital signal. This solution benefits from optical isolation in the secondary circuit. However, as this solution utilizes a conventional CT, the drawbacks called out in section 2.2 are relevant (e.g., saturation and shock).

Type 2 devices essentially utilize a conventional CT with the copper windings removed and a gapped iron core. An optical sensor is placed in the gap of the core. This optical sensor measures the magnetic field in the core. The measurement is used to determine the current in the primary winding. As this solution removes copper wiring there is no shock hazard (e.g., on the open secondary of a conventional CT). However, iron saturation issues are still possible.

Type 3 devices use no iron core or copper windings. Instead an optical path surrounds the primary conductor one time. In order to get more accurate readings, multiple paths around the primary conductor are required. Therefore, by their nature, Type 3 devices are typically not as accurate as Type 4 devices.

Type 4 devices also use no iron core or copper windings. These devices utilize an optical fiber that wraps around the primary conductor multiple times. The inclusion of multiple wraps around the primary conductor can increase accuracy. Modern applications of OCTs use type 4 devices.

3.3 OVTs

3.3.1 Principles of Operation

Most OVTs operate on the Pockels Effect. The Pockels Effect is basically described as the speed of light changing when the light passes through an electro-optic material in the presence of an electric field. More specifically, "…linearly polarized light is converted to a circular polarization through a waveplate. The circularly polarized light becomes elliptically polarized as a result of the electric field present, and it ellipticity alternates with the AC voltage. Ultimately, the amount of light passing through the end of the polarizer depends on the electric field present at the location of the electro-optic crystal." [7]

A full individual implementation of the Pockels Effect is called a Pockels Cell. [3] At higher voltages, OVTs use a distributed array of multiple Pockels Cells. The signals from individual Pockels Cells are combined to determine the voltage across the whole array.

3.3.2 Configurations

IEEE Std C37.241-2017 breaks down optical voltage measurements into two basic types: [2]

- "Type 1 – line-to-ground continuous integration"
- "Type 2 – line-to-ground distributed integration"

Type 1 devices have one Pockels Cell connected from line to ground (across the full potential). This setup is used for smaller voltages.

Type 2 devices have multiple Pockels Cells connected in series from line to ground. The output from the individual cells is combined to determine the line to ground voltage. This setup is used for higher voltages.

3.4 OIT Components

The remainder of this report will only examine modern, "purely optical" ITs (Type 4 OCTs and Type 1 and 2 OVTs). As found in IEEE Std 1601-2010, the physical construction of an OIT is broken down into three components: [8]

1. Sensor Head
2. Cabling System
3. Sensor Electronics

These three components work in concert to measure the primary current or voltage and output a secondary signal.

For a modern OCT, the sensor head is typically a loop of optical fibers (see Type 4 in section 3.2.2). For an OVT, the sensor head is a single Pockels Cell or multiple Pockels Cells (see Type 1 and 2 in section 3.3.2). In the sensor head, light undergoes a change that will be measured by the sensor electronics.

In order to pass between the sensor head and electronics, the light passes through the optical cable system. Depending on the system, there may be electrical wires (e.g., copper) that need to be run with the optical cables (e.g., compensation circuits for temperature). A cable management box may be used to organize the cabling.

The sensor electronics transmit the light signal through the optical cable system to the sensor head. The light then returns from the sensor head through the optical cable system to the sensor electronics. The sensor electronics may include compensation logic and circuits. The sensor electronics process the incoming signals from the sensor head and produce secondary outputs. These secondary outputs are typically in the form of a low energy analog (LEA) voltage signal or a digital stream.

IEEE Std C37.92-2005(R2011) includes a guideline for LEA outputs from electronic ITs for metering and relaying. [9] The voltage limits in the standard ensure proper range is given for the voltage signals. Using LEA voltage inputs to secondary devices may seem intuitive at first as inputs from conventional ITs are high energy analog (HEA) current or voltage signals.

The following data conversions occur to use an LEA output from an OCT in a digital relay:

1. Primary current converted to analog light signal
2. Analog light signal converted to digital signal at input to OCT
3. Digital signal in OCT converted to LEA signal at output of OCT
4. LEA signal converted back to digital signal at input to relay

Alternatively, the following conversions occur to use a digital output from an OCT in a digital relay:

1. Primary current converted to analog light signal
2. Analog light signal converted to digital signal at input to OCT and sent to protective relay

In the second set, there is only one conversion from analog to digital along the entire path. Any conversion of data from analog to digital or from digital to analog will introduce errors. By only having one conversion there is less error introduced in the system.

To ensure communication between digital devices from any manufacturer (e.g., OITs and merging units (MUs)), the digital communication between devices should follow IEC 61869-9 (see section 6.0 for more discussion of industry standards).

3.5 Benefits

While the following benefits are possible, not all OITs will have these benefits or be implemented to the same degree. [7] The designer of a system with an OIT must ensure the specified OIT meets the project needs. The benefits of OITs include their increased accuracy, safety, design, and availability from several vendors.

The foremost marketed benefit of OITs is the ability to more accurately reproduce primary signals than a conventional IT. By not utilizing an iron core, OITs do not magnetically saturate. For heavy symmetrical faults and faults on systems with high X/R ratios (i.e., potentially large DC offset in current waveform during a fault) convention CTs can experience saturation. In contrast, an OCT does not experience magnetic saturation by design.

Additionally, the non-linearity of a magnetic circuit does not occur in an OIT. This allows for a linear characteristic across a larger dynamic range than conventional ITs. [5], [8] Another potential cause of error in a conventional CT is stray flux from nearby conductors under heavy faults. This can lead to localized saturation of a conventional CT. This phenomenon has been known to lead to misoperation of at least one generator differential protection relay at Reclamation. [6] OCTs have no iron core and are not influenced by stray flux.

If the digital outputs from an OIT are used, there are no concerns about overburdening the output. While conventional ITs will misrepresent the primary waveform if overburdened, digital signals from OITs cannot be overburdened.

There are at least three distinct safety benefits to be gained by utilizing OITs. First, an open in the secondary circuit will mean a loss of communication, but not a shock hazard. [5] Second, during normal operation there is no shock hazard on the secondary optical fibers. Third, there is galvanic isolation from the primary circuit. [7] With conventional ITs, there are wires coming from high voltage cubicles to areas where personnel perform work. While these wires are designed to operate at around 5 A for CT wires or 120 V for VT wires, there is a possibility of a dielectric failure bringing these wires up to primary voltage levels. Additionally, conventional VTs present a potential shock hazard if back fed during an outage. With OVTs, there is no way to back feed voltage to the primary system.

The physical design of OITs can be light weight which can lead to increased seismic performance. [5], [7]

There are several benefits from the digital nature of OITs including system topology/design flexibility, metering and protection in one device, varying bandwidths, and self-monitoring. If system topology changes intelligent electronic devices (IEDs) can be reprogrammed to receive the signals from the different OITs. Rather than necessitating a rewiring as with conventional ITs, only reprogramming is necessary if a digital communication scheme is utilized. [5] When designing new stations, the same basic OIT layout can be used throughout the station. Only the rated current and voltage need to be adjusted (no need to consider burden class as with conventional ITs). Depending on the system requirements, a single OIT could be used for both metering and relaying. OITs can also be designed with varying bandwidths to capture DC, AC, harmonics, and/or transients. Whereas conventional ITs perform no self-monitoring, OITs can include self-monitoring and externally communicate failures. [7] Overall, there are multiple benefits to using digitally communicating OITs in a digital substation design.

OITs have been designed that do not use oil of SF_6 as insulating mediums, providing an environmental benefit. [7]

Finally, OITs are market available from multiple established manufacturers. [7] As identified in section 4.0 of this report, there are at least eight manufacturers who provide OITs. These OITs are available in a range of current and voltage classes and can be applied at generation, transmission, and distribution levels.

In summary, the benefits of OITs are:

- More accurate representation of the primary system
- Increased personnel safety
- Digital flexibility
- Market availability from several vendors

Electrical system designers must not assume that all OITs provide all these benefits or provide them to the same degree. Individual designs must consider the characteristics of a given system and the needs of the application.

3.6 Drawbacks

While there are many benefits to OITs, there are also several drawbacks. The drawbacks include unfamiliarity, non-standard maintenance, higher/unknown costs, other system changes, resistance to change, security concerns, space requirements, and complexity.

A major drawback to OITs is lack of familiarity with the technology among engineers and facility personnel. To the author's knowledge, there are no applications of purely optical ITs in use at Reclamation.[4] A 2013 report, "CEATI Report No: T123700-3082, High Voltage (5 kV to 800 kV) Instrument Transformer Specification Guide" includes a survey of CEATI members regarding the use of NCITs. The report does not distinguish between types of NCITs (i.e., does not specifically report on OITs). The survey results indicated that less than one percent of ITs installed at 15 utilities were NCITs. While the survey is limited in scope, the survey shows that few NCITs were in use as of 2013. [1]

As OITs are not widespread in the industry, their limitations are not well known or understood by engineers or facility personnel. Utilities do not have established maintenance programs to test and maintain these devices. Complicating matters, OITs from manufacturer to manufacturer have differing forms and electronics. Therefore, implementing a standardized maintenance program will be difficult (e.g., the standardized maintenance of conventional ITs). OIT maintenance is specialized knowledge known to relatively few personnel in industry.

Another drawback is that OIT system costs are not known. Per the authors limited experience, a specific single phase OCT costs an order of magnitude higher than a similar single phase conventional CT. However, as this is only one data point costs have not been analyzed with this report. If other OITs from the other manufacturers follow this pattern (order of magnitude more in cost than conventional ITs), the cost differential is not negligible and should be considered in any cost benefit analysis.

Another major barrier to implementing OITs is the outputs from OITs do not match the traditional outputs from conventional ITs. [7] OITs typically have LEA and/or digital outputs. If OITs are retrofitted into an existing installation, secondary devices (e.g., meters and relays) will likely need to be updated. As recently as 2018 (see reference [7]), there are not many relays with LEA inputs on the market. A more practical solution is to move directly to a digital interface. [7]

Moving to a fully digital interface from a conventional IT setup is likely to cause concern from engineering staff at utilities. There are many valid and strong arguments to continue using tried and true conventional ITs and their HEA outputs.

---

[4] Author knows of one high voltage DC sensor used for testing that has an optical communication cable. There may be other OITs implemented at Reclamation that the author is unaware of.

From a security standpoint, OITs with digital outputs also present a greater security risk. Conventional ITs are used in point to point solutions. This point to point connection does not lend itself to being compromised. Digital solutions are more readily maliciously manipulated. Especially when considering using OITs for protection and control, information technology personnel should be part of the implementation process. Without the support of information technology personnel, the OIT solution may become vulnerable to cyber-attacks. One possible solution is to use an islanded approach with no network connections to other intranet or the internet. While this solution does not lead itself to remote monitoring, the security of critical control and protection systems would be increased.

Finally, while the sensor heads themselves of OITs can be lighter weight than their convention IT counterparts, the system includes additional components not necessary to operate conventional ITs. For a conventional IT, all that is needed is the IT itself and secondary wiring. OITs require the sensor head, cabling system, and sensor electronics. The sensor electronics and any MUs necessitate extra space. Depending on the available space this may prevent an existing electrical installation from converting over to OITs (without a building modification). In additional electronic circuitry has a limited life. Electronic system in general last around 20 year before needing to be upgraded. This limited life span would most likely apply to OITs. The life span of conventional IT is much longer.

Finally, OITs are inherently more complex than conventional ITs. The addition of electronics into a previously simple system (i.e., the simplicity of conventional ITs and secondary devices) is likely to experience push back within organizations. Many will justifiably argue that OITs are an unnecessary overcomplication of a problem that did not need to be solved.

In summary, the drawbacks of OITs are:

- Unfamiliarity
- Non-standard maintenance
- Higher/unknown costs
- Possible necessity of other system changes
- Resistance to change
- Security concerns
- Space for electronics
- Complexity

Overall, this list of drawbacks shows that OITs are not a one-for-one replacement for conventional ITs. The various drawbacks can explain the slow adoption of OITs.

3.7 Performance

To ensure proper performance in an application, the qualities of the OIT must be considered and matched to the application. Complicating matters, the requirements for OITs are not always easily translatable from the requirements for conventional ITs. Many of the basic assumptions made when utilizing conventional ITs must be re-evaluated to ensure that an OIT will meet the project needs.

One good reference for OIT requirements is IEEE Std 1601-2010. This standard includes requirements and testing procedures for OITs. [8] These requirements could be used in a specification to help ensure a product delivered by an original equipment manufacturer (OEM) will meet basic requirements and tests. However, IEEE Std 1601-2010 was initially published as a trial use standard and has not been republished to date. Among the OITs evaluated in section 4.0 of this report, none were found to reference IEEE Std 1601-2010.

IEEE Standard C37.241 includes a comprehensive review of the performance requirements of OITs. The standard breaks down OIT performance into the following:

1. Accuracy
2. Bandwidth
3. Noise
4. Stability
5. Temperature
6. Vibration
7. Other

These seven performance requirements are discussed in detail in the following sections.

3.7.1 Accuracy

As with conventional ITs, the accuracy classes of OITs are broken down between metering and protection. The typical metering and protection IEEE and IEC accuracy classes for conventional ITs can be used to describe OITs. However, OITs can be more accurate than their conventional counterparts across a wide range of operation. [2]

IEEE Std 1601-2010 includes a recommended accuracy classification for metering OCTs. This recommended classification accounts for the benefits of OCTs as compared to conventional CTs. This accuracy class is in the format of xDRy-z where:

- x = accuracy class (e.g., 0.3)
- DR = non-changing characters[5]
- y = low percent bound of accuracy class x
- z = high percent bound of accuracy class x

For example, for an OCT with accuracy rating 0.3% from 5% to 133% of nominal current would be represented as “0.3DR5-133”. The 0.3% accuracy must be maintained from 5% to 133% of rated

---

[5] “DR” likely stands for “Dynamic Range”, however this was not able to be verified.

current for this example rating. See IEEE Std 1601-2010 for a full description of this recommended accuracy classification of metering OCTs and preferred values of x, y, and z. [8]

Protection OCTs rated with typical IEEE and IEC protection accuracy classes may be significantly more accurate above rated current (e.g., fault current) due to the linear nature of the optical system.

When using LEA outputs (e.g., ±10 V) from any OIT system consider clipping. For example, an OCT output may be clipped at ±10 V output during a fault if the fault current exceeds the ±10 V secondary window. Clipping could also occur on the input side of an OIT if the primary value exceeded the allowable range.

Another important characteristic of an OIT is the sensor delay time. IEEE Std C37.94-2005(R2011)[6] gives phase angle requirements for electronic ITs (see Table 1 and 2 in the standard). The standard also notes that some applications such as current differential relays, directional relays, and revenue meters can provide erroneous data if time delays vary between ITs. The standard allows for manufacturers to specify a "Phase correction value" which can help account for delays in the system. This correction could be used to meet specific application requirements. [9] In addition to sensor delay time, digital data latency between devices can negatively affect OIT systems.

For current differential relaying schemes, more than just time delay between two sets of OCTs should be considered. As with conventional CTs, the ideal differential zone has matched CTs. This same practice of matched CT sets applies with OCTs. When CTs are not able to be matched identically the accuracy, bandwidth, and delay time should be considered to make an adequately secure zone of protection. [2]

3.7.2 Bandwidth

Theoretically, the optical component of an OIT can sense primary waveforms up to the gigahertz range. [2] Actual implementations of OITs will having varying bandwidths.

IEEE Std C37.241-2017 suggests the following bandwidths for varying applications: [2]

• Revenue metering	Least need for harmonics
• Transformer differential	High accuracy through 5th harmonic
• Other protection	Up to 50th harmonic
• Power quality	Up to 50th harmonic
• High frequency application	Varies (into the MHz)

For digital outputs from OITs, the OIT's output should include anti-aliasing filtering. IEEE Std C37.241-2017 recommends this filter be at one third to one fourth of the sampling frequency.

DC measurement capability is also important to consider. Some OITs are specifically designed to measure DC quantities. Consider the DC offset of electrical waveforms when specifying OITs (e.g., to capture the DC offset during a fault condition). The filtering within the OIT will determine how the DC offset is represented to secondary devices.

---

[6] IEEE Standard for Analog Inputs to Protective Relays from Electronic Voltage and Current Transducers

3.7.3 Noise

Just like all electronic devices, noise is a factor for OITs. For most metering, power quality, and protection applications, the inherent noise from OITs will have no negative effect on the application.

Noise is less of a concern for OVTs as the voltage while energized is typically near rated voltage. In contrast, an OCT can often experience currents near no load. Noise is relevant at and near no load. Manufacturer's often utilize additional fiber turns to account for noise in OCTs. [2]

3.7.4 Stability

The stability of conventional ITs must be met or exceeded by OITs. If signals drift over time, errors in measurements can affect metering, relaying, or control processes.

One mode of ageing that can affect the output of the OIT is a change in wavelength of the light source over time. For this stability error and any others, manufacturers and end users should have clearly outlined maintenance procedures to account for and correct problems. [2]

3.7.5 Temperature

As with all electrical components, OITs have specific rated operating temperatures. This rated operating temperature range may differ between components of an individual system depending on the intended installation location (e.g., outdoor versus indoor).

Temperature dependencies of OITs can be accounted for with temperature sensors installed with the components. If an OIT utilizes temperature measurement for compensation, the temperature sensor must remain accurate. These components should be included in a maintenance program. [2]

3.7.6 Vibration

OITs must be able to maintain performance for all normal vibration. For example, the performance of the OCT installed on a circuit breaker must be designed considering the vibration caused during breaker closing and opening. [2]

3.7.7 Other

Additionally, OITs need to meet all other requirements that are typical within a substation including:

- Basic impulse insulation level (BIL)
- Dielectric/insulation requirements
- Electromagnetic compatibility (EMC)
- Seismic requirements
- Thermal current requirements (e.g., expected continuous and short time current)

3.8 Market adoption

F. Rahmatian noted in his 2018 article, "Optical Instrument Transformers" in PAC World that the highest levels of market penetration and adoption of OITs are in HVDC, industrial high current applications (above 40 kA), and UHV (>800 kVAC). [7]

A 2013 report from CEATI also includes data on market penetration and adoption into the utility sector. This report shows that out of the fifteen utilities surveyed, seven had installed NCITs (the report does not distinguish if these were OITs or other types of NCITs). One utility had over 300 NCITs installed while the rest had fewer than ten each. The other eight utilities surveyed did not report having NCITs installed. While this survey is far from comprehensive, the survey shows that utilities have seen little adoption of NCITs. [1]

3.9 Failure Modes

One of the drawbacks identified for OITs was the lack of consistent and developed maintenance programs. IEEE Std C37.241-2017 identifies several failure modes for the various components of an OIT. The failure modes are broken down by system components: [2]

Sensor Head

- Insulation failure
- Loss of gas pressure
- Corrosion
- Optical system damage

Cabling System

- Physical damage (Excavation, water, ice, animals)
- Wires not meeting minimum load requirement

Sensor Electronics

- Mechanical failure of moving parts (e.g., fans)
- Temperature extremes (outdoor installation)
- Optical light source failure

These failure modes should be considered when developing an OIT maintenance program. Some failure modes can be addressed by visual inspection by trained personnel. Others will require specialized equipment and specialized training. The cost to maintain OITs should be compared to the costs of maintaining conventional ITs. This cost should be considered in a cost benefit analysis before implementing an OIT solution.

4.0 Market Available OITs

Market research was performed to determine the availability of OITs from commercial vendors. The following OITs were found to be applicable for control, metering, monitoring, protection, and testing. The intent of this list was to capture all market available OITs. However, some market available OITs may have inadvertently been missed. Those looking to implement OITs should perform additional market research.

4.1 OCTs

The following market available OCTs were identified:

1. ABB FOCS
2. Adamant Namiki AOCM-100
3. Arteche SDO OCT
4. CONDIS EFOCT
5. CONDIS F-EFOCT
6. GE COSI-CT
7. GE COSI-CT F3
8. Hitachi ABB FOCS-FS
9. NR Electric CO PCS-9250-OAI
10. Trench TOCT

Basic characteristics of each of these OCTs have been compiled in sections 4.1.1 to 4.1.10.

These OCTs were found to come in the following form factors:

1. Flexible sensor head
2. Insulator mounted
3. Integrated into other equipment (e.g., breaker or disconnect)
4. Non-flexible wrapped around primary
5. Suspended

4.1.1 ABB FOCS

Asea Brown Boveri (ABB) offers their Fiber-Optic Current Sensor (FOCS). The FOCS is designed for DC applications. This OCT is designed to be mounted directly onto and around the primary conductor. "The device can come with inbuilt protection features for instantaneous overcurrent, inverse time overcurrent, and instantaneous reverse current." [10]

Principle of operation	Faraday/magneto-optic effect
Application	Process control and measurement
Rated Frequency	DC
Rated current	0 to ±500 kA
Rated voltage	*Unknown*
Accuracy	±0.1%
Rated temperature (sensor)	-40 °C to 80 °C
Sampling Rate	4 kHz
Power Requirements	24 V_{DC}, 60 W
Outputs	Analog (± 1V and ± 20 mA) ABB PowerLINK PROFIBUS DP slave Relay output contacts for alarm/trip
Enclosure protection class	Sensor electronics IP 00 Optics and fiber cable IP 67
Headquarters Country	Switzerland

4.1.2 Adamant Namiki AOCM-100

Adamant Namiki offers their Optical Fiber Current Sensor (AOCM-100). The AOCM-100 is an OCT for AC applications. The OCT sensor head is flexible and is intended to be wrapped around conductors. [11], [12]

Principle of operation	Faraday/magneto-optic effect
Application	Electric power, railroad, auto, aviation, other
Rated Frequency	10 Hz to 10 kHz
Rated current	5 kA
Rated voltage	U*nknown*
Accuracy	JEC1201-1PS Class (at 1kA, 50Hz)
Rated temperature (sensor)	0 °C to 50 °C
Sampling Rate	*Unknown*
Power Requirements	100-250 V_{AC} (50 Hz or 60 Hz)
Outputs	Numeric Display, Analog Voltage
Enclosure protection class	*Unknown*
Headquarters Country	Japan

4.1.3 Arteche SDO OCT

Arteche offers their SDO OCT. The SDO OCT is an OCT for AC and DC applications. This CT is mounted on an insulator column. This CT can also be suspended from a conductor or integrated into other equipment (e.g. a circuit breaker or disconnect switch). [13], [14]

Principle of operation	Faraday/magneto-optic effect
Application	Metering and Protection
Rated Frequency	U*nknown*[7]
Rated current	2.5 kA (higher available upon request)
Rated voltage	Up to 550 kV
Accuracy	0.2 S, P20
Rated temperature (sensor)	-40 °C to 85 °C
Sampling Rate	Bandwidth: 2.4 kHz at 80 samples/cycle 7.6 kHz at 256 samples/cycle
Power Requirements	100-230 V_{DC}/V_{AC} or 48-125 V_{DC}; 25 W
Outputs	Digital: IEC 61850-9-2LE 8 relay contacts
Enclosure protection class	IP 66
Headquarters Country	U*nknown*[8]

4.1.4 CONDIS EFOCT

CONDIS offers their Electronic Fiber-Optic Current Transformer (EFOCT). The EFOCT is mounted on an insulator column. [15] CONDIS has developed the EFOCT in collaboration with Profotech. [16]

Principle of operation	U*nknown*[9]
Application	Metering and Protection
Rated Frequency	*Unknown*[10]
Rated current	300 A to 190 kA[11]
Rated voltage	Up to 800 kV
Accuracy	Metering: 0.05; 0.2S/2; 0.1; 0.2S; 0.5S Protection: 5TPE, 5P
Rated temperature (sensor)	-60 °C to 70 °C
Sampling Rate	80 samples/cycle or 256 samples/cycle
Power Requirements	50 W
Outputs	Digital: IEC 61850-9-2LE, IEC 61850-9-2, IEC 61850-8-1
Enclosure protection class	*Unknown*
Headquarters Country	CONDIS – Switzerland Profotech – Russia

---

[7] Unable to verify, likely DC, 50 Hz, and/or 60 Hz

[8] Unable to verify, possibly headquartered in Spain

[9] Unable to verify, likely the Faraday/magneto-optic effect

[10] Unable to verify, likely DC, 50 Hz, and/or 60 Hz

[11] 190 kA is likely a fault current rating, a continuous current rating of that magnitude is unreasonable

4.1.5 CONDIS F-EFOCT

CONDIS offers their Flexible Electronic Fiber-Optic Current Transformer (F-EFOCT). The F-EFOCT OCT has a flexible sensor head which is intended to be wrapped around conductors. [17] CONDIS has developed the F-EFOCT in collaboration with Profotech. [16]

Principle of operation	*Unknown*[12]
Application	Metering and Protection
Rated Frequency	*Unknown*[13]
Rated current	300 A to 190 kA[14]
Rated voltage	Up to 800 kV
Accuracy	Metering: 0.05; 0.2S/2; 0.1; 0.2S; 0.5S Protection: 5TPE, 5P
Rated temperature (sensor)	-60 °C to 70 °C
Sampling Rate	80 samples/cycle or 256 samples/cycle
Power Requirements	50 W
Outputs	Digital: IEC 61850-9-2LE, IEC 61850-9-2, IEC 61850-8-1
Enclosure protection class	*Unknown*
Headquarters Country	CONDIS – Switzerland Profotech – Russia

4.1.6 GE COSI-CT

General Electric (GE) offers their Compact Sensor Intelligence Optical Current Transformer (COSI-CT). The COSI-CT is designed for DC, 50 Hz, and/or 60 Hz applications. This OCT is designed to be mounted on top of an insulating column. [18], [19]

Principle of operation	Faraday/magneto-optic effect
Application	Metering and Protection
Rated Frequency	DC, 50 Hz, and/or 60 Hz
Rated current	Up to 4 kA
Rated voltage	Up to 800 kV
Accuracy	Metering: IEC 0.2S; IEEE 0.3, 0.15S Metering: Extended range: 0.15% from 0.2 to 150% rated current Metering: Extended range: 0.2% from 0.2 to 150% rated current Protection: IEC 5P; IEEE 10%
Rated temperature (sensor)	-40 °C to 55 °C
Sampling Rate	Bandwidth: DC to 100th harmonic
Power Requirements	70 to 150 V_{DC}, 60W
Outputs	HEA: 1 Arms (2 ohms burden) or 5 Arms (B0.1 (12.5 VA) burden) LEA: 4 Vrms metering, 200 mVrms protection Digital: IEC 61850
Enclosure protection class	*Unknown*
Headquarters Country	United States of America

---

[12] Unable to verify, likely the Faraday/magneto-optic effect

[13] Unable to verify, likely DC, 50 Hz, and/or 60 Hz

[14] 190 kA is likely a fault current rating, a continuous current rating of that magnitude is unreasonable

4.1.7 GE COSI-CT F3

General Electric (GE) offers their Compact Sensor Intelligence Flexible Optical Current Transformer (COSI-CT F3). The COSI-CT F3 is designed for DC, 50 Hz, and/or 60 Hz applications. This OCT is flexible and is intended to be wrapped around conductors. [20]

Principle of operation	Faraday/magneto-optic effect
Application	Metering and Protection
Rated Frequency	DC, 50 Hz, and/or 60 Hz
Rated current	Up to 2 kA
Rated voltage	*Unknown*[15]
Accuracy	0.1, 0.15S, 0.2S, 0.3, 1, 5
Rated temperature (sensor)	*Unknown*
Sampling Rate	*Unknown*
Power Requirements	70 to 150 V_{DC}, 60W
Outputs	Analog: 1 A, 11.3 V Digital: IEC 61850
Enclosure protection class	IP66
Headquarters Country	United States of America

4.1.8 Hitachi ABB FOCS-FS

Hitachi/ABB offers their Fiber-Optic Current Sensor – Free Standing (FOCS-FS). The FOCS-FS is designed for 50 Hz or 60 Hz applications. This OCT is mounted on a hollow silicon rubber insulator column filled with nitrogen at ambient pressure. Redundancy is discussed by Hitachi/ABB in their documentation. The system is offered in none, single, and double redundant systems. [21], [22]

Principle of operation	Faraday/magneto-optic effect
Application	Metering and Protection
Rated Frequency	50 Hz or 60 Hz
Rated current	4 kA
Rated voltage	Up to 800 kV
Accuracy	Metering: IEC 0.2S; IEEE 0.15S Protection: IEC class 5P, 5TPE; IEEE 10%
Rated temperature (sensor)	-40 °C to 45 °C
Sampling Rate	*Unknown*
Power Requirements	*Unknown*
Outputs	Digital: IEC 61850-9-2LE
Enclosure protection class	Control Cabinet IP 65
Headquarters Country	Switzerland (Japanese owned)[16]

---

[15] Several types of this sensor are available. Some are intended to be installed at the base of a bushing, allowing them to be installed on any voltage class.

[16] As of July 1st, 2020, Hitachi and ABB launched a joint venture called "Hitachi ABB Power Grids" [41]

4.1.9 NR Electric CO PCS-9250-OAI

NR Electric Co offers their PCS-9250-OAI. The PCS-9250-OAI is designed for DC applications. This CT can be mounted on an insulator or hung from a conductor. [23]

Principle of operation	Faraday/magneto-optic effect
Application	Control and Protection
Rated Frequency	DC
Rated current	Up to 6.25 kA
Rated voltage	Up to 1,100 kV_{DC}
Accuracy	10-120% rated current: ±0.2%
	200% rated current: ±1.5%
	600% rated current: ±3%
Rated temperature (sensor)	*Unknown*
Sampling Rate	*Unknown*[17]
Power Requirements	*Unknown*
Outputs	Digital: IEC 60044-8 or TDM bus protocol
Enclosure protection class	*Unknown*
Headquarters Country	China

4.1.10 Trench TOCT

Trench offers their Trench Optical Current Transformer (TOCT). The TOCT is designed for 16.7, 50, or 60 Hz applications. This CT can be mounted on an insulator or hung from the conductor. [24], [25], [26]

Principle of operation	Faraday/magneto-optic effect
Application	Metering and Protection
Rated Frequency	16.7, 50, or 60 Hz
Rated current	Up to 5 kA
Rated voltage	Up to 800 kV
Accuracy	Metering up to 0.2
	Protection up to 5P
Rated temperature (sensor)	-40 °C to 40 °C
Sampling Rate	*Unknown*
Power Requirements	*Unknown*
Outputs	Digital: IEC 61850-9-2
Enclosure protection class	*Unknown*
Headquarters Country	Owned by Siemens, Siemens headquartered in Germany

---

[17] Cutoff frequency is 4 kHz

4.2 OVTs

The following market available OVTs were identified:

1. ABB EOVT[18]
2. Eaton GridAdvisor Insight RE
3. Eaton GridAdvisor Insight RI

Basic characteristics of each of these OVTs has been compiled in sections 4.2.1 to 4.2.3.

These OVTs were found to come in the following form factors:

1. Electrical elbow mounted
2. Insulator mounted
3. Mounted onto conductor

---

[18] Possibly not in current production.

4.2.1 ABB EOVT

As of 2018, ABB was redesigning their Electro-Optical Voltage Transformer (EOVT). [27] A pilot installation had been used with the intent to detect switching transients.

Principle of operation	Pockels Effect
Application	*Unknown*[19]
Rated Frequency	*Unknown*[20]
Rated voltage	Pilot installation at 800 kV
Accuracy	*Unknown*
Rated temperature (sensor)	*Unknown*
Sampling Rate	*Unknown*[21]
Power Requirements	*Unknown*
Outputs	*Unknown*
Enclosure protection class	*Unknown*
Headquarters Country	Switzerland

4.2.2 Eaton GridAdvisor Insight RE

Eaton offers their GridAdvisor Insight RE Series Optical Underground Elbow Sensor System as an OVT. This OVT is designed for 60 Hz applications. The sensor can to be installed “directly inside standard… elbows.” [28], [29]

Principle of operation	*Unknown*[22]
Application	Distribution Monitoring
Rated Frequency	60 Hz
Rated voltage	4 kV to 15 kV (200 A class)
Accuracy	± 0.5%
Rated temperature (sensor)	-30 °C to 85 °C
Sampling Rate	“Harmonic voltage response up to 50th harmonic”
Power Requirements	To GridAdvisor Insight M410: 12-24 V_{DC}
Outputs	From GridAdvisor Insight m410: Analog: 0-10 V
Enclosure protection class	Submersion rated (25 feet (ft) for 7 days)
Headquarters Country	Ireland [30]

---

[19] Potentially metering and/or protection

[20] Likely 50 Hz and/or 60 Hz

[21] Potentially around 500 kHz [27]

[22] Unable to verify, likely the Pockels Effect

4.2.3 Eaton GridAdvisor Insight RI

Eaton offers the GridAdvisor Insight RI Series Optical Standoff Insulator Sensor System as an OVT. This OVT is designed for 60 Hz applications. The sensor is intended to be installed on bus bar (i.e., not from a ground plane to the conductor, but mounted onto the conductor itself). [29], [31]

Principle of operation	*Unknown*[23]
Application	Distribution Monitoring
Rated Frequency	60 Hz
Rated voltage	4 kV to 15 kV
Accuracy	±0.5 %
Rated temperature (sensor)	-30 °C to 85 °C
Sampling Rate	“Harmonics: measurements to 50th voltage harmonic”
Power Requirements	To GridAdvisor Insight M410: 12-24 V_{DC}
Outputs	From GridAdvisor Insight m410: Analog: 0-10 V
Enclosure protection class	IP-65
Headquarters Country	Ireland [30]

---

[23] Unable to verify, likely the Pockels Effect

4.3 Combined OCT and OVT

The following market available combined OCTs and OVTs were identified:

1. Eaton GridAdvisor Insight RE
2. Eaton GridAdvisor Insight RIC
3. Eaton GridAdvisor Insight RG235
4. Eaton GridAdvisor Insight RP

Basic characteristics of each of these combined OCTs and OVTs has been compiled in sections 4.3.1 to 4.3.4.

These combined OCTs and OVTs were found to come in the following form factors:

1. Electrical elbow mounted
2. Insulator mounted
3. Mounted onto conductor
4. Suspended

4.3.1 Eaton GridAdvisor Insight REC

Eaton offers their GridAdvisor Insight REC Series Optical Underground Elbow Sensor System as a combined OIT (OCT and OVT). This OIT is designed for 60 Hz applications. This sensor is designed to be installed “directly inside standard… elbows.” Compared to the GridAdvisor Insight RE (see section 4.2.2) a current ring is added to sense current. [28], [29]

Principle of operation	*Unknown*[24]
Application	Distribution Monitoring
Rated Frequency	60 Hz
Rated current	200 A class [32]
Rated voltage	4 kV to 15 kV
Accuracy	± 0.5%
Rated temperature (sensor)	-30 °C to 85 °C
Sampling Rate	“Harmonic voltage response up to 50th harmonic”
Power Requirements	To GridAdvisor Insight M410: 12-24 V_{DC}
Outputs	From GridAdvisor Insight m410: Analog: 0-10 V
Enclosure protection class	Submersion rated (25’ for 7 days)
Headquarters Country	Ireland [30]

4.3.2 Eaton GridAdvisor Insight RIC

Eaton offers their GridAdvisor Insight RI Series Optical Standoff Insulator Sensor System as a combined OIT (OCT and OVT). This OIT is designed for 60 Hz applications. This sensor is designed to be installed on bus bar (i.e., not from a ground plane to the conductor, but mounted onto the conductor itself). Compared to the GridAdvisor Insight RI (see section 4.2.3) a current ring is added to sense current. [29], [31]

Principle of operation	*Unknown*[25]
Application	Distribution Monitoring
Rated Frequency	60 Hz
Rated voltage	4 kV to 15 kV
Rated current	Up to 20 kA [32]
Accuracy	±0.5 %
Rated temperature (sensor)	-30 °C to 85 °C
Sampling Rate	“Harmonics: measurements to 50th voltage harmonic”
Power Requirements	To GridAdvisor Insight M410: 12-24 V_{DC}
Outputs	From GridAdvisor Insight m410: Analog: 0-10 V
Enclosure protection class	IP-65
Headquarters Country	Ireland [30]

---

[24] Unable to verify, likely Faraday/magneto-optic effect for the OCT and Pockels Effect for the OVT

[25] Unable to verify, likely Faraday/magneto-optic effect for the OCT and Pockels Effect for the OVT

4.3.3 Eaton GridAdvisor Insight RG235

Eaton offers their GridAdvisor Insight RG235 Optical Medium Voltage and Current Sensor System as a combined OIT (OCT and OVT). This OIT is designed for 60 Hz applications. This sensor is designed to be installed directly onto an overhead conductor, hanging from the conductor. [29], [33]

Principle of operation	*Unknown*[26]
Application	Distribution Monitoring
Rated Frequency	60 Hz
Rated current	5 A to 25 kA
Rated voltage	4 kV to 35 kV
Accuracy	±5 %
Rated temperature (sensor)	-30 °C to 85 °C
Sampling Rate	"Harmonics: measurements to 50th voltage harmonic"
Power Requirements	To GridAdvisor Insight M410: 12-24 V_{DC}
Outputs	From GridAdvisor Insight m410: Analog: 0-10 V
Enclosure protection class	Outdoor rated (class unknown)
Headquarters Country	Ireland [30]

4.3.4 Eaton GridAdvisor Insight RP

Eaton offers their GridAdvisor Insight RP Series Optical Line Post Medium-Voltage and Current Sensor System as a combined OIT (OCT and OVT). This OIT is designed for 60 Hz applications. This sensor is designed to be installed on a ground plane with a conductor passing through the sensor head. [29], [34]

Principle of operation	*Unknown*[27]
Application	Distribution Monitoring
Rated Frequency	60 Hz
Rated current	5 A to 30 kA
Rated voltage	4 kV to 35 kV
Accuracy	±0.5 %
Rated temperature (sensor)	-30 °C to 85 °C
Sampling Rate	"Harmonics: measurements to 50th harmonic"
Power Requirements	To GridAdvisor Insight M410: 12-24 V_{DC}
Outputs	From GridAdvisor Insight m410: Analog: 0-10 V
Enclosure protection class	Outdoor rated (class unknown)
Headquarters Country	Ireland [30]

---

[26] Unable to verify, likely Faraday/magneto-optic effect for the OCT and Pockels Effect for the OVT

[27] Unable to verify, likely Faraday/magneto-optic effect for the OCT and Pockels Effect for the OVT

5.0 Digital Substation

Standard practice in the electrical industry has become to utilize digital devices for control, monitoring, and protection following the advent of digital systems. This evolution to digital processes and signals is slowly making its way throughout electrical installations. There are commercially available solutions to push digital applications beyond just the control, monitoring, and protection secondary devices themselves into the communication between these devices as well as the signals provided to these devices.

Describing the implementation of a "digital substation" is not the intent of this report. However, in order to discuss the interoperability of digital ITs (including OITs) and IEDs, some implementations of the digital interfaces are identified below.

In 2002, IEC 60044-8 was released. This standard was used by some manufacturers to implement digital communication between digital ITs and IEDs. [7]

IEC 61850-9-2 and the UCA implementation guide, "Implementation Guideline for Digital Interface to Instrument Transformers using IEC 61850-9-2," [35] have experienced large usage in the implementation of digital interfaces between digital ITs and IEDs. The latest revision of the UCA implementation guide, also known as "9-2LE," is from 2004. [7]

In 2016, IEC 61869-9 was published and became the standard for implementation of the IEC 61850-9-2 interface between digital ITs and IEDs. IEC 61869-9 replaced IEC 60044-8 and is backwards compatible with the UCA implementation guide 9-2LE. [36] New implementations of communication between digital ITs (including OITs) and IEDs should follow IEC 61869-9.

5.1 Relaying

Many Reclamation facilities utilize Schweitzer Engineering Laboratories, Inc (SEL) relays for protection. A majority of SEL relays are based around utilizing inputs from conventional ITs (i.e., HEA outputs). However, SEL does support digital communication solutions. The following list of SEL relays can subscribe to up to seven steams of 9-2LE compliant digital samples:

- SEL-421-7 – Protection, Automation, and Control System with Sampled Values
- SEL-451-6 – Protection, Automation, and Bay Control System with Sampled Values
- SEL-487B-2 – Bus Differential and Breaker Failure Relay with Sampled Values
- SEL-487E-5 – Transformer Protection Relay with Sampled Values

The seven streams that these four relays can receive can include more than one IT per stream. The content of these streams depends on the upstream device or MU. MUs can take multiple sources of data (e.g., conventional ITs or OITs) and combine them into one data stream.

The following SEL relays can take in analog data from conventional ITs and publish those values as IEC 61850-9-2 sampled value streams:

- SEL-401 – Protection, Automation, and Control Merging Unit
- SEL-421-7 – Protection, Automation, and Control System with Sampled Values

The only relay from SEL that is capable of both subscribing and publishing sampled value streams is the SEL-421-7. However, the SEL-421-7 can only be configured to either subscribe or publish digital samples, not both.

The lists of SEL relays were compiled from information on SEL's website in mid-2020. This list is likely to change as more utilities begin implementing digital relay communication solutions in their substations and powerplants. [37]

It should also be noted that other relay manufacturers (e.g., ABB, GE, Siemens, Eaton…) have relays that list support for IEC 61850. As Reclamation utilizes less of these relays throughout its facilities, relays from these manufacturers have not been reviewed in detail.

6.0 Industry Standards

There are many industry standards relevant to the application and implementation of OITs. The following list includes many of these standards as of summer 2020 (**bold emphasis** in standard names used to call out relevance of a given standard).

IEEE Standards and Guides:

- IEEE Std 1601™-2010 – IEEE Trial-Use **Standard** for **Optical** AC Current and Voltage **Sensing Systems** [8][28]
    - Includes:
        - Basic overview of OITs
        - Performance and test requirements for OITs
    - Could use in a specification to ensure quality of OIT system
- IEEE Std C37.92™-2005(R2011) – IEEE Standard for Analog Inputs to Protective Relays from Electronic Voltage and Current Transducers
- IEEE Std C37.241™-2017 – IEEE **Guide** for Application of **Optical Instrument Transformers** for Protective **Relaying** [2]
    - Includes:
        - Basic types
        - Review of performance
        - Outputs (HEA, LEA, digital) and relevant reference standards
        - Applications
        - Installation, commissioning, and testing guidance
        - Discussion of reliability and redundancy
    - Could use to ensure a comprehensive program implementing OITs
- IEEE Std C57.13™-2016 – IEEE Standard Requirements for Instrument Transformers
- IEEE Std C57.13.6™-2016 – IEEE Standard for High-Accuracy Instrument Transformers

International Electrotechnical Commission (IEC) Standards:

- IEC 61850-9-2 Edition 2.1 2020 – Communication networks and systems for power utility automation – Part 9-2: Specific communication service mapping (SCSM) – Sampled values over ISO/IEC 8802-3
- IEC 61869-1 Edition 1.0 2007 – Instrument transformers – Part 1: General requirements
- IEC 61869-6 Edition 1.0 2016 – Instrument transformers – Part 6: Additional general requirements for **low-power instrument transformers**
- IEC 61869-9 Edition 1.0 2016 – Instrument transformers – Part 9: **Digital interface** for instrument transformers

---

[28] This trial use standard is no longer active.

7.0 Procuring an OCT

As part of this research, an OCT was procured via the standard Reclamation procurement process (for items above the $10,000 credit card micro-purchase threshold). The support and service received from the Reclamation procurement team was excellent. However, there were several items of note in the process.

The procured OCT was intended to be used only in a lab environment to gain familiarity and perform some basic tests on the operation of the device. To the author's knowledge, this was the first OCT procured by Reclamation. Being the first OCT to be procured, there were several challenges. Primarily, personnel writing and reviewing the salient characteristics (specifications) did not have hands on experience with the final product. Writing and reviewing a procurement package without experience with the final product is challenging. As OITs are vastly different from conventional ITs, adequate research is necessary to ensure the solution will meet the project's needs.

During the initial stages of procurement there was a high amount of coordination between personnel writing the specifications and the procurement personnel. In contrast, the procurement for a more standard item that was more commonplace would have been able to proceed in a more expedited manner. For first time procurements of OITs the procurement process will likely not proceed at the same rate as more commonly procured products.

After the procurement package was awarded to a vendor, there was a reasonable time delay between award and delivery. Upon approaching the delivery date, the vendor indicated there were manufacturing issues related to meeting the specified accuracy. The agreed upon delivery date was passed without delivery of the device. The vendor was able to meet the specified accuracy before delivery. While OITs seem to meet the definition of commercially available off-the-shelf (COTS), this experience procuring an OCT indicated that at least this vendor needed to work through several issues on production in order to meet an agreed upon accuracy.

As delivered, the OCT was specified to have:

- Metering accuracy of 0.15S (or more accurate)
- Rated primary current: 1,000 A
- Both DC and 60 Hz capability
- Include an analog current and/or voltage output

8.0 Set up of an OCT

After the OCT was received, the OCT was brought into the lab to be set up. The following sections detail the experience setting up the OCT and conclusions drawn from the set up process.

8.1 Set up Experience

The procured single phase OCT came in four boxes. Three of the boxes were large enough that a conventional CT of similar characteristics could have fit in each box. The single phase OCT system took approximately the physical space of a full, three phase set of similarly rated conventional CTs. After removing all the components from the four boxes, the OCT was wired and configured.

The instructions that came with the OCT were not adequate to set up the OCT without manufacturer support. The following issues came up during set up that were only able to be overcome with manufacturer support:

1. Initially, wiring diagrams not sent
2. Conflicting ferrite choke installation instructions
3. Insufficient labeling of LEA outputs
4. Communication issues between laptop and sensor electronics

The first issue was the lack of wiring diagrams from the vendor. The vendor quickly supplied the drawings upon request. This honest mistake on the vendor's part did not cause anything but a short and minor inconvenience. However, the need of a drawing package to set up an OCT illustrates that OCTs are more complex than conventional CTs. Conventional CTs require no such supplemental wiring diagrams. The basic fact that wiring diagrams are drafted shows the additional complexity of the OCT system. The wiring diagrams called out compensation circuits that needed to be installed in parallel to the optical fiber. There was an expectation that utilizing an OCT removed the need for copper wiring from the sensor electronics to the OCT sensor head. However, the system necessitated copper wiring for two compensation circuits.

The second issue was conflicting information regarding ferrite choke installation. The chokes are included to ensure the OCT would meet rated accuracy. This conflicting information was further complicated with the arrival of the wiring diagrams. For an installation in a power facility these instructions must be clear to ensure that rated accuracy is met. While this OCT required ferrite chokes for noise control on the copper wiring, conventional CTs have no such requirement.

The third issue identified was the insufficient labeling of the LEA outputs. These outputs were not sufficiently labeled on the sensor electronics or in the documentation. After requesting guidance, a supplemental email from the vendor was provided clarifying the LEA outputs.

These first three issues point to the fact that OCTs are more complex than conventional CTs. Additionally, for the specific vendor that provided the procured OCT, the product does not seem to be in high demand or mature. If the OCT were in high demand or mature, these issues would likely have been worked through long ago.

The fourth issue was communication between a Reclamation laptop (running proprietary vendor software) and the sensor electronics. Establishing first time communication between laptop computers running proprietary vendor software and electronics is challenging (e.g., USB driver issues). After many attempts taking several hours, communication was established between the computer and the MU. A conventional CT includes no electronics to communicate with and configure. This time to troubleshoot communications to an electronic device takes real time and money. This time should not be ignored in cost benefit analysis for OITs as compared to conventional CTs. This cost is likely to occur every time maintenance is performed on the device as computers receiving regular updates can "break" previous successful methods of communication.

8.2 Set up Conclusions

As compared to a conventional CT, the set up of an OCT is more complicated and requires technical competencies not required to set up a conventional CT. These technical competencies include:

- Basic knowledge of OCTs
- Utilization of proprietary vendor interface software
- Troubleshooting of network/inter device communication
- Splicing and laying fiber optic cable
- Installation of rack mounted hardware

While none of these additional competencies are beyond the reach of personnel working in power facilities, additional training and time likely will be necessary to install and commission OITs as compared to conventional ITs.

Upon arrival to the lab, the procured single phase OCT was in four boxes. Three of these four boxes would have been large enough to each hold a similar single phase conventional CT. This basic observation shows that an OCT installation requires additional space as compared to an installation of a conventional CT. The four boxes for the single phase OCT included the OIT components as called out in section 3.4 of this report:

1. Sensor Head
2. Cabling System
3. Sensor Electronics

While the footprint of the actual OCT sensing head was comparable to a conventional CT, the additional items take up space beyond the requirements of a conventional CT. In a truly digital substation design, there is an elimination of secondary copper wiring from ITs. However, the use of OITs, sensor electronics, and MUs takes up space that is not necessary for a conventional IT installation. The additional space requirement alone may bar some existing power stations from retrofit installation of OITs (i.e., without a building modification or other solution).

Additionally, OITs can include compensation circuits (e.g., for temperature). In the case of the procured OCTs for this project, shielded twisted pair needed to be installed from the sensor electronics all the way to the final optical control box (installed near the OCT sensor head). So instead of truly eliminating copper wiring, there was copper wiring almost all the way to the sensor head.

All the additional components to set up and operate an OCT show that OCTs are more complex than conventional CTs. While OCTs do provide benefits when compared conventional CTs, additional complexity is a major drawback to the use of OITs.

The electrical generation, transmission, and distribution industries are designed around high reliability. Conventional ITs are highly reliable devices with well-known drawbacks. Adding in additional complexity by utilizing OITs requires proper justification. OITs should not simply be used in place of conventional ITs without considering the additional complexity, and therein additional failure modes, of OIT systems.

9.0 Lab testing an OCT

After the OCT was successfully set up, several basic experiments were performed. The intent of this testing was not to perform accuracy testing to fully verify the performance of the OCT.[29] Rather, the intent was to discover the general response and use of the OCT system. As such, the following analysis will include qualitative rather than quantitative discussion of the procured OCT. While other OCTs may not necessarily operate similarly to the procured OCT, the insights still provide a view into the operation of any OCT.

The lab used to test the OCT does not have any devices capable of interfacing with the digital output of the OCT. Therefore, all tests were performed observing the metering and protection LEA outputs as well as the digital magnitude readout within the proprietary vendor software.[30] Future work could include procuring a device to read the digital stream and comparing this to the LEA and digital magnitude readout.

Rather than performing tests at high voltage and current, the tests were performed at low voltages and current near the rated current of the OCT. The rated current of the procured OCT was 1,000 A. The following tests were performed with the OCT:

1. Verification of AC operation (see section 9.1)
2. Verification of DC operation (see section 9.2)
3. Power loss to sensor electronics (see section 9.3)
4. AC magnitude (see section 9.4)
5. AC frequency response (see section 9.5)
6. Flux-summing (see section 9.6)
7. DC magnitude (see section 9.7)[31]

The performance and results of the testing is reviewed in the following sections.

---

[29] The lab used to perform the testing is not typically used for metrology nor was the test operator trained in the practice of metrology.

[30] The digital magnitude readout only gives a magnitude of the current through the OCT's sensing head. The readout was found in the proprietary vendor software installed on the computer connected to the OCT.

[31] The validity of the data from Test 7 is questionable. Therefore, this report does not review or make conclusions from this test.

9.1 Test 1: Verification of AC operation

To verify initial operation of the OCT with AC current, test currents from 100 A_{AC} to 500 A_{AC} were passed through the OCT sensing head. The current was output in 100 A_{AC} steps (i.e., 100 A_{AC}, 200 A_{AC}, 300 A_{AC}, 400 A_{AC}, and 500 A_{AC}). All currents were alternating current at 60 Hz.

Alternating current for this test (and all remaining tests with alternating current) was sourced from an Omicron CPC 100 universal primary injection test set (CPC 100). [38] To verify the output of the CPC 100 for all tests, a 500 A to 50 mV shunt was placed in the circuit. All current from the CPC 100 passed through the window of the OCT sensor head as well as this shunt (see Figure 1 and Figure 2).

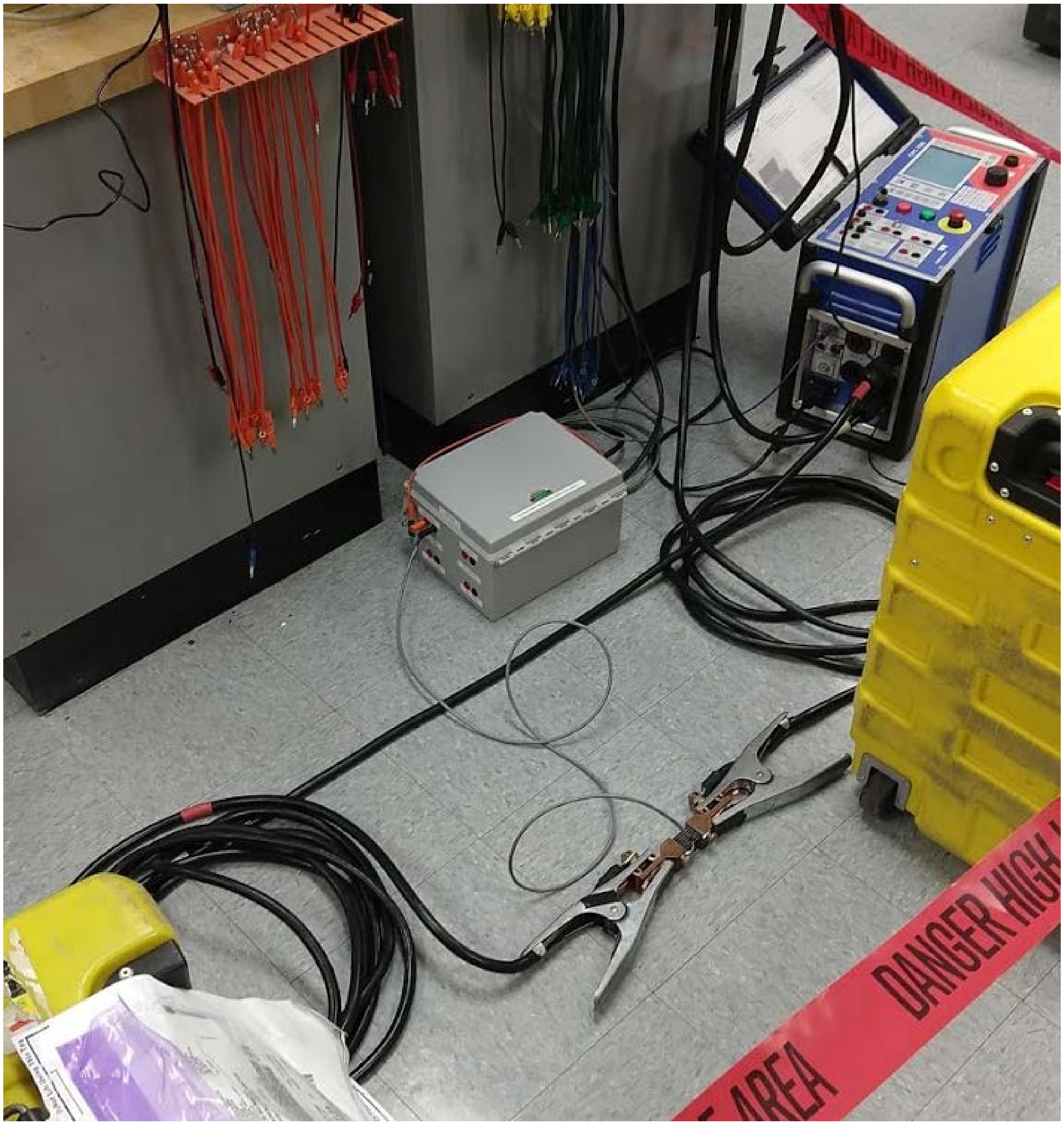


Figure 1.–CPC 100, current path (cables), and shunt
Note: OCT just off picture to top right, intentionally left out of photo

Figure 2.–500 A to 50 mV shunt in primary circuit

As current was stepped from 100 A to 500 A, the CPC 100 and shunt both indicated the same current (via display of CPC 100 and multimeter on output of shunt), but the digital magnitude readout from the computer connected to the OCT and LEA outputs indicated the current at 1.2 times higher.

Upon arrival, the fiber optic measuring head of the OCT came pre-wrapped. Per the nameplate of the OCT, the sensing head should be wrapped around the primary conductor 20 times. When counted, the measuring head was wrapped around the primary conductor 24 times. As such, the measured current was being reported at 1.2 times the current through the window (24/20 = 1.2). The vendor intended the sensor head to be re-wrapped before use to the rated 20 wraps (see Test 4 for a description of the results with the correct number of wraps).

This basic mistake and assumption (i.e., operator error) in running the test illustrates an important consideration. Any easy assumptions to make when working with OCTs is that OCTs are entirely like conventional CTs. This assumption has good basis but leads to basic misinterpretations and misunderstandings of the OCT. While this specific mistake in set up only applies to CTs other basic assumptions on the similarities of conventional CTs and OCTs could lead to other incorrect assumptions.

9.2 Test 2: Verification of DC operation

To verify initial operation of the OCT with DC current Test 2 was performed. The procured OCT was rated to work at both DC and 60 Hz.

The CPC 100 and shunt were both used again for this test. A first test point at 100 A_{DC} was attempted. The results were not as expected. Rather than reading 100 A_{DC}, the digital magnitude readout on the computer and the LEA outputs both initially showed approximately 100 A_{DC} and then slowly decreased to approximately 0 A_{DC}. The drop off appeared to occur as if a filter was slowly reducing the DC value to 0 A_{DC}. However, the actual test value through the OCT was constant at 100 A_{DC}.

The manufacturer was contacted regarding this issue. The manufacturer identified a registry setting to enable DC operation had been disabled before the OCT left the manufacturer's facility. The manufacturer provided the method to log in to the sensor electronics as an administrator and change the registry value. This enabled DC operation.

Having onsite manufacturer support to perform the initial set up and commissioning of the OCT would have been highly valuable. For any installations of OITs consider including onsite manufacturer installation, commissioning, and post-commissioning in contracts.

This sequence of events to enable DC operation also illustrates the complexity of an OCT. There are no electronics or registry settings for a conventional CT. However, a conventional CT cannot be used to measure direct current through a conductor. The additional complexity of the OCT does allow for additional modes of operation.

9.3 Test 3: Power loss to sensor electronics

During the initial set up the OCT sensor electronics the OCT was turned on and off several times. A light emitting diode (LED) on the front of the OCT indicated "Data Invalid" for a period whenever the OCT was powered up. This period was timed at 90 seconds from initial power up.

OIT sensor electronics should be powered from a UPS or battery backup system. If power was lost to the sensor electronics, the controllers, meters, and relays within the station would lose indication of the operation of the primary system. These devices rely on continual, uninterrupted signals to perform their function.

Conventional ITs require no additional power source other than the primary circuit to create their secondary signal. This creates an additional failure mode for OITs by adding in the necessity of a continual power supply. Power loss is an additional failure mode for OITs that should to be considered.

9.4 Test 4: AC magnitude

The fourth test of the OCT used the setup from Test 1 (CPC 100 and shunt). Additionally, an oscilloscope was connected to the output of the shunt and LEA outputs from the OCT sensor electronics. The inclusion of the oscilloscope allowed the waveforms from the shunt and OCT to be compared.

In order to not use the shunt outside of its rated current range, the current from the CPC 100 was only run up to 500 A_{AC}. To get to 2,000 A_{AC} through the sensing head of the OCT, the primary conductor was run through the sensing head four times.

The current on the CPC 100 was then stepped up in 50 A_{AC} steps (corresponding to 200 A_{AC} steps through the OCT sensing head). Output current values were run up to 500 A_{AC} (2,000 A_{AC} through the OCT) all at 60 Hz.

The test demonstrated that the OCT was reliably reproducing the primary waveform magnitude, waveshape, and phasing. The intent of the lab testing was not to perform metrology to verify the specified accuracy of the OCT. Therefore, the specific, quantitative results have not been included with this report. However, the test showed that the OCT was reproducing the primary waveform as expected.

9.5 Test 5: AC frequency response

The fifth test of the OCT used the same setup as Test 4 (with CPC 100, shunt, and oscilloscope). This test was performed with four wraps of the primary winding through the OCT window with the CPC 100 outputting 125 A_{AC}. Therefore, the OCT itself had 500 A_{AC} through its sensing head.[32]

The current magnitude from the CPC 100 was held constant while the frequency was varied from 15 Hz to 400 Hz. Tests were performed with 5 Hz increments from 15 Hz to 60 Hz and 30 Hz increments from 60 Hz to 390 Hz (with an additional point at 400 Hz). Additionally, the frequency was slowly swept from 15 Hz to 400 Hz to visually observe any other changes at untested frequencies.

This testing revealed that the procured OCT introduces significant phase shift whenever the frequency of the primary signal is not at 60 Hz or one of its harmonics (i.e., ≅ 0° phase shift at 1st, 2nd, 3rd, 4th, 5th, and 6th harmonics). Observing the output of the shunt and LEA as the frequency was swept from 15 Hz to 400 Hz, the LEA signals would lag the shunt signal by an additional cycle between each harmonic. For example, at 60 Hz the shunt and LEA signals were in phase. When the frequency was slowly raised to 120 Hz, the LEA signal lagged the shunt signal before coming back into phase with the shunt signal as 120 Hz. Rather than being truly in phase, the signal was really lagging by an additional 360°. Continuing to ramp the frequency from 120 Hz, the LEA would continue to lag by another 360° each harmonic. At 30 Hz increments between the 60 Hz harmonics, the signal from the shunt and LEA outputs were 180° out of phase.

In addition to the phase shift, the magnitude of the metering LEA output slightly reduced as the frequency increased. However, the maximum reduction was only ~5% of the current through the CT at 400 Hz. The relaying LEA output showed no reduction in magnitude at any frequency level (15 Hz to 400 Hz).

The digital magnitude readout on the computer connected to the sensor electronics was only correct at 60 Hz. Below 60 Hz, this readout gave a value significantly above the primary current (e.g., >150% of primary magnitude at 15 Hz). Above 60 Hz, the digital magnitude readout gave a value significantly below the primary current (e.g., <25% of primary magnitude at 400 Hz).

---

[32] 500 A is half of the rated 1,000 A of the OCT. This allowed the setup to be run continually without heating concerns for the wiring, shunt, and other connectors in the primary current path. Heating was observed via a thermographic camera during all tests (1 through 7) to verify that no components were overheating.

The lab in which testing was performed did not have the capability to read and interpret the digital waveform output signals from the OCT. How the digital signal reacts to the change in frequency is unknown. However, the digital signals likely follow the response of the LEA outputs.

The frequency response of this OCT is unlikely to match the frequency response of other OCTs (different make/model). Therefore, ideally OCT technology (make/model) should be matched when going to a single device (or even within an entire electrical station). This is particularly true when working with a differential relay. Common practice with conventional CTs is to match the make/model of conventional CTs within a differential zone whenever possible. Ideally, OCTs in a differential zone should also be of the same make/model to account for differing frequency responses. Varying technologies (e.g., a mix of conventional CTs and OCTs) may work in a differential zone. However, the variations in frequency response could create unintended differences between the secondary signals. This error could likely be accounted for in the differential relay settings.

Another concern when considering relaying applications is the ability of the ITs to transmit harmonic content to the relay. For example, when protecting transformers with differential relays the 2nd, 4th, and 5th harmonics are used by relay manufacturer's to ensure security of the differential element. [39] The procured OCT did reliably reproduce the harmonic data on the relaying LEA output. Therefore, with the procured OCT, the relay should receive the correct harmonic phase and magnitude data.

Additionally, any applications with non-60 Hz frequency (e.g., static start of a synchronous motor from standstill or reduced frequency start) need consider not only the frequency response of the OCT, but any protection devices (e.g., relays) at the non-60 Hz frequency to understand what protection will be provided during non-60 Hz operation.

Future work to test the digital output of OCTs with varying frequency could provide further insight to installations utilizing the digital outputs.

9.6 Test 6: Flux-summing

For the sixth test, two separate scenarios were simulated to determine the ability of the OCT window to perform flux-summing. For the purposes of this paper, flux-summing will be defined as the OCT adding the components of flux from a conductor that passes into the OCT window in one direction and then back out in the opposite direction. IEEE Std C37.241-2017 refers to this flux-summing as "effectively-flux nulling." [2]

One possible application of flux-summing with OCTs is to pass the current into and out of a device through the same sensing head. For example, the current from the generator neutral and generator terminal could be passed through the same OCT (more easily completed with a flexible OCT sensing head). This would allow the current into and out of the generator (or other device) to cancel one another, leaving any differential current to be detected by the OCT. Another example is passing all three conductors of a balanced three phase load through the OCT. This would sum all three phases and detect any unbalance. This protection is typically used on three phase motors. Depending on the expected differential current, the noise of the system would need to be considered. For example, high impedance grounded synchronous generators at Reclamation typically have single line to ground fault currents on the order of 10 A_{AC}. The noise of the system would have to be substantially below this value for a differential flux-summing configuration to be viable.

This scenario was simulated in the lab by passing a conductor through the OCT sensing head and then several feet past the head the conduct was looped back and passed back through the OCT sensing head in the opposite direction. For an ideal CT, the current through the sensing head would sum to zero. This scenario was tested with up to 500 A_{AC} at 60 Hz running through the OCT sensing head. For all outputs (computer magnitude and LEA's) there was no change from the base level of noise from no current to 500 A_{AC}.

In addition to the first scenario, a second setup included the conductor being wrapped twice in one direction through the OCT sensing head and then the conductor was brought back through in the opposite direction one time. For an ideal CT, this would represent only one pass through the OCT sensing head in the direction of the original two wraps. This setup was tested with 100 A_{AC} to 500 A_{AC} at 60 Hz (in 100 A_{AC} steps). The results from this test showed that the OCT was reproducing only one "wrap" worth of current as expected.

The flux-summing testing showed that OCT could potentially be used to perform flux-summing. Future research with this implemented on an actual electrical system could be used to further prove out a differential current scheme based on flux-summing.

9.7 Test 7: DC magnitude

The seventh and final test performed with the procured OCT was to run DC current through the sensing head. The initial DC current test (Test 2) used the "DC" output of the CPC 100. This DC output was found to have a duty cycle/ripple rather than being a flat DC waveform.

Therefore, in order to develop a true DC test signal that consistently stayed on (without a duty cycle), four 12 V_{DC} automotive batteries were connected in series using a battery test set as a load. This allowed the current from the batteries to be varied from 0 A_{DC} to 100 A_{DC}. The primary current through the procured OCT's window was wrapped four times to allow for testing up to 400 A_{DC}.

Upon re-reviewing the data for this specific test, inconsistencies in the results lead to suspicion of the data's validity. Therefore, the data was not analyzed for this report. Future tests could re-perform this DC testing.

9.8 Testing conclusions

The following basic conclusions are drawn from the testing performed on the procured OCT:

1. OITs have basic differences from conventional ITs that need to be considered when designing systems with OITs (see Test 1, section 9.1).
2. OITs have additional installation requirements and constraints that may not be immediately obvious to personnel unfamiliar with OITs. Consider having onsite manufacturer support for installation, commissioning, training, and post commissioning support (see Test 1 and 2, sections 9.1 and 9.2).
3. OITs should be powered by a UPS or battery system (see Test 3, section 9.3).
4. OITs are not ideal ITs. The OIT tested for this report introduced phase and magnitude shifts at non-fundamental and non-odd-harmonic values (see Test 5, section 9.5).
5. OCTs used for differential protection should ideally be the same make/model (see Test 5, section 9.5).
6. OCTs could potentially be used to perform differential protection via flux-summing (see Test 6, section 9.6).

10.0 Potential future work

Currently, there is no planned future work with OITs within the Reclamation Technical Service Center, Power System Analysis & Controls group. However, there are many potential future work opportunities in lab testing, pilot installation, and electrical diagnostics.

Future lab testing could include:

1. Re-performing the DC testing from this review (results were found to be invalid)
2. Testing with DC and AC superimposed, mimicking an actual electrical fault
3. Performing metrological studies to verify the accuracy of OITs
4. Connecting into the digital stream from an OIT and performing basic functionality testing

Future pilot installations of OITs could include installations at:

1. Pump/generator units with reduced frequency or static start, observe non-60 Hz response
    a. Potentially implementing a flux-summing current differential scheme
2. Locations with high fault current and/or high X/R ratios
3. Locations with known stray flux problems
4. Locations with other known saturation issues (e.g., overburdened conventional ITs)

Future use in electrical diagnostics testing could include:

1. Replacing conventional ITs with OITs (e.g., for high potential (hipot) testing)

Other potential future work:

1. Implement IEC 61869-9 digital communication between secondary devices (e.g., relays)
    a. Potentially before implementing digital ITs or OITs (i.e., step by step implementation)
2. Develop robust maintenance program for OITs accounting for unique abilities/failure modes
    a. Potentially in conjunction with pilot installations
3. Develop full list of costs to compare conventional IT and OIT installations
    a. Potentially in conjunction with pilot installations

11.0 Conclusion

ITs are an integral part of the power grid. Conventional ITs constructed with copper and iron continue to be prolific due to their well-known reliability, benefits, and operation. The drawbacks of conventional ITs are accounted and compensated for in designs to ensure a robust, reliable system.

OITs are marketed as a solution to the inaccuracies and safety issues related to conventional ITs. However, OITs are not a one-for-one replacement for conventional ITs in the generation, transmission, or distribution system. OITs are more complex than conventional ITs. Varying OITs have varying characteristics. In contrast, conventional ITs from different manufacturers delivered to the same specification will have less differences. For OITs built to the same generic specification, the proprietary vendor optical system, electronics, and software implementation will vary.

The additional complexity of OITs means additional failure modes and shorter predicted life span than conventional ITs. These failure modes must be accounted for in design as well as in a robust maintenance program. For a utility to effectively implement OITs, a maintenance program will have to be developed. This program will need individual requirements for devices from individual manufacturers.

An additional hurdle is that OITs will not readily integrate with the installed systems in many power facilities. Traditionally, installed secondary systems are designed around HEA outputs. OITs typically have LEA and digital outputs. To utilize either LEA or digital outputs will require new equipment designed to receive and process these signals. The implementation of a digital system should include information technology personnel to ensure the system is secure. The costs to procure, set up, operate, and maintain OITs are not well known or established.

Many will justifiably argue that OITs are an unnecessary overcomplication of a problem that did not need to be solved. The various drawbacks explain the slow adoption of OITs. However, for all these downsides and unknowns, the use of OITs in place of conventional ITs can provide real, measurable benefits. For installations with high fault currents, non-60 Hz operation, and the need for a wide dynamic range of operation, OITs can provide benefits. Safety can also increase from the use of OITs as OITs provide a high level of electrical isolation from the primary system.

A cost benefit analysis should be conducted prior to retrofits and new installations of OITs. Pilot installations to further evaluate the set up, commissioning, operation, and maintenance of OITs would provide additional insights before any paradigm shift away from tried and true conventional ITs.

OITs have the potential to provide measurable benefits at the cost of increased complexity. OITs are not a silver bullet for the drawbacks of conventional ITs. Rather, OITs introduce their own set of drawbacks and complications that need to be considered. The continued use of conventional ITs throughout the power grid is both rational and justified.[33]

---

[33] A final, additional consideration related to OITs is important to include. Executive Order 13920 issued by the President of the United States, Donald J. Trump, on May 1, 2020 titled "Securing the United States Bulk-Power System" restricts the use of electrical equipment manufactured outside of the United States in the "bulk-power system." The order specifically includes "instrument transformers" in the definition of "bulk-power system electric equipment." The final implementation of this order as related to OITs is yet to be determined. However, the order may restrict the use of OITs developed/manufactured outside of the United States. [43]

12.0 References

[1] CEATI Internation Inc., PowerNex Associates Inc., "CEATI Report No: T123700-3082, High Voltage (5kV to 800 kV) Instrument Transformer Specifications Guide," CEATI International Inc., Montreal, Quebec, Canada, 2013.

[2] IEEE Power and Energy Society, Power System Relaying Committee, "IEEE Std C37.241-2017: IEEE Guide for Application of Optical Instrument Transformers for Protective Relaying," IEEE, New York, NY, 2017.

[3] Bureau of Reclamation, "Facilities Instructions, Standards, and Techniques Volume 3-8 Operation, Maintenance, and Field Test Procedures for Protective Relays and Associated Circuits," May 2011. [Online]. Available: https://www.usbr.gov/power/data/fist/fist3_8/vol3-8.pdf. [Accessed 21 August 2020].

[4] Schweitzer Engineering Laboratories, *SEL-300G Multifunction Generator Relay Instruction Manual,* Schweitzer Engineering Laboratories, 2019.

[5] A. Apostolov, "It is time for a change," *PAC World,* p. 4, March 2018.

[6] J. DeHaan and R. Hogg, "Addressing Localized Saturation of Generator Neutral Current Transformers," in *85th International Conference of Doble Clients*, Boston, MA, 2018.

[7] F. Rahmatian, "Optical Instrument Transformers," *PAC World,* pp. 18-25, March 2018.

[8] IEEE Power and Energy Society, Power System Instrumentation and Measurements Committee, "IEEE Std 1601-2010: IEEE Trial-Use Standard for Optical AC Current and Voltage Sensing Systems," IEEE, New York, NY, 2010.

[9] IEEE Power Engineering Society, Power System Relaying Committee, "IEEE Std C37.92-2005(R2011): IEEE Standard for Analog Inputs to Protective Relays from Electronic Voltage and Current Transducers," IEEE, New York, NY, 2011.

[10] ABB, "FOCS - Fiber-Optic Current Sensor, ABB FOCS Brochure," 2011. [Online]. Available: https://search.abb.com/. [Accessed 30 July 2020].

[11] Adamant Namiki, "Optical Fiber Current Sensors," 2020. [Online]. Available: https://www.ad-na.com/en/product/optical/current-sensor.html. [Accessed 31 July 2020].

[12] Adamant Namiki, "Optical Fiber Current Sensor Brochure," Adamant Namiki, [Online]. Available: https://www.ad-na.com/en/product/optical/pdf/CurrentSensor.pdf. [Accessed 31 July 2020].

[13] Arteche, "Optical Current Transformer SDO-OCT," Arteche, 2020. [Online]. Available: https://www.arteche.com/en. [Accessed 31 July 2020].

[14] Arteche, "Arteche SDO OCT IEC 61850 Optical Current Transformer Brochure," [Online]. Available: https://www.arteche.com/en. [Accessed 31 July 2020].

[15] CONDIS, "Electronic Fiber – Optic Current Transformer," CONDIS, 2019. [Online]. Available: https://condis.ch/products-and-solutions/metering/efoct/. [Accessed 31 July 2020].

[16] CONDIS, "Metering Novel Technology," CONDIS, 2019. [Online]. Available: https://condis.ch/2018/08/metering-novel-technology/. [Accessed 31 July 2020].

[17] CONDIS, "Flexible Electronic Fiber-Optic Current Transformers," CONDIS, 2019. [Online]. Available: https://condis.ch/products-and-solutions/monitoring-and-protection/flexible-electronic-fiber-optic-current-transformer/. [Accessed 31 July 2020].

[18] General Electric, "COSI Digital Instrument Transformers," 2020. [Online]. Available: https://www.gegridsolutions.com/hvmv_equipment/catalog/digital-instrument-transformers.htm. [Accessed 31 July 2020].

[19] General Electric, "COSI-CT Optical Current Transformer Brochure," General Electric, 2016. [Online]. Available: https://www.gegridsolutions.com/products/brochures/grid-ga-l3-cosi_ct-0907-2016_07-en.pdf. [Accessed 31 July 2020].

[20] General Electric, "COSI-CT F3 Flexible Optical Current Transformer Brochure," 2017. [Online]. Available: https://www.gegridsolutions.com/products/brochures/cosi_ct_f3-brochure-en-2017_08-grid-ga-0909.pdf. [Accessed 31 July 2020].

[21] Hitachi ABB, "FOCS-FS (245 - 800 kV)," 2020. [Online]. Available: https://www.hitachiabb-powergrids.com/. [Accessed 31 July 2020].

[22] Hitachi ABB, "Fiber Optics Current Sensor- Free Standing (FOCS-FS) Brochure," Hitachi ABB, 2018. [Online]. Available: https://search.abb.com/. [Accessed 31 July 2020].

[23] NR Electric, "PCS-9250 DC Electronic and Optical CT/VT," 2020. [Online]. Available: http://www.nrec.com/en/web/upload/2019/05/08/1557300020807393mrh.pdf. [Accessed 31 July 2020].

[24] Trench, "Optical Current Transformers," 2018. [Online]. Available: https://trench-group.com/wp-content/uploads/2019/03/Optical-Current-Transformers.pdf. [Accessed 31 July 2020].

[25] Trench, "Optical Current Transformers," Trench, 2020. [Online]. Available: https://www.trench-group.com/products/optical-current-transformers/. [Accessed 31 July 2020].

[26] Trench, "Optical Current Transformers for Air Insulated Substations," August 2016. [Online]. Available: https://docplayer.net/54235969-Optical-current-transformers-for-air-insulated-substations.html. [Accessed 19 August 2020].

[27] N. Powers, "NCITs and Digital grid: Make sense of modern sensing," in *CEATI International Spring Meeting - Protection and Control Session*, Tucson, 2018.

[28] Eaton, "GridAdvisor Insight RE series optical underground elbow sensor system," December 2018. [Online]. Available: https://www.eaton.com/content/dam/eaton/products/utility-and-grid-solutions/grid-automation-systems/gridadvisor-optical-sensor/gridadvisor-optical-deadbreak-elbow-adapter-medium-voltage-sensor-system-pa910002en.pdf. [Accessed 19 August 2020].

[29] Eaton, "GridAdvisor Insight optical sensor," Eaton, 2020. [Online]. Available: https://www.eaton.com/us/en-us/catalog/utility-and-grid-solutions/gridadvisor-optical-sensor.technical.html. [Accessed 19 August 2020].

[30] S. Bullard, "Crain's Cleveland Business, Eaton Corp. to complete move to new Beachwood campus by Feb. 18," 07 February 2013. [Online]. Available: https://www.crainscleveland.com/article/20130207/FREE/130209815/eaton-corp-to-complete-move-to-new-beachwood-campus-by-feb-18. [Accessed 19 August 2020].

[31] Eaton, "GridAdvisor Insight RI series optical standoff insulator sensor system," December 2018. [Online]. Available: https://www.eaton.com/content/dam/eaton/products/utility-and-grid-solutions/grid-automation-systems/gridadvisor-optical-sensor/gridadvisor-optical-standoff-insulator-medium-voltage-sensor-system-pa910004en.pdf. [Accessed 19 August 2020].

[32] Eaton, "GridAdvisor optical sensors," July 2018. [Online]. Available: https://www.eaton.com/content/dam/eaton/products/utility-and-grid-solutions/grid-automation-systems/gridadvisor-optical-sensor/gridadvisor-optical-sensor-ca910002en.pdf. [Accessed 19 August 2020].

[33] Eaton, "GridAdvisor Insight RG235 optical medium-voltage and current sensor system," December 2018. [Online]. Available: https://www.eaton.com/content/dam/eaton/products/utility-and-grid-solutions/grid-automation-systems/gridadvisor-optical-sensor/gridadvisor-optical-medium-voltage-and-current-sensor%20system-pa910003en.pdf. [Accessed 19 August 2020].

[34] Eaton, "GridAdvisor Insight RP series optical line post medium-voltage and current sensor system," December 2019. [Online]. Available: https://www.eaton.com/content/dam/eaton/products/utility-and-grid-solutions/grid-automation-systems/gridadvisor-optical-sensor/gridadvisor-optical-RP-series-medium-voltage-and-current-sensor-system-pa910005en.pdf. [Accessed 2020 August 2020].

[35] UCA International Users Group, "Implementation Guideline for Digital Interface to Instrument Transformers using IEC 61850-9-2," UCA International Users Group, Raleigh, NC, 2004.

[36] International Electrotechnical Commission, "IEC 61869-9:2016-04(en): Instrument transformers – Part 9: Digital interface for instrument transformers," IEC, Geneva, Switzerland, 2016.

[37] Schweitzer Engineering Laboratories, "Robust Solutions for Digital Secondary Systems," Schweitzer Engineering Laboratories, 2020. [Online]. Available: https://selinc.com/solutions/p/digital-secondary-systems/. [Accessed 21 August 2020].

[38] Omicron, "CPC 100," Omicron, 2020. [Online]. Available: https://www.omicronenergy.com/en/products/cpc-100/. [Accessed 20 August 2020].

[39] Schweitzer Engineering Laboratories, *SEL-387-0, -5, -6 Relay Current Differential Overcurrent Relay Data Recorder Instruction Manual,* Schweitzer Engineering Laboratories, 2019.

[40] ABB, "FOCS - fiber-optic current sensor," ABB, 2020. [Online]. Available: https://new.abb.com/power-electronics/focs. [Accessed 30 July 2020].

[41] S. Patel, "Power: Hitachi Absorbs ABB Power Grids in New $10B Joint Venture," Power Mag, 1 July 2020. [Online]. Available: https://www.powermag.com/hitachi-absorbs-abb-power-grids-in-new-10b-joint-venture/. [Accessed 31 July 2020].

[42] CONDIS, "Flexible optical measurement system for grid monitoring," CONDIS, 2019. [Online]. Available: https://condis.ch/2019/11/flexible-optical-measurement-system-for-grid-monitoring/. [Accessed 31 July 2020].

[43] D. Trump, "Executive Orders, Executive Order on Securing the United States Bulk-Power System," 1 May 2020. [Online]. Available: https://www.whitehouse.gov/presidential-actions/executive-order-securing-united-states-bulk-power-system/. [Accessed 28 August 2020].