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Topic #14: Advanced protection, automation and control functions and applications

Differential Protection of Multi-Ended Transmission Circuits using Passive, Time-Synchronised Distributed Sensors

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Abstract

New grid connections for low-carbon technologies can lead to costly engineering work to install and protect the resulting multi-ended circuit. Circuit protection for multi-ended feeders is conventionally implemented via distance or line differential protection. Distance protection is often used in areas where there are poor or no data communications possibilities. However, this method is not 100% accurate due to the under-reaching effects caused by fault infeeds from teed circuits, and the setting strategy, often called “throttling factor”, can become very complex. This can lead to incorrect tripping due to accuracy levels or drifting zone reach. Line differential protection requires a protection relay at each feeder-end with reliable alignment of current measurement, plus a robust telecommunications infrastructure. This duplication of equipment at each line end results in significant total costs and, in older substations, space constraints can be a limiting factor. Operators seeking to protect multi-ended circuits are therefore often required to utilise distance protection, resulting in complex setting calculations, reduced resilience, and increased operation time of the scheme.

This paper describes the installation and testing activities of passive sensor technologies to overcome the challenges associated with either of the previously described conventional approaches to multi-ended circuit protection. The presented solution, which has been installed in a 132 kV system in the UK, provides a full multi-ended differential protection scheme, but without requiring IEDs or any active electronics in all substations. Standard CTs are passively coupled to an optical fibre and a central Interrogator unit is able to access current measurements from both the local substation and a remote substation 30 km away (with distances of approximately 60 km also being possible), and publish time synchronised IEC 61850-9-2 LE Sampled Value data streams. The paper will describe the system design, how validation was performed, and practical details of the final 132 kV installation. It will be shown how this approach offers a highly cost-effective solution for protecting circuits, particularly for complex arrangements with multiple ends and space restrictions.

This project represents the first time that passive distributed sensors have been deployed for multi-ended circuit protection, and therefore this capability is likely to be of interest to protection engineers faced with delivering affordable and resilient protection of multi-ended transmission circuits or similarly challenging networks that would benefit from multi-zone differential protection capability.

1 Introduction

New grid connections, which are typically required for connecting renewable generation sources, often create multi-ended feeders in high voltage systems. It is clearly important that these circuits are properly protected, but it can be challenging to achieve this cost-effectively. There may also be space restrictions in one or more substations involved, which limits the ability to install modern protection IEDs, communications equipment, and equipment for aligning current measurement data (i.e., time synchronisation equipment). This paper presents a robust solution to these challenges using passive, distributed sensing, which has been proven in a 132 kV system.

SSEN Transmission and Synaptec have collaborated in the UK to demonstrate the application of this technology, with the goal to demonstrate reduced overall equipment costs, reduced infrastructure requirements, and faster installation of the protection scheme. By enabling line differential protection to be deployed on multi-ended circuits, the approach will offer improved protection accuracy in locations where distance protection would previously have been required due to space, cost, or telecommunications bandwidth constraints.

One of the major challenges in smart grid applications is how to protect the system in a cost-effective way. Often it is possible to use proven protection solutions and technologies which are commonly applied in high voltage power networks, but these solutions are typically also very expensive. The project described in this paper contributes a robust and cost-effective multi-terminal line differential solution using passive, distributed sensing, which has been proven in a 132 kV installation and which can see many installations in future smart grid networks.

2 Protecting Multi-Ended Circuits

2.1 Challenges of Conventional Approaches

Figure 1 illustrates a conventional multi-ended protection scheme using differential protection, where three substations need to communicate with each other.

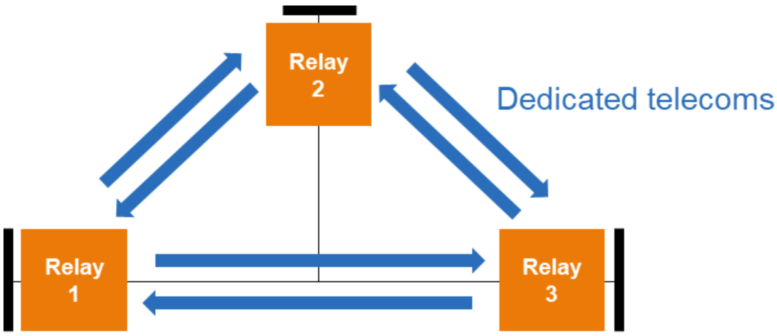

Figure 1: Convential multi-ended differential protection scheme

Reference [1] describes the disadvantages of this approach, which can be summarised as follows:

- To achieve unit protection, protection IEDs are required at all terminals, with the associated capex costs, integration testing, and maintenance costs. Being able to reduce the number of devices to manage is highly desirable.
- Requires complex telecoms infrastructure for continuous comparison of current measurements. While this can be achieved with SDH/PDH- and MPLS-based networks, there is complexity in validating the performance for protection requirements (i.e., low latency and jitter) under all conditions.
- Requires robust GNSS access at every location for measurement synchronisation. Alternatively, synchronisation using the “ping-pong” method requires a stable communications network with low jitter and asymmetry [2].
- There may be imitations on space and the available telecommunications data bandwidth in remote substations, meaning that upgrades are not feasible.
- Compatibility and interoperability with other IEC 61850 devices in the long term is not a given, as existing line protection IEDs will typically use IEEE C37.94 interfaces (or proprietary equivalents). This can be exacerbated by the potential for mismatch of firmware versions for IEDs communicating over a wide-area network.
- Distance protection offers an alternative, but has significant limitations, such as over- and under-reach caused by fault infeeds from teed circuits. It is also challenging to design and validate distance protection schemes under all possible conditions.
- Depending on the operator’s policies, it may be required or desirable to secure the data streams between substations with encryption and/or authentication. This can add significant complexity, such as requiring the use of Routable-SV and associated infrastructure for cryptographic key management.

2.2 Single-Ended Scheme using Passive Sensors

Distributed electrical sensing is a technology platform which allows measured values from over 30 current transformers to be acquired passively using a single optical fibre core (e.g., an available OPGW core) over distances of up to 60 km. These measurements can then be utilised as part of centralised protection schemes or communicated to conventional protection devices for analysis via IEC 61850-9-2/61869-9. This method eliminates the need of having multiple protection relays, complex time synchronisation systems to align current measurement data, and telecommunications equipment at each line end.

Figure 2 illustrates a three-ended scheme using distributed sensing. Passive current sensors are installed at each terminal, and existing CT can be interfaced via a Secondary Connected Module (SCM) (see Figure 4). These sensors are coupled to existing singlemode fibre and the Interrogator. This results in centralised publishing of protection-class measurements to local protection IEDs using IEC 61850-9-2 Sampled Values (SV). All measurements are synchronised to a global reference using IEC 61850-9-3 PTP (the slight delay due to the speed of light in fibre is automatically compensated). A useful benefit is that global time synchronisation (and provisioning of a PTP clock) is not required to provide protection functionality, because the current measurements are inherently synchronised relative to each other – therefore the system is resilient if the PTP source fails or is not available.

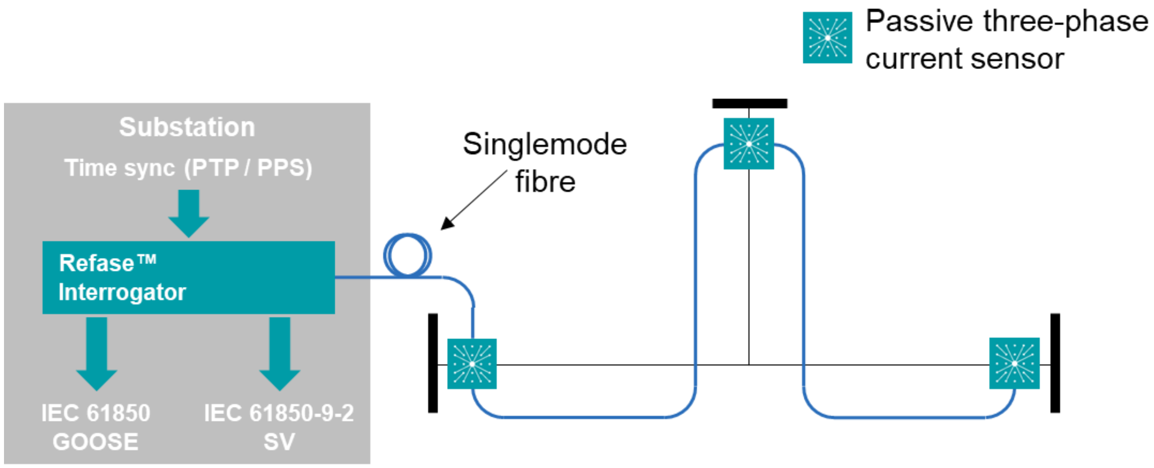

Figure 2: Multi-ended scheme using passive, distributed sensing

There are several technical benefits arising from this centralised, single-ended approach to line differential protection:

- Faster-acting multi-ended differential protection, due to elimination of the typical wide-area communications delay of 2-6 ms, and elimination of other complications such as asymmetrical delay [3], [4].
- Removal of vulnerability to loss-of-sync errors between terminals. In conventional schemes, this would cause incorrect tripping or require the protection function to be blocked.
- Enables rapid and accurate post-event response – all measurements are accurately time synchronised and published in a standard format (IEC 61850-9-2/IEC 61869-9) which facilitates examining of fault records for complex events.
- Publishing synchronised waveform data, sometimes referred to as Continuous Point on Wave (CPOW), to the process bus permits further analysis from the same data used by the protection scheme, including for power quality and transient analysis. This can lead to condition monitoring insights resulting from the same infrastructure.
- Readily supports new grid connections with the potential to reduce civil engineering works by avoiding the need for new equipment housings.
- The measurement information is inherently secure as it is transferred via modulated wavelengths of light. This cannot be eavesdropped or interfered with, except by breaking the fibre, which is instantaneously detected by the Interrogator.

3 Implementation and Live Trial on 132 kV Circuit

3.1 Scheme Overview

The passive sensing solution outlined in Section 2 has been implemented and tested using two approaches:

1. Factory acceptance tests (FATs) of two- and three-ended schemes (Sections 3.2 and 3.3).
2. Live trial of a two-end scheme on a 132 kV circuit in the SSEN Transmission network in Scotland (Section 3.4).

3.2 FAT Approach

Figure 3 shows the single-line diagram of a proposed three-ended implementation. The scheme consists of three main hardware components:

1. Interrogator: rack-mount device, located in the substation, for collating and publishing measurements from arrays of passive fibre optic sensors.
2. Photonic Current Transducers (PCTs): Passive fibre optic current sensor, comprising an industry-standard solid or split-core current transformer (CT), insulated as required for the voltage level and environment and integrated with Synaptec's photonic sensor technology.
3. External protection relays to subscribe to SV data published by the Interrogator and perform the line protection function. Alternatively, the Interrogator can implement protection onboard, to further reduce the number of devices required (including Ethernet switches) and trip times.

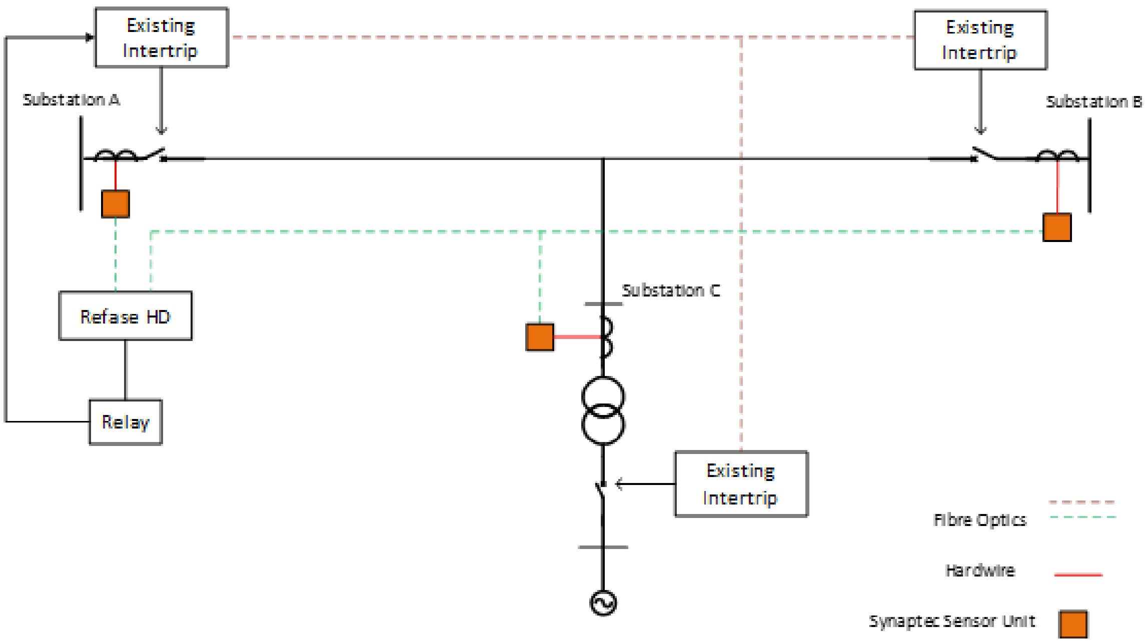

Figure 3: Schematic of three-ended system

The Interrogator interfaces with the sensors at feeder terminals using one core of the existing singlemode fibres in the Optical Ground Wire (OPGW). The PCTs are spliced into the existing fibre network at the splice trays present at each feeder end substation. Figure 4 illustrates how the equipment is connected. Note that reels of fibre are used to emulate the required distances to ensure that the testing is realistic. Protection relays from three different vendors were used to ensure full interoperability of the solution.

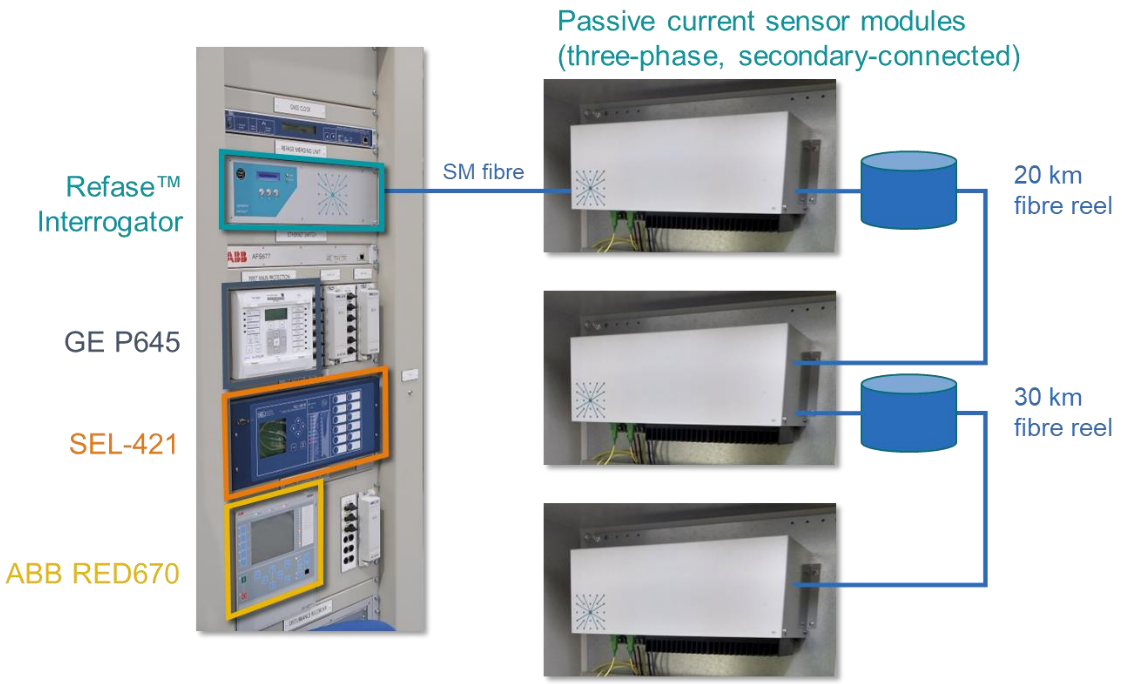

Figure 4: FAT equipment connections for three-ended scheme

A remote virtual FAT procedure was also performed during the UK lockdown in 2020. This involved using multiple cameras and videoconferencing software to ensure full visibility of the system to all participants – allowing validation to be performed safely. This approach was also useful for rapidly repeating tests on multiple occasions, after interoperability issues were resolved.

3.3 FAT Results

Figure 5 provides an example of a three-phase fault simulated during the FAT process, and the resulting trip signals from external protection relays. In summary:

- Fault scenarios are generated and injected onto all three passive sensor modules synchronously.
- Three relays receive SV and all trip consistently in <20 ms following fault inception.
- System stability was also proven, as external faults result in no false trip from any relay.

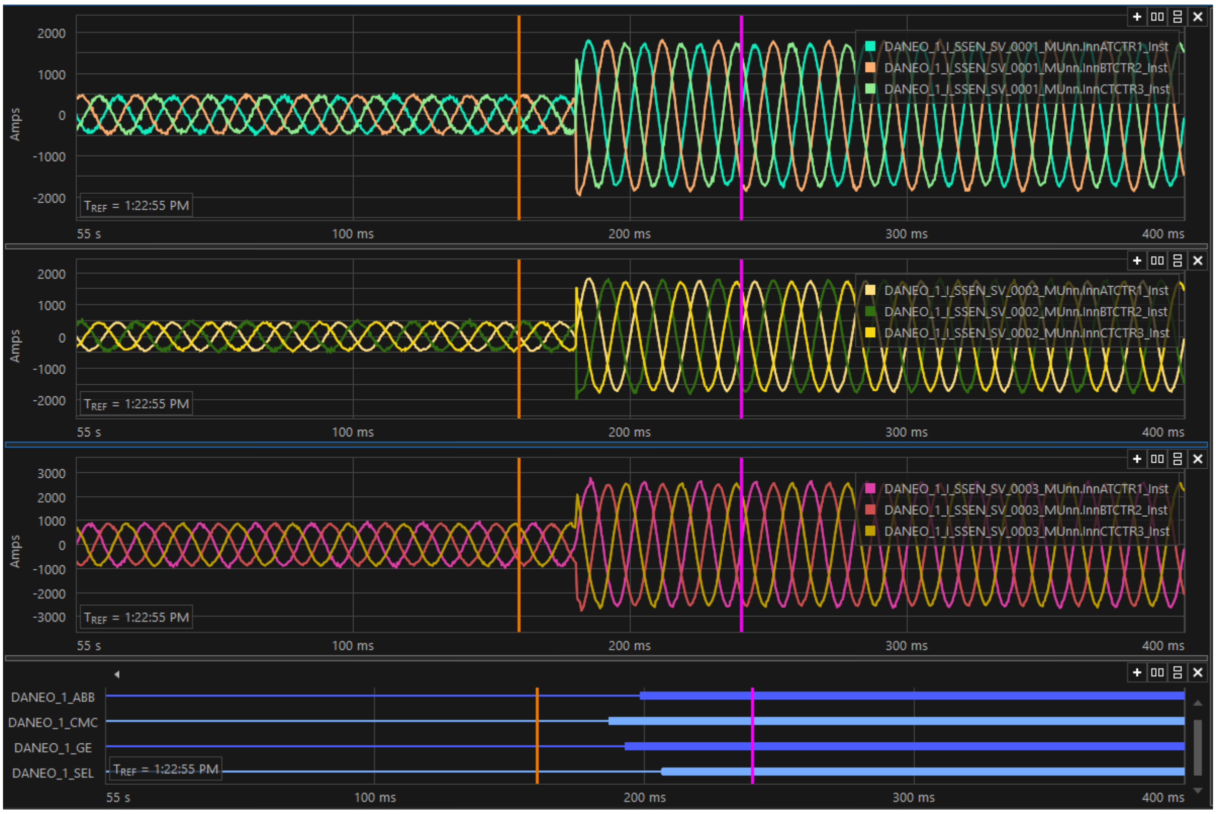

Figure 5: Typical protection trip results

3.4 Live Trial Deployment

A full two-ended system has been installed on an SSEN Transmission 132 kV circuit during Summer 2021 for operational testing. The protection scheme performance will be compared with the existing conventional system over two winter periods, to comprehensively validate the solution in realistic conditions. Figure 6 illustrates the scheme, which operates between two substations in Scotland that are approximately 30 km apart.

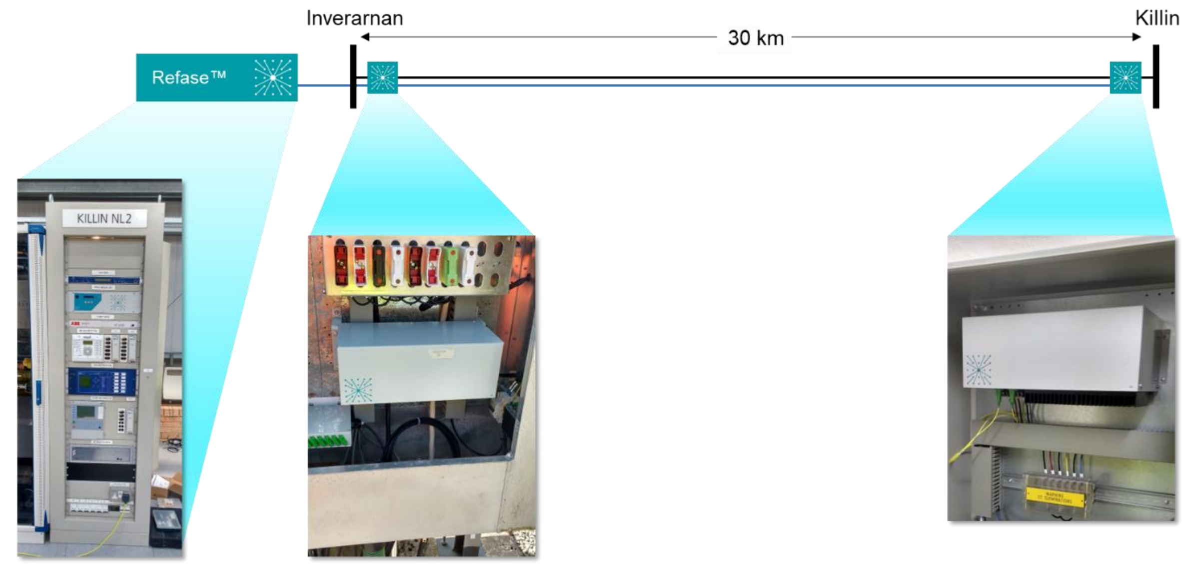

Figure 6: Overview of live trial installation

The sensor units have been installed in an HV compound marshalling kiosk at Inverarnan substation during Summer 2021. At the remote end at Killin substation, the sensor units were installed in a wallbox within telecoms room which is temperature controlled. Figure 7 and Figure 8, respectively, show these installations in more detail. This shows that the passive sensors are suitable for diverse installation locations, and can be designed for a wide range of temperature and IP requirements. During the trial, the performance of each sensor installation type will be monitored.

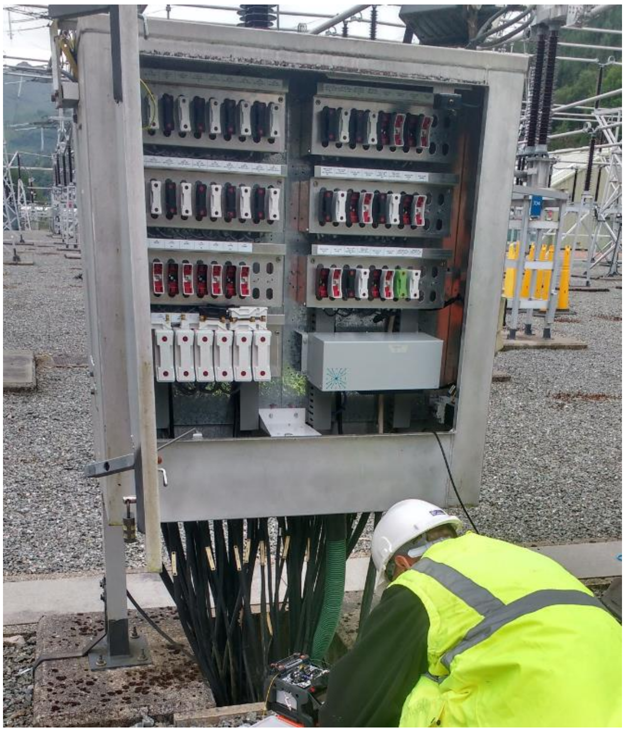

Figure 7: HV compound installation of sensor units at Inverarnan substation

Figure 8: Wall-mounted installation of sensor units at Killin substation

There is also an important safety benefit from only installing passive equipment in HV compounds or switchyards, as all active electronic equipment, which will require configuration and maintenance, can be located elsewhere (away from HV equipment), with only a fibre optic cable required to the HV areas. In contrast, a Stand-Alone Merging Unit (SAMU) IED must be located either near to the CTs in the HV compound, or long copper leads are required from the CTs into the IED room. The passive sensing approach avoids both of these undesirable approaches.

Furthermore, being able to secondary-connect to existing CTs provides a retrofit option for “brownfield site” installations.

4 Lessons Learned

The core function of the system has been realised and installed, leading to the world’s first demonstration of a single-ended unit protection scheme over 30 km (with a 50 km system also undergoing factory acceptance testing).

However, several factors have been observed during the project which can lead to refinement in the future:

- There is a lack of standards for Low Power Instrument Transformers (LPIT) to validate the accuracy. The passive sensing approach does not map directly to existing standards for LPITs and SAMUs, so care must be taken in how these standards are applied.
- It is important to specify and understand the system performance of the full range of load and fault currents. During the implementation of the system, the Interrogator was required to be recalibrated and the CT ratio changed from 1200/1 to 600/1 to be more accurate at lower load currents. This resulted in improved signal acquisition of the fundamental component and reduced noise and harmonic distortion.
- Interpretations of the IEC 61850 standards can lead to variations in implementations between vendors. For example, the behaviour of an external protection relay during degraded conditions, such as loss of global time synchronisation, should be specified and tested [5].
- Significant time is also required to set up devices from various vendors for interoperation. Typically, each vendor will have different configuration tools, SV settings, VLAN settings, and support for different PTP versions.
- It is important to provide time for testing interoperability, as this requires coordination between multiple parties to resolve issues.
- New tools and skills are required – spanning protection, telecoms, IEC 61850, and the practicalities of using optical fibres. Training at early stages is essential to become acquainted with the technologies involved. Collaboration between the vendors and contractors involved in the trial project was important to identify and resolve technical issues.

5 Business Case Analysis

A comprehensive commercial evaluation of the passive sensing and protection system has been performed, including capital equipment cost reductions, operational cost reductions, health and safety benefits, system resilience improvements, and environmental impact reductions.

The approach summarised in this paper has the potential to save significant capital expenditure, compared to conventional approaches to multi-ended circuit protection. This is due to requiring less secondary equipment, the reduced substation footprint, minimising civil engineering work, reduced copper wiring, and the ability to use existing standard optical fibres available in OPGW.

There are also other important factors which reduce operational costs and enable improved functionality over conventional protection schemes:

- Faster and safer installation and maintenance with optical isolation on secondary side.
- Fewer IEDs to test, commission, and maintain over time. This also results in a lower carbon footprint for this system operation.
- Faster protection by eliminating asymmetrical and wide area communications delays.

- Eliminates the need for dedicated telecoms channels and related equipment between feeder ends (with the exception of the fibre required for the passive sensor network). For conventional protection of three-ended circuits, a minimum of two telecoms channels are required whereas the solution in this paper only requires a single fibre core.
- Continuous synchronised waveform streaming enables power quality and transient analysis.
- Provides readiness for incoming IEC 61869 standards from IEC TC 38.
- Facilitates new connections, particularly for low-carbon generation and other technologies.

6 Conclusions

Trial projects are important building blocks for delivering digital substations and related technologies which are the future for many utilities, including SSEN Transmission. This project successfully demonstrated single-ended differential protection over 30 km on a 132 kV circuit. The performance of the installed system will be reviewed periodically, and data will be captured to establish internal standards and specifications for future projects.

The approach is standards-based and compatible with multi-vendor relays. Local and remote measurements are delivered as synchronised SV streams within 1 ms, without wide-area communications networking. This offers the opportunity to deploy unit protection in areas where distance protection previously had been the only option. Compared to conventional approaches, passive sensing leads to greatly reduced capex, fewer devices to install, test, and maintain, and improved safety (due to no CT wiring in the protection panel for safe maintenance).

An in-depth, multi-stage Factory Acceptance Test (FAT) process for innovative solutions is required to eliminate risks. Creating test procedures at early stages is useful for benchmarking and repeating at later stages. In this project, fast fault clearing performance has been demonstrated. There is room for fine tuning and optimising, such as by executing protection algorithms directly on the Interrogator IED to further reduce trip times and the number of IEDs required.

Finally, the protection community dealing with IEC 61850 implementations is eagerly awaiting the publication by TC 95/WG 2 of the document IEC 60255-216-1 “Digital Interface – Guidelines for requirements and tests for protection functions with digital inputs and outputs” which is expected to give a significant contribution to minimize the variations in interpretations of IEC 61850 for power system protection applications [5], [6].

7 References

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