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Photonic Combined Voltage and Current Transformers – Demonstration for the Nepalese Grid

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SUMMARY

This paper provides highlights of recent progress in the development of photonic voltage and current transformers and their application to supporting the expansion of hydro generation capacity and digitalisation in the Nepalese grid. It is shown how the passive distributed sensing system can provide real-time synchronised measurements, which can be used to provide detailed assessment of harmonics, earth faults, and other phenomena over a wide area. It is also shown how new grid connections can be conveniently monitored and protected with unit protection to allow continued expansion of renewable generation while ensuring safe and efficient operation. The platform technology improves grid visibility, enables targeted system response to improve energy transport efficiency, enables new connections of distributed generation to improve availability of supply, and supports grid digitalisation in Nepal. Sensor hardware for this trial is presently under construction by the project partners, with installation date targeted for May 2022. Following installation, the system will be operated over several months during which data will be streamed to NEA for evaluation and recorded for further analysis and development of further applications.

KEYWORDS

Photonic Voltage Transducer, Photonic Current Transducer, Power Network Monitoring, Smart Grid, Low-power instrument transformer, IEC 61869, IEC 61850-9-2, sampled values

1. INTRODUCTION

With the presence of abundant flowing water resources, Nepal has potential for hydroelectric power generation capacity in the region of 42 GW [1]. Despite this, only 2.7% of the viable resource has been harnessed to generate electricity. The transmission network operator, Nepal Electricity Authority, aims to develop 15 GW of hydroelectricity by 2030 and 40 GW by 2040 [2]; however, electricity demand is expected to double by 2030 and, even today, the installed generation capacity cannot meet peak demand. This has led to issues where systematic load shedding has been required to stabilise the electricity system.

Grid infrastructure for monitoring and control plays an important role in ensuring a reliable power system. The existing instrumentation technology combining conventional instrument transformers with phasor measurement units (PMUs) are important components of such a system. Although conventional iron-core current transformers (CTs) and voltage transformers (VTs) remain the dominant technology in the energy sector to monitor power network parameters, they are bulky and heavy, lack galvanic isolation, suffer core saturation effects and pose a risk of explosion, causing safety concerns [3]. Data from CTs and VTs require timestamping for accurate phasor measurements, which necessitates access to global positioning system (GPS) infrastructure, significantly increasing the cost of the measurement system.

As opposed to conventional CTs and VTs, the optical voltage transducers (OVTs) based on Pockels effect and optical current transducers (OCTs) based on Faraday effect have been proposed over the last decades [4], [5], [6], [7]. In contrast to CTs and VTs, they offer a range of benefits such as light weight, small size, wide bandwidth, high accuracy, immunity to electromagnetic interference and galvanic isolation. While the conventional OCTs and OVTs may offer a direct replacement for CTs and VTs, they are incapable of being deployed passively over long distances to offer distributed measurements without the need for additional infrastructure. Therefore, several concepts of photonic voltage and current transformers combining fibre Bragg grating (FBG) sensors, piezoelectric transducers, and dedicated current-to-voltage converters were previously proposed by the authors [3], [8], [9]. The devices enabled multiple, remote, distributed, passive current and voltage measurement over long distances that could be applicable to a wide range of metering and protection functions, unachievable with current technology. The developed photonic transformers were designed for protection and metering applications and their performance was evaluated in the laboratory conditions according to the IEC 60044 and IEC 61869 standards.

In this paper, we report on the first-time development of FBG-based combined current and voltage transformers to be trialled on 33 kV and 132 kV networks and validated against the IEC 61869 standard for instrument transformers. The fiber-based sensing technology allows multiple discrete measurements of electrical and mechanical parameters, including voltage, current, strain, vibration, and temperature to be obtained at distances of up to 60 km from the substation. The only active component of the system is a substation based state-of-the-art FBG interrogator, with functionality specifically tailored to the needs of the power industry. The interrogator collects sensor signals, digitises these signals at a high sampling rate, and publishes measurements in accordance with the IEC 61850 digital process bus communications standard. This is achieved by eliminating the need for supporting infrastructure such as power supplies, active digital telecommunications infrastructure, and GPS receivers at each measurement location.

2. NEPALESE GRID INFRASTRUCTURE

The substation to be used for the field trial provides electricity to 35,000 customers. Records show that the average power outage in this area is almost 20 to 25 hours per month, typically resulting from earth faults on the incoming and outgoing feeders. This is due to the challenging combination of long length of feeders through harsh topography, dense vegetation, and unpredictable weather. The field trial will prove the viability of the combined current and voltage sensor technology, which can be expanded to include many more measurement locations. This will enable clear visibility of the system to rapidly identify and respond to earth faults and other operational challenges.

A system, comprising three combined voltage and current transformers and a dedicated interrogator, will be deployed on 33 kV level within a substation in the Tansen district in Nepal and constitutes a unique, digital sensor platform for transmission networks that allows a large number of measurements to be acquired over a wide area with relatively low capital expenditure. The point of the system installation on a Nepalese grid is shown in Fig. 1.

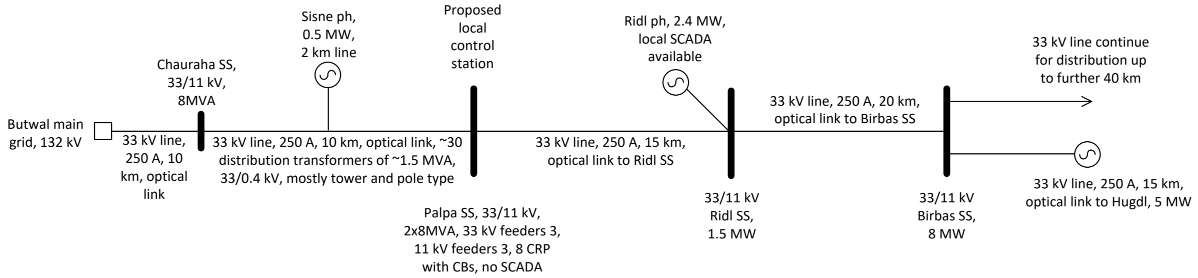

Fig. 1. Considered Nepalese grid infrustructure and the measurment system installation point on the 33 kV network.

3. COMBINED PHOTONIC VOLTAGE AND CURRENT TRANSFORMERS

The presented novel combined photonic voltage and current transformers (cPVCT) consist of an assembly of the following components:

- Photonic voltage transformer (PVT) – combining an FBG, piezoelectric transducer and capacitive voltage divider (CVD)
- Photonic current transformer (PCT) – combining an FBG, piezoelectric transducer and current transformer (CT)
- Interrogator

All these components are described as follows.

3.1. Fibre Bragg gratings technology

An FBG sensor is formed by exposing a 5-10 mm section of an optical fibre to an Ultraviolet (UV) light of modulated intensity to create a periodic alteration of the refractive index. When broadband light is projected through the FBG (see Fig. 2), it reflects a range of wavelengths of the incident light with a distinctive peak at so called Bragg wavelength, λ_B. The peak wavelength is determined during production of the FBG and is a function of the grating period, Λ, and the effective refractive index, n_e of the fibre [10]:

$$\lambda_B = 2 n_e \Lambda \qquad (1)$$

Both variables in (1) are functions of temperature and strain affecting the optical fibre; therefore, FBGs can be utilized to measure temperature and strain directly or, other quantities, such as voltage, current, magnetic field, indirectly. The change in the reflected FBG peak wavelength due to change in temperature, ΔT, and strain, ε, is describe by the formula:

$$\frac{\Delta\lambda_B}{\lambda_B} = k_T \Delta T + k_\varepsilon \varepsilon \qquad (2)$$

where k_T and, k_ε are the temperature and strain sensitivities, respectively. To measure temperature only, an FBG must be isolated from strain, and to measure mechanical strain, temperature compensation is required. This is usually achieved by means of an additional temperature measuring FBG [10].

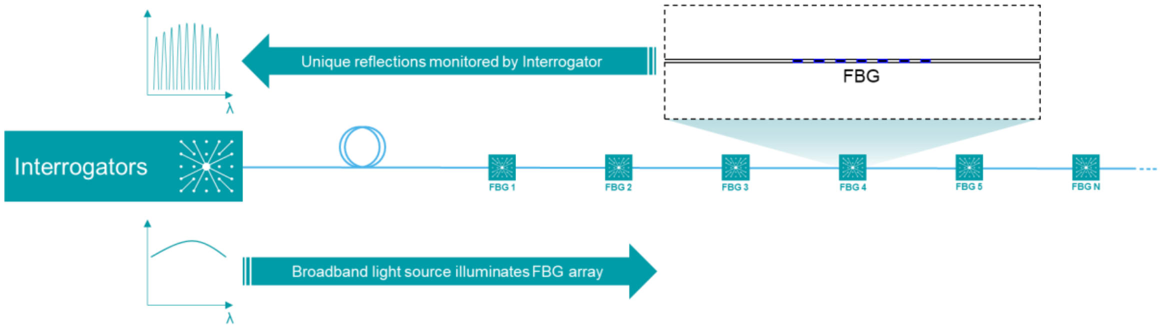

Fig. 2. Schematic diagram of an array of FBGs connected to an interrogator.

In sensor applications, their wavelength-encoding nature coupled with their simple reflected spectra mean that FBGs are relatively easy to interrogate and multiplex and are effectively immune to the problems of intensity fluctuations and attenuation [10].

3.2. Photonic voltage transformer

The photonic voltage transformer (PVT) consists of a combination of a capacitive voltage divider, to which a low voltage transducer (LVT) is connected on the secondary terminals, as well as an electronic unit, the interrogator, which converts the optical transmitted signals from the LVT into IEC 61850-9-2 conformed sampled value (SV) measurements.

3.2.1. Low voltage transducer

The low voltage transducer (LVT) construction comprising a low-voltage piezoelectric multilayer stack with a bonded fiber Bragg grating (FBG) sensor is shown in Fig. 3 [3]. The FBG is suspended between two ceramic arms attached to a rectangular block of PICMA® stack from Physik Instrumente (PI) [11].

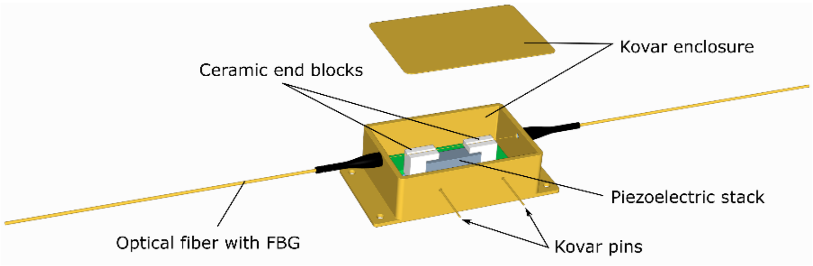

Fig. 3. Low voltage transducer [3].

The stack has nominal dimensions 5×5×18 mm and the operating voltage range of -30 V ÷ 120 V. It has a resonant frequency of 70 kHz and can reach its full displacement in approximately 4.8 µs after the driving voltage change. The transducer is housed in a telecommunication industry standard, hermetically sealed butterfly package. Voltage input to the piezoelectric stack is provided through two Kovar pins isolated from the package (see Fig. 3). The sensor can be interrogated remotely by measuring the peak wavelength reflected by the FBG, which shifts in proportion to the strain generated in the piezoelectric material due to the applied voltage. By tracking the instantaneous peak wavelength, the voltage input can be reconstructed, and by tracking the average wavelength, local sensor temperature can be derived that can be used for temperature compensation of the sensor voltage readings [8], [9]. The LVT construction ensures strain amplification [12], and its operating voltage range is limited to ±30 V by means of an external protection circuitry formed by a protection resistor and a bidirectional transientvoltage-suppression (TVS) diode to avoid the piezoelectric component depolarization and permanent damage [3].

3.2.2. Photonic voltage transformer

Considering that the operating voltage range of the LVT is ±30 V, any high voltage on the primary side of a medium or high voltage network, needs to be transformed to an adequate low voltage to accommodate the LVT and form a functional photonic VT. This can be achieved using capacitive voltage dividers (CVD) with a varying dividing ratio between primary and secondary terminals, depending on nominal primary voltages. An example of a design for 132 kV networks along with a schematic representing the equivalent circuit is given in Fig. 4. The CVD is housed in a composite insulator and is interfaced with the LVT placed in a die-cast enclosure at ground level. The access to the CVD low voltage terminal is provided inside the hermetic enclosure and the optical measurement is fed out via standard single mode fiber (SMF) and sent to the optoelectronic device, namely the interrogator, which is explained in more detail in Section 3.4. The PVT underwent successfully tests against the power frequency and lightning impulse withstand voltages and partial discharge tests, meeting the IEC 61869 standard requirements.

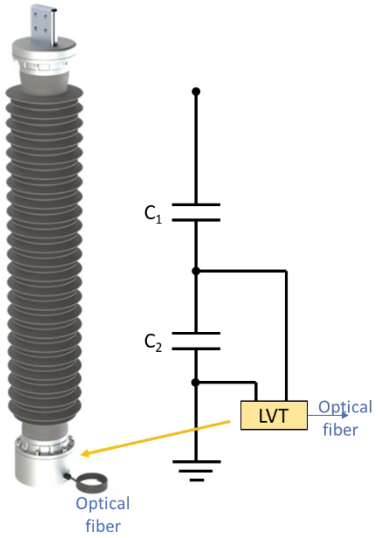

Fig. 4. Photonic voltage transformer for 132 kV networks. (*NB the 33 kV version consists of a shorter CVD and insulator.*)

3.3. Photonic current transformer

The Photonic Current Transformer (PCT) consists of an industry standard iron-core current transformer (CT), to which an LVT is connected at the secondary terminals. A precision burden resistor is employed to convert the secondary current into a low voltage measurable by the LVT. The CT design is based on conventional current transformers with a steel or nanocrystalline core and copper windings. The current ratio is determined according to the system parameters, in this case a ratio of 160/1A. The output voltage, at full load current, is 1 V which is developed across a 1 Ω burden resistor (R_b). The protection class is 5P30 with the output being accurate to 5% up to 30 times full load current. The PCTs are encapsulated in epoxy resin to ensure excellent weatherproof protection and terminated within the terminal box having IP65 rating. The PCT and its equivalent circuit diagram with an LVT connected across the CT burden resistor is shown in Fig. 5.

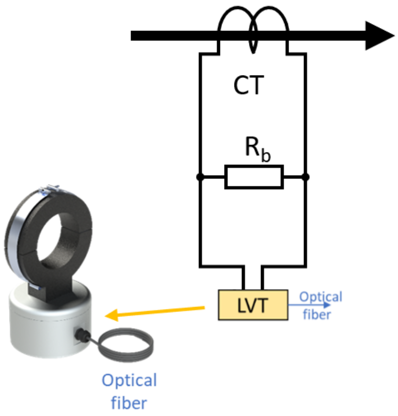

Fig. 5. Photonic current transformer and its equivalent circuit diagram.

Depending on the application, the PCT is placed on a standalone composite insulator suitable for either 33 kV or 132 kV.

3.4. Interrogator

While many commercial options exist for interrogation of FBG sensors, compliance with IEC standards for sampling rates, accuracy, installation environment and communications protocols necessitate a custom solution. The Interrogator developed for this work consists of a thermally stabilized spectroscopic fiber interrogator and associated optical components integrated with custom readout electronics and deployed within a high-performance EMC chassis. A schematic diagram of the system is shown in Fig. 6.

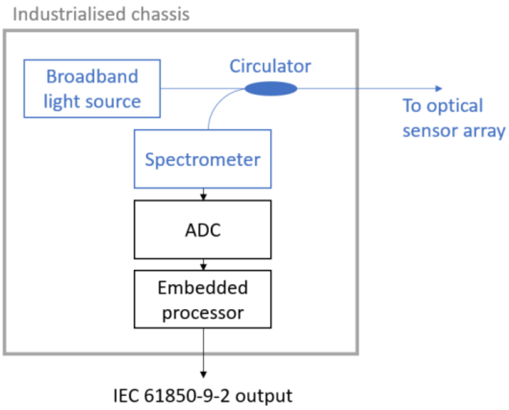

Fig. 6. Simplified schematic diagram of industrialised sensor interrogator.

The Interrogator samples the complete optical spectrum at standard rates of 4 kHz, 4.8 kHz, and 14.4 kHz for compliance with the standard rates dictated by IEC 61869-9. Optical measurements are extracted and converted to the measurand (voltage or current) using a powerful embedded system and published in the IEC 61850 61850-9-2 Sampled Value (SV) format on up to six gigabit Ethernet ports for interoperation with other 61850-enabled substation equipment. Each Interrogator can monitor up to 30 individual PCTs and PVTs simultaneously, with total processing time from sampling to SV output of 1 ms, which makes it suitable for application in protection, metering and power quality use as per requirements defined in IEC 61869-9.

The Interrogator accepts time synchronization in pulse-per-second (PPS) and Precision Time Protocol (PTP, IEE 1588). Since the time of flight of the optical signal from each sensor can be accurately measured, this enables each measurement to be accurately and centrally timestamped without requiring GPS receivers at the measurement locations. This has the additional benefit of maintaining relative synchronization of all measurements obtained by a single Interrogator, even in the event of loss of global time synchronization. This may be particularly valuable for protection applications, since a unit protection scheme served by a single Interrogator will retain relative sync and thus remain active in the event of loss-of-synchronization to the GPS clock.

In readiness for deployment in a substation environment, the Interrogator will be qualified against the relevant IEC standards for product safety, electromagnetic compatibility, and climatic and mechanical vibration effects. The main standards being considered are IEC 60068, IEC 60255 and IEC 61000. Initial pre-compliance testing against these standards gives confidence that the system will be fully compliant with these standards.

3.5. Combined photonic voltage and current transformer

Fig. 5 presents the complete cPVCT for a 132 kV network, with one primary sensor and the interrogator on the secondary side. This kind of hybrid instrument transformer combines the advantages of known and proven components such as CVDs, hollow core CTs as well as the FBG and piezo elements, combined with an optical fiber as a means for signal transmission. Considering the passive nature of the primary components, this system is immune to external perturbations. Furthermore, signal transmission via fiber can enable measurement up to a nominal maximum distance of 60 km (extensible using fiber amplifier schemes) allowing multiplexing of up to 30 different sensors in one fiber while using only one Interrogator. Hence, this approach allows for highly efficient, cost-effective asset management as well as decentralized protection schemes with centralized electronics, the Interrogator.

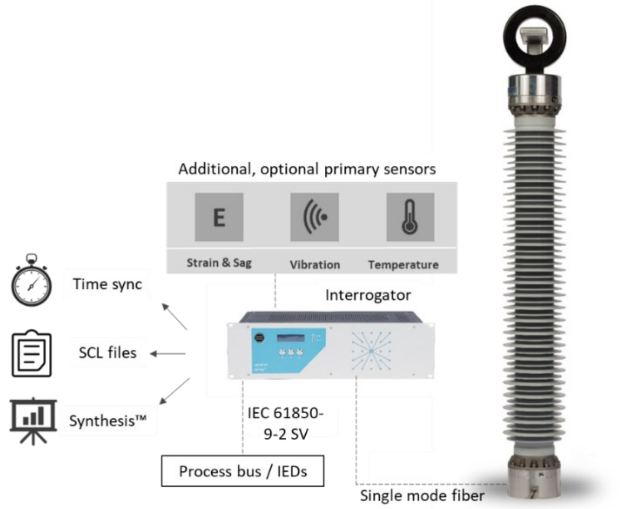

Fig. 7. Combined photonic voltage and current transformer for 132 kV networks. (*NB the 33 kV version consists of a shorter CVD and insulator.*)

4. MEASUREMENT SYSTEM PERFORMANCE AND COMPLIANCE WITH STANDARDS

The performance of the photonic voltage and current transformers was previously verified experimentally in the laboratory. Accuracy tests were performed according to the relevant parts of IEC 61869. The devices were tested at the nominal frequency of 50 Hz and within voltage and current ranges specified by the respective standards. The amplitude and phase errors were estimated, and the measurement accuracy classes were assigned accordingly.

As previously shown in [3], the PVT for 132 kV networks exhibited amplitude errors below 0.2% at any voltage between 80 % and 120 % of the rated voltage (64 kV and 96 kV, respectively) satisfying the requirements of the 0,2 metering class (Fig. 9). The voltage errors at 20 % of the nominal voltage (16 kV) and between 80 % and 120 % of the rated voltage (at 1.2 voltage factor for this sensor) should be below

3 %. At 2 % of the nominal voltage (1.6 kV) the errors were well below the 6 % limit. The PVT performance was better than the requirements set by the standard with the amplitude errors below 1.4 % at 2 % of the rated voltage, and 0.2 % at 20 % and between 80 % and 120 % of the nominal voltage, respectively. In addition, for multipurpose devices, the requirements for the amplitude errors at 2 %, 20 %, and between 80% and 120 % of the rated voltage remained below 2 %, 1 % and 0.5 %, respectively, for the 0,5P class. The expected phase displacement between the primary voltage and the voltage across the LVT was estimated to be below 7 minutes, thus the device was shown to have the potential to meet the 0,2, 0.5P and 3P class requirements specified by IEC 61869-11.

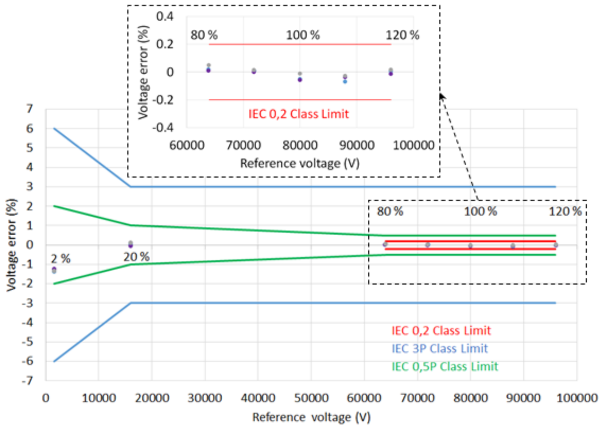

Fig. 8. PVT amplitude errors for three consecutive test runs.

The previously developed prototype PCT enabled current measurements with accuracy better than 1% for the 50 Hz rated currents and was capable of meeting the accuracy requirements of the 5P protection class with amplitude errors below 1 % at the nominal current and below 10 % at the relevant harmonics. The phase errors were below the required 1° and 10° at the nominal current and at the relevant harmonics, respectively (Fig. 9) [8].

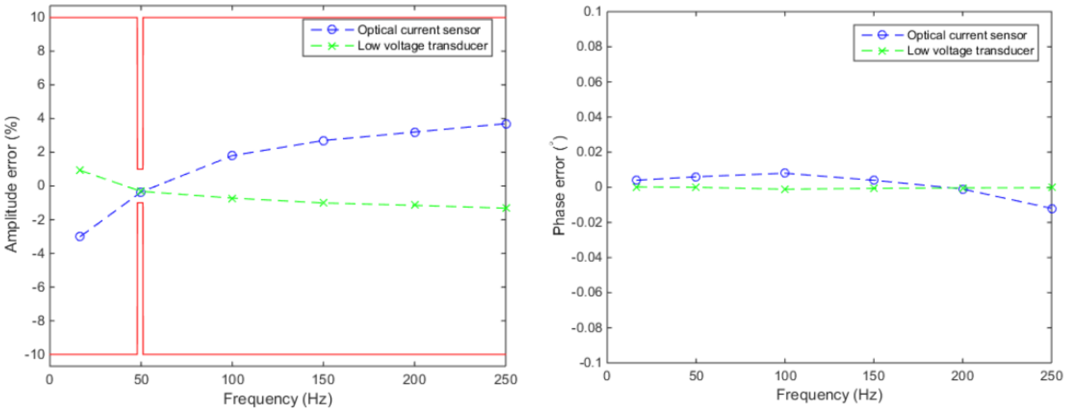

Fig. 9. Amplitude and phase errors for the 1/3rd to 5th harmonics, and at primary frequency, for the LVT and PCT.

5. POTENTIAL APPLICATIONS TO THE NEPALESE GRID

Nepal’s electricity grid is highly dependent on domestic hydro-electric generation, with most hydropower projects being of the ‘run-of-river’ type with little or no water storage. Because of this, a significant portion of generation to the Nepalese grid has a seasonal nature, creating challenges to balancing of supply and demand throughout the year. Proper coordination of generation, storage and demand during both summer and winter months relies on effective data collection and communication across the network, which today is severely lacking, leading to problems of overloading and load shedding. A lack of effective protection and monitoring system coordination and centralisation ultimately results in frequent unplanned outages throughout the year, affecting energy availability to the population.

As discussed in the previous sections, the proposed photonic system can offer passive, distributed and remote voltage and current measurements on the 33 kV or 132 kV power lines and is ideally suited for monitoring and control of the section of the Nepalese grid presented in Section 2 (Fig. 1). Because of its ability to provide centralised digital measurements from long-distance multiplexed sensors, this technology is uniquely able to address many of the problems affecting the Nepalese energy grid, with significant potential scale economies relevant to emerging markets.

The system is suitable for multi-terminal protection applications (Fig. 10) and centralized optical protection that can operate over wide areas reducing the number of the required devices and the related communication traffic [13]. The long-distance nature of the technology allows long and high-risk sections of a transmission network to be sectionalised for discrete unit protection and targeted fault response.

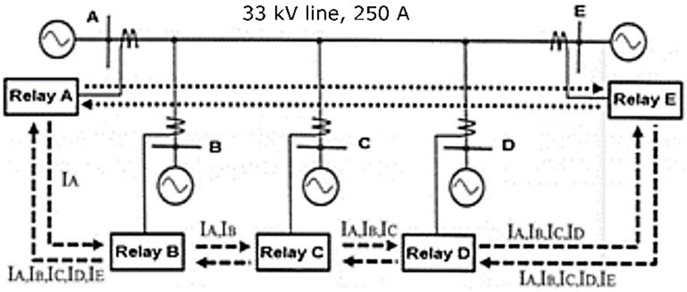

Fig. 10. An example of typical multi-terminal protection scheme [13].

Another application would be protection of MV or HV transformers in the substations which normally require a large number of CTs and VTs delivering measurements to the protection relays [13]. The use of compact, inherently insulated transducers would be highly desirable in this application and can be realised using the proposed photonic scheme, offering greater flexibility to multiplex all measuring devices on a single fiber.

In addition, the interrogation system for the proposed cPVCTs is also capable of measuring other parameters with the use of distributed mechanical sensors, such as line tension, sag, temperature, and vibration, delivering full electrical and mechanical monitoring capability for the grid assets. Since in the photonic scheme the relative delay between measurement points is inherently known, the use of the long-distance passive cPVCTs network could facilitate synchrophasor measurement without the use of GPS at the cPVCT location [13].

6. TRIAL INSTALLATION

As noted in Section 2, the trial system comprises three combined photonic current and voltage transformers and a dedicated sensor interrogator. This sensor scheme will be deployed on the 33 kV network within the Palpa substation in the Tansen district of Nepal. This trial system will constitute the first live installation of this novel passive sensor technology for combined voltage and current measurements. The sensors will be qualified to the 5P protection class per IEC 61869-10, with sensor data provisioned to the Nepal Energy Authority for examination throughout the winter and summer periods following installation. The system is representative of the hardware that would be installed for any of the multiple potential applications discussed in Section 5, and is readily extensible up to 30 individual sensors per 60 km of fibre optic. Sensor hardware for this trial is presently under construction by the project partners, with installation date targeted for May 2022. Following installation, the system will be operated over several months during which data will be streamed to NEA for evaluation and recorded for further analysis and development of further applications.

7. CONCLUSIONS

In this paper, a suite of combined photonic voltage and current transformers together with a dedicated interrogator have been presented. The system was designed to ensure remote monitoring of 33 kV network with the interrogation distance up to 60 km from the substation. The only active component of the system was a substation based state-of-the-art FBG interrogator, with functionality specifically tailored to the needs of the power industry. It was shown that the interrogator collects sensor signals, digitises them at a high sampling rate, and publishes measurements in accordance with the IEC 61850 digital process bus communications standard. This could be achieved by eliminating the need for supporting infrastructure such as power supplies, active digital telecommunications infrastructure, and GPS receivers at each measurement location. Future work will focus on the installation of the proposed measurement system on a 33 kV line in Nepal and the relevant field trials at various electrical faults scenarios.

8. ACKNOWLEDGMENTS

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