Line Differential Protection for Long-Distance Remote Assets using Passive Optical Sensing

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Abstract

Distinguishing between faults on mixed conductor circuits can be challenging when relying only on measurements from within the substation. Auto-reclose must be controlled differently for faults on cable sections compared to overhead line (OHL) sections. Conventional approaches are impractical, inaccurate, or expensive to deploy. This paper describes a solution using passive sensing to acquire remote measurements from current transformers (CTs) at the cable/OHL transition points. In particular, this paper focuses on a challenging circuit requiring CTs located over 60 km away from the nearest substation. The solution passively collects the CT measurements by converting their secondaries to an optical signal at the CT locations, but without requiring any active electronics, control power, or conventional telecommunications. This represents the first time that line differential protection, using entirely passive sensing, has been delivered over such a long distance. The results in the paper demonstrate that sub-cycle differential protection operation can be achieved for the remote cable sections. This provides a convenient and cost-effective approach to resolving the issue of allowing or blocking auto-reclose on these complex circuits.

1. Introduction

Utilities often need to deploy mixed or hybrid circuits – containing multiple sections of overhead lines and underground cables – when trying to balance resilience, cost, convenience, and public opinion considerations. These mixed circuits present protection challenges which are expensive to address using conventional instrumentation technologies. The key challenge is accurately discriminating between faults on cable sections and overhead line (OHL) sections. It is important that auto-reclose (AR) is blocked for cable faults but allowed for OHL faults, as illustrated in the circuit in Figure 1. Without a solution to intelligently block or allow AR, there is a risk that reclosing could occur for cable faults resulting in significant asset damage. Similarly, there is a risk to security of supply for customers if AR is not used for OHL faults, which are typically transient in nature.

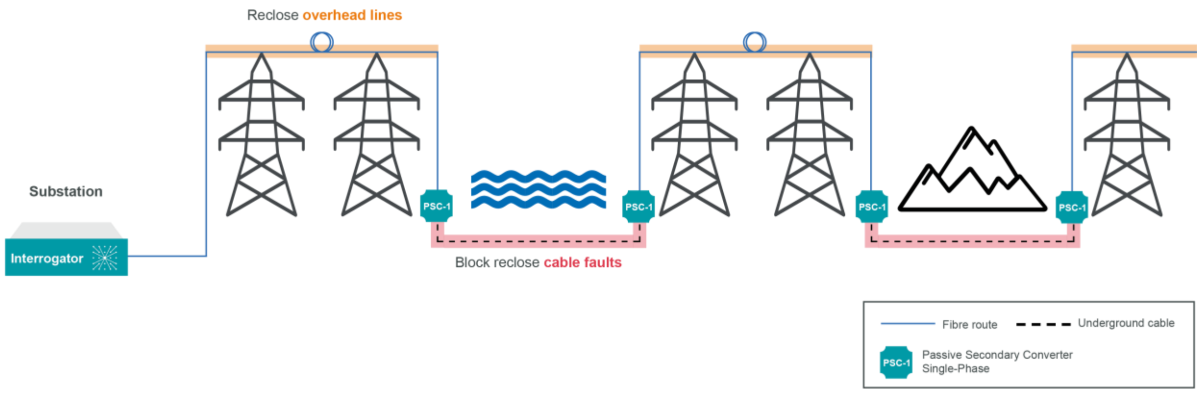

Figure 1: Example of a mixed circuit with multiple OHL and cable sections

This paper will demonstrate a solution to this challenge using passive sensing. No active electronics, control power sources, or data networks are required outside of the substation fence. In particular, a case study will be used which illustrates the system operating over a very long distance of 62.1 km to implement line differential protection for a 132 kV double circuit. The paper will explain how this has been experimentally verified, including testing of the differential protection scheme operation. It will also provide practical guidance on how to deploy and commission this system, such as the required optical constraints.

2. Issues Protecting Mixed Circuits

There are many complex circuits with a mixture of overhead and underground conductor types. However, it is difficult to reliably protect such circuits because of the need to auto-reclose only for faults on overhead lines, but block reclosing for underground cable faults. Usually, the substation relays do not have full visibility of the location of the fault in real-time, and cannot properly determine the exact faulted zone.

As described in CIGRE Working Group B5.23 report 587 [1], conventional protection solutions for mixed circuits have significant disadvantages, as they are expensive, inaccurate, or impractical to deploy in remote cable-to-OHL transition points outside the substation. Distance protection is challenging to design and validate and leads to ambiguity for faults close to a transition point. Installing conventional differential protection relays is often impractical due to the lack of control power or secure telecommunications access at remote sites and the very high cost of civil infrastructure works to house them. Travelling wave protection typically has an error of about 250 m, so it cannot perfectly discriminate between cable and OHL faults in all cases. It is also not suitable for short cables of 1 km or less (due to additional reflections), or for circuits with short OHL sections (due to the low accuracy). Circuits with long cable sections (above 40 km) are also not suitable for travelling wave protection. Optical current transformers based on the Faraday effect can typically only passively interrogate sensors at distances of 5-20 km outside the substation fence. Otherwise, active optical amplification is required which involves provisioning power supplies and other supporting infrastructure at sensor locations.

3. Solution using Passive Sensing

3.1. Overview

An alternative solution is required for providing accurate fault discrimination in complex or remote feeder topologies. Passive distributed sensing enables multi-zone unit protection schemes to be deployed, using passive optical sensors outside the substations fence, without requiring the conventional infrastructure for these measurements [2]. These passive sensors are coupled to standard current transformers (CTs). This allows differential protection zones to be created around all cable sections on a mixed circuit, which provides perfect discrimination for deciding to block or allow AR on the circuit. Reference [3] previously demonstrated that this approach operates correctly for various circuit topologies, fault types, and cable bonding/grounding approaches.

A central optical interrogation device in the substation provides broadband light into a fibre, as shown in Figure 1. At each CT location, a Passive Secondary Converter (PSC) device couples to the fibre and the CT’s secondary output (in exactly the same way a normal protection relay would connect to local CTs). The PSC converts the electrical output from the CT into modulation of a wavelength of light in the fibre, which is reflected back to the interrogation system. The interrogator is able to reconstruct and digitise the current waveform, typically sampled at 4 kHz or 4.8 kHz. IEC 61850-9-2 Sampled Value output streams are delivered to the local process bus for all CTs, including remote measurements. The samples from all CTs are inherently time synchronised and absolute synchronisation can be added by connecting a PTP or 1PPS source to the interrogator. This arrangement can be readily retrofitted to existing circuits, and requires no active electronics or telecommunications at the remote sensor locations.

This approach has been deployed and validated on several HV circuits, including over distances of up to 30 km [4]. This paper demonstrates a significant extension of that capability, by delivering protection schemes at a distance of over 60 km from the substation. The remote sensors are all passive. Specifically, a 17.2 km cable section starts at 44.9 km from the substation, requiring instrumentation over a total distance of 62.1 km. The solution provides a cost-effective method for ensuring selective use of AR under all fault scenarios.

3.2. Case study circuit

The system considered in this paper is a 132 kV 50 Hz AC double circuit (i.e. with two parallel conductors to increase the power transfer capacity) as shown in Figure 2. The full circuit has four cable sections, but this paper will focus only on the most challenging cable section which starts 44.9 km from the nearest substation. Optical fibre will naturally attenuate signals over such a long distance, so careful design of the sensor parameters and use of the light source spectrum is important. Additionally, an optical amplifier located in the substation as part of the interrogation system is used to amplify the received sensor signals.

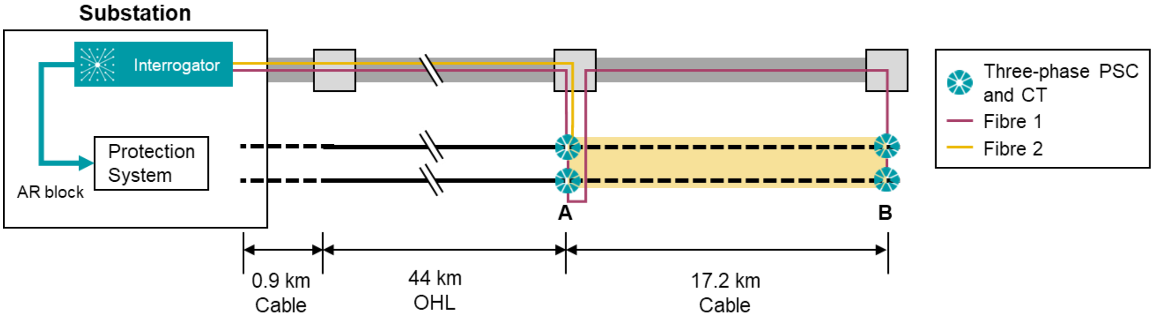

Figure 2: System schematic

This cable section requires three-phase CTs at each end of the cable, for each parallel conductor, totalling 12 sensors. The CTs are rated for 5P20 accuracy class. The system supports configuring up to ten independent differential protection zones. In this case, two zones are configured to protect each of the parallel cable conductors separately. The differential protection uses a two-slope characteristic as illustrated in Figure 3, with the setting values specified in Table 1. Each phase is protected independently.

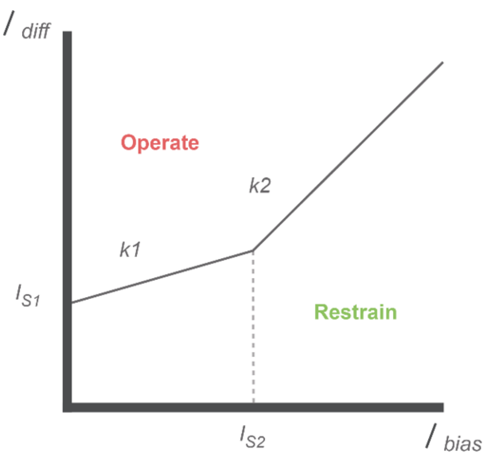

Figure 3: Differential protection characteristic

Setting description	Symbol	Value	Unit
Minimum operating/pickup current	*Is1*	0.3	per unit
Bias slope breakpoint threshold	*Is2*	0.3	per unit
Gradient of first slope	*k1*	0.3	n/a
Gradient of second slope	*k2*	1.5	n/a
Trip confirmation time	*t1*	0.002	s
Trip output latch time	*t2*	1.0	s

Table 1: Differential protection settings

4. Experimental Demonstration

4.1. Laboratory test setup

Figure 4 illustrates the sensor arrangement for laboratory validation of the case study circuit. Each "PSC-1-C" is spliced onto an optical fibre and connected to the outputs of a secondary injection unit (which replaces the CTs for testing). Fibre reels of the appropriate distance have been used to emulate the properties of the actual fibres available at the 132 kV circuit for deployment.

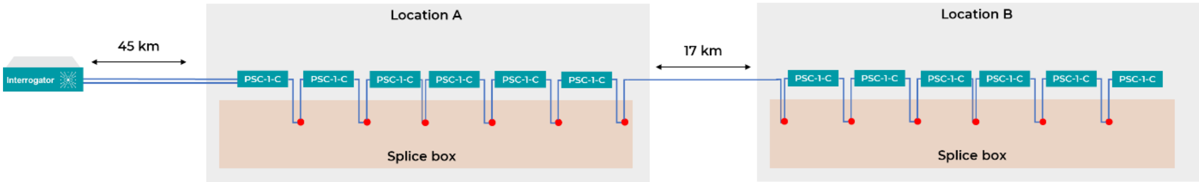

Figure 4: Laboratory test setup

Figure 5 illustrates the optical spectrum measured by the interrogator, where each peak represents the optical signal from a specific current sensor. The spectrum is shaped by the use of an optical amplifier. This is the cause of the higher noise floor for the sensors furthest away from the substation, indicated by the higher "pixel number" values. Overall, the optical amplifier reduces the measurement noise for these sensors.

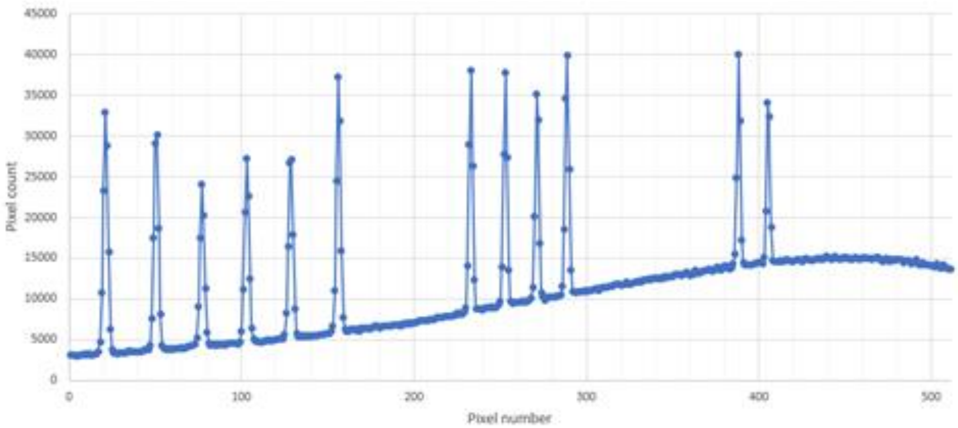

Figure 5: Optical spectrum for all current sensors

4.2. Protection Operation Results

The system has been tested by secondary injection of currents that represent typical fault scenarios. These currents are applied to the PSC devices to emulate the role of the CTs. To summarise the results, two fault scenarios are presented here:

1. An internal fault on a cable section, where AR should be blocked.
2. An external fault on an OHL section, where AR should be allowed.

In both cases, a single-phase fault is applied on one of the cables. Figure 6 shows results for a typical fault within the cable section. The currents from the CTs at both ends for the cable are plotted, but for simplicity only phase A is shown. Figure 7 provides the same result, but zoomed in on the current waveform at the point the fault occurs. As highlighted by the plots, the system's differential protection correctly detects the fault and trips within 9.8 ms, meaning that AR should be blocked for this cable fault. This approach benefits from not requiring any conventional wide-area communications to transfer current measurements between substations, which can add several milliseconds of delay depending on the distance, technologies, and protocols used [5]. For reference, the time taken for the optical signals to travel in fibre over 60 km is 290 µs.

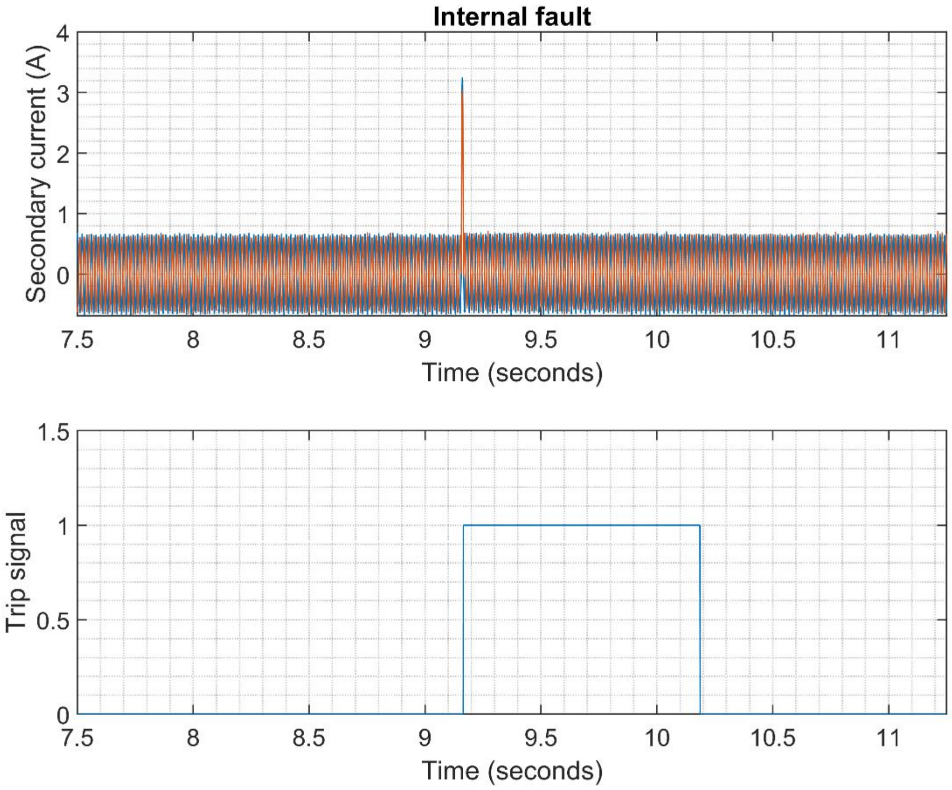

Figure 6: Trip for internal cable fault

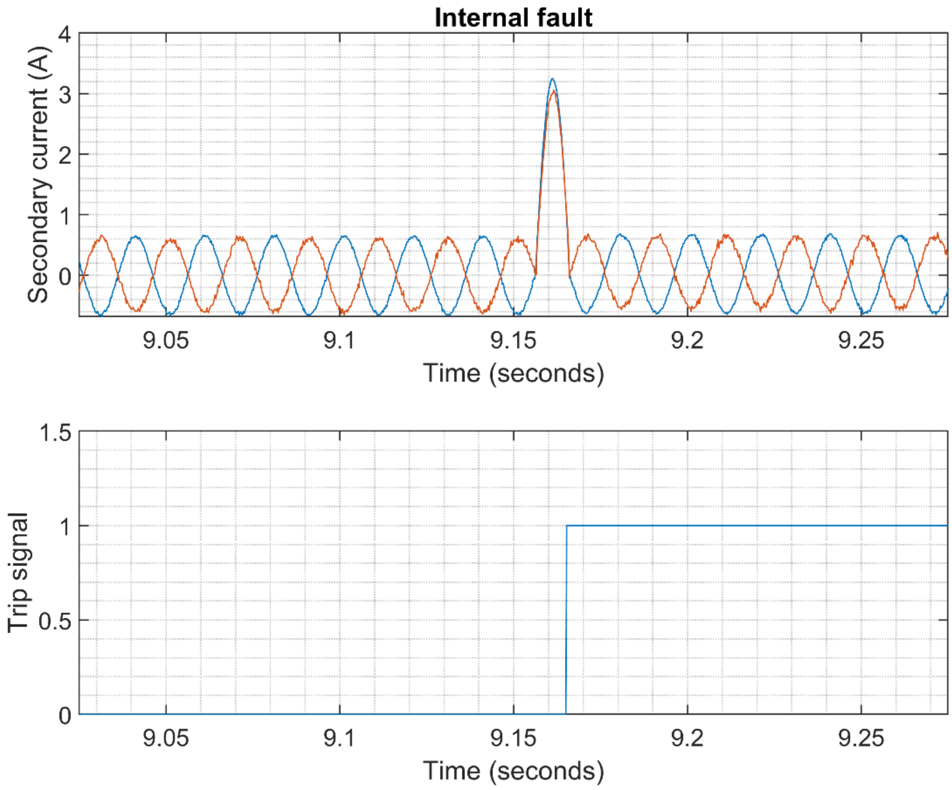

Figure 7: Trip for internal cable fault (zoomed)

Note that the injection test software includes operation of the circuit breaker to clear the fault at the first current zero-crossing following the trip signal. In this case, the fast trip means that the fault is cleared with the first half-cycle. However, typical circuit breakers may require several cycles to operate, and trip conditioning is often used to delay direct tripping to cater for a possible DC component in the fault current. In this application, however, the “trip” signal would simply be transferred to the protection relay which controls the AR process to block AR for this fault.

Figure 8 illustrates the behaviour for an external (OHL) fault. The differential protection remains stable and does not issue a trip. Therefore, the relay controlling the AR process will allow AR as usual.

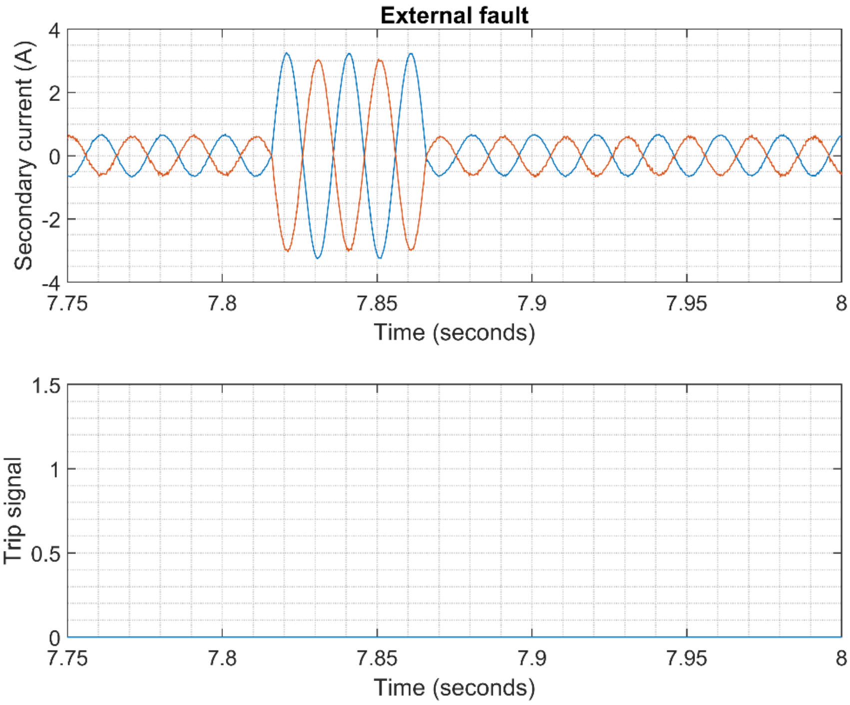

Figure 8: Stability during external OHL fault

4.3. Practical Considerations

Optical time-domain reflectometer (OTDR) studies of the fibre available at the real circuit are essential to design the optical system for long distance circuits like this case study. Optical losses during the sensor manufacture and installation must be tightly controlled.

The interrogation system is able to compensate for the time-of-flight of light in the fibre (approximately 290 µs for 60 km, as noted above) to align samples when they are digitised. However, for such long distances it is especially important that thorough testing of sensor magnitude and phase accuracy is performed, to meet the application requirements.

5. Conclusions

This paper has demonstrated a novel approach to protecting remote cable sections within mixed circuits. In the case study system, a differential protection function is used to intelligently control the circuit's auto-reclose system in real-time. The results have proven that this approach can be designed and deployed for very long circuits, at distances of more than 60 km. Due to the signals travelling at the speed of light in fibre, the protection operation is very fast, delivering sub-cycle trip times. All sampled waveforms are also inherently time synchronised relative to each other, so the system is robust even if an absolute time synchronisation source is unavailable. The solution will be deployed on a 132 kV circuit with multiple cable sections later in 2024.

6. References

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[3] K. Kawal, S. Blair, Q. Hong, and P. N. Papadopoulos, ‘Selective Auto-Reclosing of Mixed Circuits Based on Multi-Zone Differential Protection Principle and Distributed Sensing’, *Energies*, vol. 16, no. 6, Art. no. 6, Jan. 2023, doi: 10.3390/en16062558.
[4] M. Mohemmed *et al.*, ‘Differential Protection of Multi-Ended Transmission Circuits Using Passive, Time-Synchronised Distributed Sensors’, presented at the PAC World, Prague, Czech Republic, 2022.
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