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FIELD TRIALS OF FIBRE OPTIC CURRENT TRANSDUCERS IN HIGH VOLTAGE NETWORKS

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1. SUMMARY

This paper reports the results from two full-scale field trials of a Fibre Optic Current Transducer, FOCT, interfaced with energy metering and protection in EHV systems. Properties of the optical system and possible arrangements for interfacing with the secondary equipment are described. Laboratory tests are listed with the specified test criteria.

Field log results are tabled showing comparison of the responses of the optical transducers and conventional equipment to a line fault for the protection installation, together with a long-term comparison of metering performance from the optical and conventional transformers.

KEY WORDS:
EHV Substation, Fibre-optic, Current transducer, Revenue metering, Digital protection, Non-conventional sensors, Composite insulators.

2. INTRODUCTION

Optical current transducers are already available from a number of suppliers. One well-proven concept, commercially used for integrated Control and Protection systems, is the hybrid technology using optically powered electronics at high voltage to provide a digital output signal. For passive optical sensors the most common concept is still with bulk glass optics with a low-level analogue output signal.

Fibre-optic sensors with active feedback to achieve high sensitivity and stable operation are also commercially available, but require either the processing electronics be located close to the sensing head or special fibre between sensor and relay control room.

This paper reports on a totally passive all-fibre sensor configuration with a modular system using standard components. Only standard optical fibre is used in the switchyard, simplifying installation.

Over 30 sensors have been built and tested in the laboratory and a number of field trials have been

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conducted. The paper reports results from two installations, one for energy metering and one for protection and both continuously monitored for comparison with conventional current transformers.

3. APPLICATION OF OPTICAL SENSORS IN HV NETWORKS

Hybrid electro-optic sensors and bulk optical sensors utilising the Faraday effect have been used successfully for current measurement in the power industry for in excess of 20 years.

The opportunity for integration into other HV equipment and signal transmission via optical fibre cable to the control room has generated a great deal of interest in the power transmission industry. Other advantages include immunity to electromagnetic interference and full galvanic insulation between HV and secondary equipment. However they have had limitations on their application in HV networks, particularly in regard to physical arrangement, dynamic range and lack of standard equipment and protocols for interfacing with conventional meters and relays.

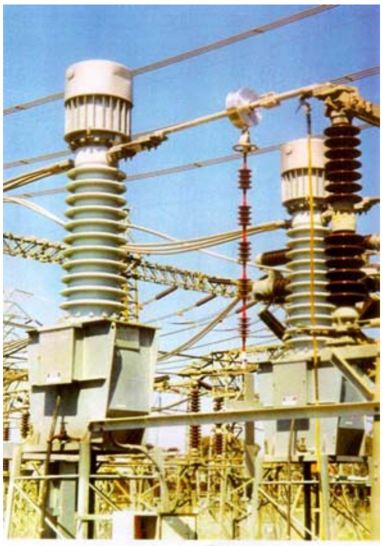

Figure 1 - FOCT with fibre optic composite high voltage downlink

The fibre optic current sensor reported here addresses the dynamic range issue by use of a unique optical fibre as the sensing element at high voltage in combination with intelligent high speed digital signal processing in the control room. The high dynamic range enables protection and metering for a large range of rated currents with one sensor reducing system complexity.

The modular design of the FOCT with the fully passive and dielectric sensing head and the use of standard optical fibre for signal transmission simplifies integration with other sub-station equipment and one practical solution is described to overcome the interface problems. Retrofit installation is possible by using compact and lightweight composite HV insulator downlinks with embedded optical fibres, see .Figure 1

4. FIBRE OPTIC CURRENT SENSOR

4.1. Optical System

The current in the primary system is measured by interrogation of the optical fringes produced by the interference of two counter-propagating polarised light-waves travelling in the sensing optical fibre coil surrounding the primary conductor. The optical configuration is a typical Sagnac interferometer with the loop closed by an optical fibre coupler [1].

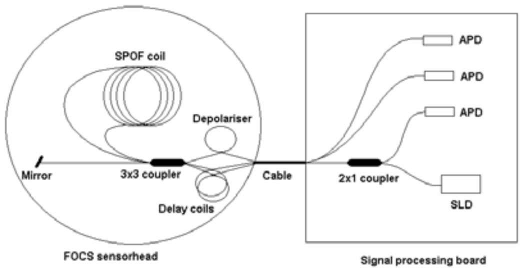

Figure 2 - Sensor configuration

The sensing fibre is a spun High Birefringent polarising fibre (SPOF), filtering out one of the polarisation modes over a broad wavelength range [2]. By use of the three signal algorithms from the outputs of the three fibres from the 3x3 coupler, changes in visibility and attenuation in the sensing coil are eliminated. Variations in optical attenuation and receiver gains are compensated by use of a reference system between the transducer and the signal processing. The referencing signal is achieved through adding a reflective mirror to the unused fibre of the 3x3 coupler on the sensor side.

Figure 2 shows the basic configuration of the sensor used for the metering installation. Note the cable connection is standard single-mode optical fibre cable, which can be up to 800 metres in length. A later version with optical multiplexed return signals, to reduce to one the number of optical receiver elements, was used for the protection installation.

4.2. Electronic Signal Processing

The digital signal processing board used to obtain the primary current values is housed in an industrial computer with the later multiplexed version used for the protection installation incorporated onto a standard PCI card format.
This single PCI board processes the outputs from a three-phase set of sensors and provides both serial digital and real-time low-level analogue output signals. All computer hardware and electronics were located in the substation control building some 250 to 500 metres away from the protection and metering trials respectively.

5. INSTALLATION CONFIGURATIONS

5.1. Functional description

For the field trials the FOCT was interfaced to a Digital Optical Instrument Transformer system [3]. This enables the measurement of the voltages as well as to provide an interface, through the signal processing of the interface module, to the secondary equipment. The principle arrangement is shown in figure 3 where the signal transmission between primary transducer heads and interface module is via optical fibres through high voltage optical downlinks and optical cables.

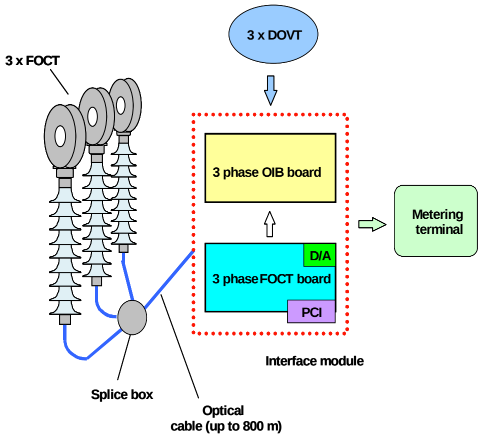

Figure 3 - Principle configuration for metering installation

For the metering installation the voltage signals were obtained through use of a digital optical voltage transducer (DOVT). In the DOVT the primary voltage is measured using a capacitive divider. The output voltage from the capacitive divider is converted to optical digital format using an A/D converter and a photoluminescence diode. The A/D converter is optically powered from the electronic interface board (OIB) in the interface module, see Figure 3.

In the protection installation the voltage signals were obtained from existing capacitor voltage transformers with the secondary analogue output converted to a digital optical signal in the control room using only the analogue electrical to optical digital conversion part of the DOVT.

5.2. Protection trial

For the three-phase protection installation the FOCT was located on a 330 kV feeder at Sydney West sub-station, a major metropolitan switchyard in TransGrid's transmission network.

Demonstrating the flexibility in physical arrangement of the FOCT, the three sensor heads were housed in aluminium housings and mounted directly onto the primary terminal palms of the conventional 362 kV current transformers.

Figure 4 - FOCT Protection Installation on the 330 kV feeders with fibre-optic downlinks

Lightweight fibre optic composite insulator downlinks with embedded optical fibres were used to provide a path for the optical signals from HV to ground potential. The standard single mode fibres were spliced to the optical cable in the switchyard to complete the optical signal path from the transducer head at HV to the electronics in the control room.

The required voltage signals for the protection relay were taken from existing 362 kV capacitor voltage transformers. The analogue output was converted to a digital optical signal in the control room to provide a voltage measurement compatible with the optical current measurement from the FOCT.

The digital current and voltage measurements from the optical transducers were converted by the signal processing of the interface module to a protocol compatible with the secondary line protection relay REL 511 supplied by ABB.

Figure 4 shows the installed FOCT transducer heads with the fibre-optic HV downlinks.

5.3. Metering trial

The three-phase metering installation was located on a 132 kV feeder in the same switchyard as the protection installation. To take advantage of, and demonstrate the integration possibilities, each FOCT transducer head was mounted on the top of a digital optical voltage transducer (DOVT). The DOVT provided the optical voltage signals compatible with the optical current values as well as a path for the optical signals from HV to ground potential. The standard single mode fibres required for signal transmission were embedded in the wall of the composite high voltage insulator shell.

Figure 5 - FOCT metering installation at 132 kV mounted on top of the digital optical voltage transducer

The fibres in the polymer HV insulator were spliced to the transducer head and switchyard cable respectively during installation to complete the optical signal path into the control room. The modular design of the FOCT and the use of standard optical fibres throughout the switchyard reduced the required outage time to less than 3 hours.

Figure 5 shows the installed equipment with the sensor heads enclosed in cast aluminium housings rated for 4000 A.

The digital values from the optical current and voltage transducers were converted through internal algorithms in the interface unit into active and reactive energy pulses and transmitted to the digital metering terminal. Additional information such as phase current and voltages, power factors and accumulated active and reactive energy were also provided from the interface module on a continuous basis.

6. LABORATORY TESTS

Optical transducers require additional tests to those applied to conventional transformers. Normal accuracy, temperature rise and short circuit tests were performed according to IEC 6004. Tests on the electronic interface module located in the control room is subjected to the same environment as the protection relay and was tested in accordance with EN 61000 and IEC 255. These tests include EMC, environmental and supply variation tests all of which were performed on the FOCT electronic board when mounted in the interface module.

In addition to these standardised tests there are more specific tests to assess the satisfactory performance of the FOCT under abnormal conditions. One such test is to check the behaviour in case of a fibre break, where the self-supervision should operate and prevent false operation of the protection relay when connected to the FOCT.

Special consideration has to be given to digital metering where compliance with the total system accuracy from primary sensor to metering equipment requires a more accurate test than that used for normal accuracy measurements on conventional transformers. In the laboratory tests all three sensors for the metering trial were shown to have total system errors of less than 0.5 %.
This complies with standard accuracy requirements for conventional transformers of metering class 0.2 to IEC Standards.

7. RESULTS FROM PROTECTION INSTALLATION

7.1. Basis of comparison

The protection trial is installed on a 238 km 330kV feeder at TransGrid's Sydney West Substation. The feeder was chosen due to its length and the mountainous terrain it traverses increasing the probability of a feeder fault.

The feeder is protected with duplicated distance protection connected to conventional current and capacitive voltage transformers. A high-resolution substation digital fault recorder monitors the feeder current and the operation of the protection schemes. In the control room the fibre optic cable from the high voltage current sensor and the digital voltage signal are connected into the interface module. The signal processing combines and synchronises the voltage and current waveforms before sending the digital current and voltage information over a single fibre optic cable to the REL 511 distance protection relay. This relay has an integrated fault waveform recorder. For the purpose of the trial the installation was configured to alarm only.

To provide a comparison between the conventional and the optical protection systems the configuration as shown in Figure 6 was implemented.

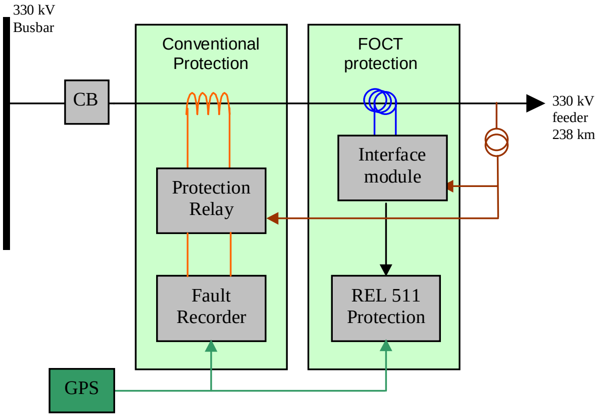

Figure 6 - Protection Comparison, System Configuration

The conventional protection system and the optical system are independent except for a common time synchronisation signal and the primary voltage source. The secondary voltage signal for the optical system is obtained from the common capacitor voltage transformers and converted to a digital optical signal compatible with the optical current measurement from the FOCT. The time synchronisation signal allows the waveforms of the two independent systems to be synchronised.

Comparisons are made using fault recorder data from the high-resolution substation fault recorder and the REL 511 protection relay fault recorder. Both fault recorders will trigger if the protections operate. To test the system both fault recorders are triggered manually over a WAN connection. The two fault recorder waveforms were used as a method of comparing the voltage and current waveforms and the phase relationship between them.

The REL 511 protection relay settings for the optical input signals were exactly the same as the conventional protection relay settings. Hence the protection relays should behave identically on the system.

7.2. Protection results

During the trial a heavy fault occurred 10 km from the substation on the circuit with the FOCT transducers. The fault was caused by the failure of a communication antenna during a period of sustained high wind, resulting in a single phase to ground fault. The current waveforms from the conventional current fault recorder and the fibre optic protection relay are shown in Figure 7.

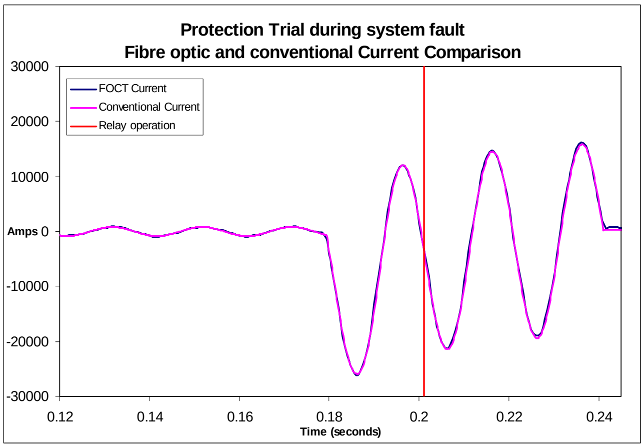

Figure 7 - Fibre Optic and conventional Current Comparison for protection trial

The current waveforms of show that the fibre optic current sensor accurately provided the heavy DC offset current waveform to the REL 511 protection relay. The relay operated correctly within 20ms and the fault was cleared within 60ms.

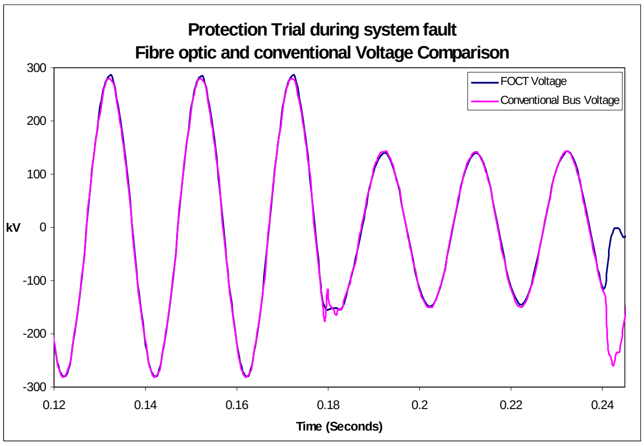

Figure 8 - Optical and Conventional Voltage Comparison for protection trial

To check that the correct signals were provided to the distance algorithm, the voltage signals were also recorded. The voltage can be seen in Figure 8, which shows that the REL 511 protection relay has been provided with the correct voltage waveforms along with the correct phasing of the voltage signal.

The results achieved in the protection trial demonstrate that the optical transducers have the capability to accurately reproduce digital representations of analogue fault waveforms and when coupled to a REL 511 protection relay enable protection against high voltage system faults.

8. RESULTS FROM METERING INSTALLATION

8.1. Basis of comparison

The metering trial has been installed since July 2000 on a 132 kV feeder in the same sub-station as the protection trial. The monitoring principle is similar for the two trials with comparative logging of optical and conventional secondary data.

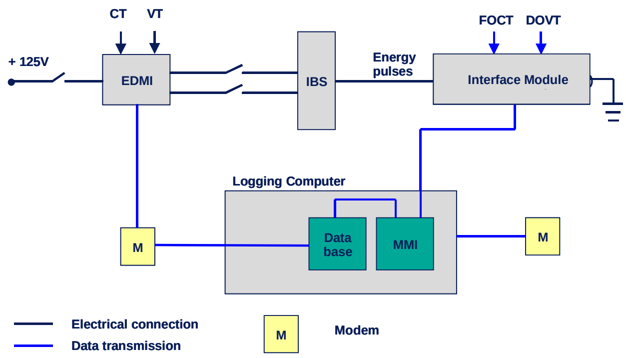

Figure 9 - Metering Comparison, System configuration

In the metering trial the digital optical current and voltage output signals are connected through the optical interfacing module in the control room to an EDMI energy meter. The signal processing combines and synchronises the voltage and current waveforms before sending the information through the digital metering output port (IBS) to the EDMI energy meter.

The EDMI energy meter is also connected to nearby conventional current and capacitive voltage transformers on the same feeder. The comparison between the two systems is provided through a monitoring configuration as shown in Figure 9.

The EDMI energy meter outputs optical energy pulses that are recorded by the optical interface module as well as the conventional energy pulses as derived from the conventional transformers. The energy pulses are used to compare the performance of the two systems.

The EDMI energy meter and the optical interface unit additionally outputs 15 minute averaged data values of current, voltage, phase angle and active power from respective transducers.

8.2. Metering results

Two sets of data are presented for the trial. The first shows a three-month comparison from 2001 of optical and conventional energy pulse as shown in Figure 10

The comparison shows a result stable over an extended period with a maximum percentage error of less than ± 1 %.

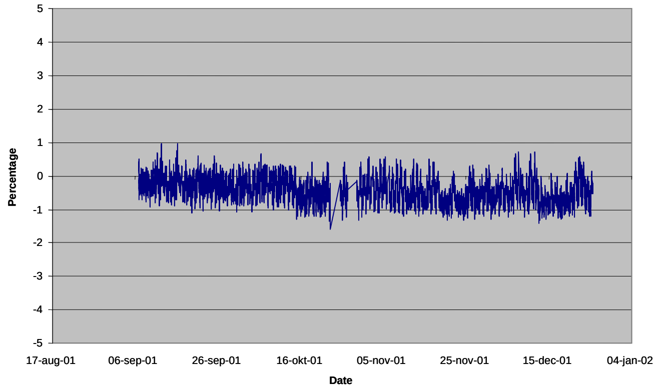

Figure 10 - Active Energy Export (Whrs) for metering trial

For the second comparison in September 2003 the 15-minute averaged, voltage, current and phase angle data was extracted from both the conventional EDMI and the optical interface unit.

Figure 11 demonstrates the accuracy of the FOCT under load conditions. It also indicates the overall percentage error of the fibre optic metering system against the conventional metering solution. The result is again a ±1% error between the two metering systems.

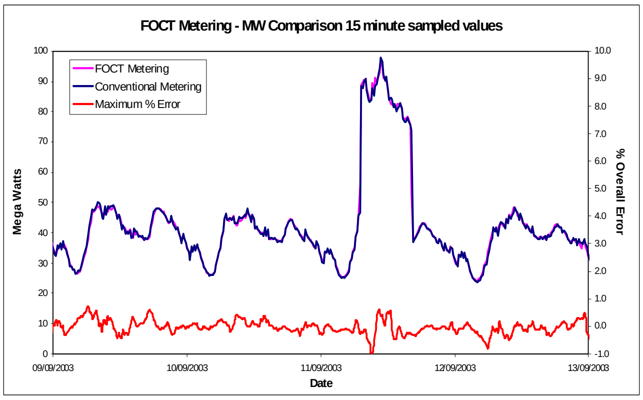

Figure 11 - MW comparison for metering trial

The metering trial has demonstrated that the FOCT has the ability to accurately and stably reproduce digital representations of load currents. The FOCT can, when coupled with digital metering, provide a complete metering system.

9. FUTURE APPLICATIONS

The optical transducers described in this paper interface to secondary equipment through proprietary protocols. It is however an essential requirement from utilities that OEM secondary equipment can be employed. To date this has not been possible due to the absence of a common industry standard for the interface between non-conventional sensors and secondary equipment.

With the adoption of IEC 61850-9-1 standard for a point-to-point communication and IEC 61850-9-2 for a serial communication between primary and secondary equipment, the situation should change. A break-through in the market place for non-conventional transducers, such as the FOCT presented in this paper, will however also require a possibility to mix conventional and optical transducers in the same application.

The use of optical current transducers together with conventional voltage transformers can be implemented through IEC 61850-9-1, but will require a merging unit and a GPS in the switchyard for time synchronisation of optical transducers and secondary equipment. A complete mix of optical transducers and conventional instrument transformers will also require adoption of IEC 61850-9-2 as shown in Figure 12.

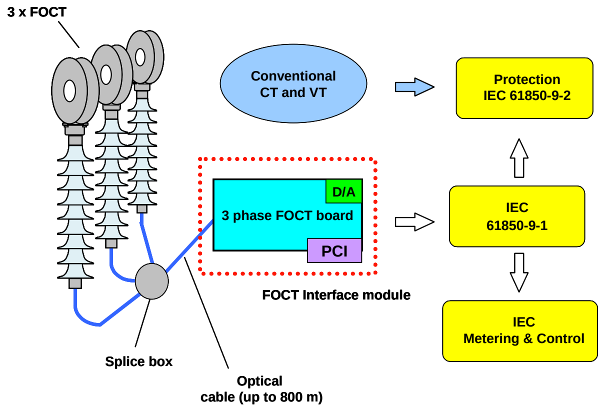

Figure 12 - Optical and Conventional Instrument Transformers used together without Merging Unit

Although the two trials reported in this paper were separate metering and protection applications, a single FOCT can meet both requirements due to its very large dynamic range. Future applications will integrate both functions into one and the same sensor.

10. CONCLUSIONS

This paper presents field trial results for a new type of totally passive Fibre Optic Current Transducer, FOCT, providing a modular system with standard components allowing integration possibilities and simple installation. The reported results demonstrate that the FOCT has the ability to adequately protect against system faults on EHV systems and accurately measure line currents using digital techniques to provide a complete energy metering system.

Accredited laboratory test results show compliance with IEC 60044 requirements and the electronic interface module has passed necessary supply voltage variation and immunity tests according to EN61000 and IEC 255.

It is concluded that a breakthrough of optical sensing in the marketplace will require the platform for the optical transducer to be compatible with the platform for the secondary equipment. It must also be possible to mix conventional and optical transducers in the same application with open system architecture to enable use of OEM secondary equipment. For this to happen a major adoption of common industry standards such as IEC 61850-9-1 and IEC 61850-9-2 for the input protocol of the secondary equipment will be required.

11. ACKNOWLEDGEMENTS

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12. REFERENCES

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