Utility Experience of System-Based End-to-End Testing of EHV Feeder Protection Schemes

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Abstract

System-based end-to-end testing focuses on the validation of protection schemes independently of protection relay type and settings. Fault values for tests are based on actual system parameters and plant characteristics rather than idealised values which are used in conventional steady state protection testing methods.

The following paper describes a utilities approach to end to end testing, from traditional steady state methods to the evolution of system-based testing to test a complex extra high voltage (EHV) over line protection scheme, and outlines the test methods used and the issues identified.

1 Introduction

The EU has set legally binding national targets in member states to increase the use of renewable energy sources by 2020. Ireland has a target under the National Renewable Energy Action Plan (NREAP) to increase the level of renewable electricity on the Irish power system to 40% by 2020.

Ireland's main indigenous source of renewable energy is generated by wind resources which are predominantly located in the west coast of Ireland.

The south west region had insufficient network capacity to cater for such high penetration levels of variable renewable generation, therefore, significant grid infrastructure upgrades were necessary in order to avoid excessive curtailment of renewable energy sources.

There are five types of system security limits that necessitate curtailment:

- System stability requirements (synchronous inertia, dynamic and transient stability)
- Operating reserve requirements, including negative reserve
- Voltage control requirements
- Morning load rise requirements
- System Non Synchronous Penetration (SNSP3) limit (currently 50%)

At present, the System Non Synchronous Penetration (SNSP3) limit is 50%, but with the planned strategic network infrastructure upgrades this is set to increase to 75%.

Gate 3 allows for the connection of circa 4000 MW of wind generation and also allows for connection offers to be issued to about 1,700 MW of new conventional generator projects across the country. This includes new and efficient gas-fired power stations and pumped storage hydro plants.

It will ensure that a high capacity of renewable and conventional projects can connect to the Irish network over the next decade, in a way that is efficient, maintains our security of supply, promotes competition and achieves the 40% renewables target by 2020.

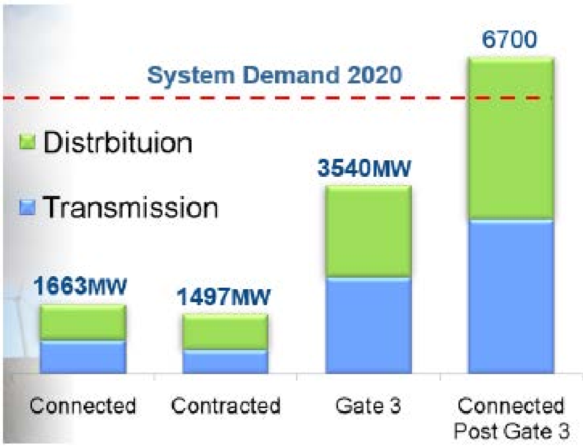

Figure 1: Projected Renewable Energy by 2020

In order to facilitate the integration of a planned 1076 MW of renewable energy onto the power system in the south west region, four new 220/110 kV stations and one new 400/220/110 kV station were constructed simultaneously.

The energisation plan for the south west stations was such that commissioning of the five south west stations would be required to be completed over a 6-7 month period. This commissioning drawdown effectively doubled the normal baseload requirement and in order to meet the required milestones, contract transmission commissioning resources were introduced for the first time.

System-based testing was considered a good approach for auditing and technical validation of the contract commissioning work, providing an increased level of assurance.

Figure 2: Location of the 5 South West 220kV Stations

2 Protection Overview

2.1 Typical Protection Arrangement for EHV Line Protection

At extra high voltage (EHV) level in Ireland, namely 220kV and 400kV, a duplicate protection scheme is normally in place. A typical protection scheme consists of a distance relay with a duplicate differential/distance relay. Where fibre optic or pilot wire links are available, the duplicate protection device must be a differential relay, otherwise a distance relay may be used. The main and duplicate protection relays must also be from different manufacturers. The following is a list of protective functions incorporated into the line protection IEDs:

- Distance protection
- Differential protection
- Directional comparison earth fault (DCEF)
- Permissive inter-tripping (predominantly POTT)
- 1/3 pole high speed Auto-Reclosing (AR).
- Synchro-check AR functions
- AR blocking zones for cable sections
- Remote AR blocking and zone acceleration from bus-zone protection schemes
- Emergency/back up overcurrent

2.2 Setting Policy Surrounding Distance Zone Reaches in Ireland

Distance protection is generally configured to have five main protective zones and an additional controlled zone. The controlled zone may be employed to block auto reclose operation for faults on cable sections at either the local or remote end of the line. Typical cable sections leading into the stations are short in length, approximately 100-500 metres.

Of the five main protective zones there are 3 forward and 2 reverse zones, typical zone reaches are shown in table 1.

Table 1: Typical Distance Reaches and Times

Zone	Reach	Time
1st Forward	80% - 85% of the protected line	0 sec
2nd Forward	100% of the protected line + 60% of the shortest line out of the next station.	0.3 sec
3rd Forward	100% of protected line + 120% of the longest line out of the next station.	0.9 sec
1st Reverse	70% of the shortest reverse line.	0.45 sec
2nd Reverse	200% of the longest reverse line.	1.1 sec

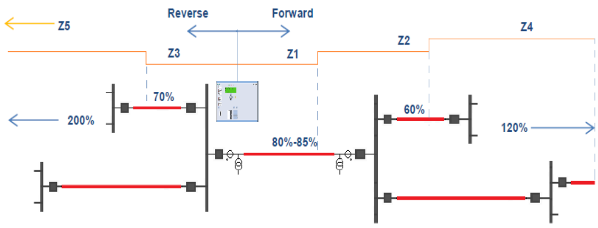

Figure 3: Impedance Zone Reaches Shown on a Typical Network Topology

3 Auto Reclosing

3.1 Auto Reclosing Philosophy

In Ireland, more than 80% of system faults are transient, therefore auto reclosing (AR) is used to allow plant restoration without operator intervention or inspection, and to maintain system robustness and integrity. Auto reclosing is not permitted on XLPE cable sections, as the fault is unlikely to be transient nor on oil filled cables, as it is considered hazardous.

The auto reclose philosophy at EHV is high speed single and/or three pole AR. Only single pole AR is allowed near large generation feeders, as a triple pole reclose may result in generator rotor damage due to loss of synchronism.

Only single shot reclosing is used at transmission level, as repeated voltage depressions and high fault currents cannot be tolerated.

Typical dead times for reclosing are in the order of 600-700ms for three pole operation for multiphase faults, and 900-1000ms for single phase faults.

3.2 Auto Reclosing Supervision

As discussed in section 2.2, auto reclose supervision is sometimes used in the form of an additional controlled distance zone, which can be used to block auto reclosing for a local cable section fault (within the controlled zone) or a cable section fault at the remote end of the line (outside controlled zone). An additional “AR cross block” binary output is used to block reclosing of the duplicate device.

Where cable sections are installed at both the local and remote ends of the protected line, or there is a section of cable within the line, a dedicated distance IED is used to supervise the cable sections. Synchro check functions may also be incorporated into this type of IED.

Figure 4: Quadrilateral Impedance Zone Reaches for Blocking AR on Local and Remote Cable Sections

3.3 Zone Acceleration Schemes Used in Ireland

In Ireland, typically, transmission lines are short to medium in length. For these types of lines Permissive Overreach Transfer Tripping (POTT) schemes are used in association with distance protection. POTT schemes use an over reaching zone or use zone 2 to cover a reach greater than the protected line length. An accelerated trip will be issued by both local and remote IEDs to their opposite ends, for a fault detected anywhere on the protected line. POTT schemes are also useful where the remote end circuit breaker is open or there is a weak infeed at the remote end, as accelerated tripping on 100% of the line can still be achieved.

Permissive Under-reach Transfer Tripping (PUTT) schemes are less common and are generally reserved for use on longer lines where actual line impedance settings may not be accurately calculated due to cumulative errors. With PUTT schemes, a transfer trip is issued for any fault detected in the 1st protective distance zone. In these types of schemes it is assumed that the fault is on the line if detected in 1st zone at either end of the line.

3.4 Tele-protection Schemes

Where a fibre connection is available in the station, a binary input/output interface is used, elsewhere, conventional power line carrier (PLC) devices are used. On a duplicate distance protection scheme, two forms of tele-protection must be employed.

Certain tele-protection communication media, such as Power Line Carrier (PLC), have a limited number of channels available to cater for the full protection scheme tele-protection requirements. The main advantage of utilising a fibre connection over a power line carrier device is that there are four channels, as opposed to two. Furthermore, the fibre I/O interface devices have very low propagation delays which are in the order of less than 10ms.

In situations where there are insufficient I/O tele-protection channels available, the AR block to the remote end from the local bus zone protection (BZP) is shared over the PTT channels. This is achieved by prolonging the PTT pulse from the local end BZP to the remote end. A decoding timer set up in the user defined logic of the distance IED in the remote end is then used to block AR, if the PTT pulse received is longer than 300ms. The purpose of providing a prolonged PTT pulse from the BZP to the remote end relay is to accelerate tripping of the protection and also to block the remote reclosing.

Table 2: Tele-Protection Channel Assignments

Device	77-1 (TEBIT)			
	Channel			
	1	2	3	4
	POTT	DCEF	POTT	AR Block
Main 1 Distance	X	X		X
BZP	X		X	X
Main 2 Distance			X	X

Device	77-2 (PLC)	
	Channel	
	1	2
	POTT	DCEF
Main 1 Distance	X	X
BZP	X	
Main 2 Distance	X	

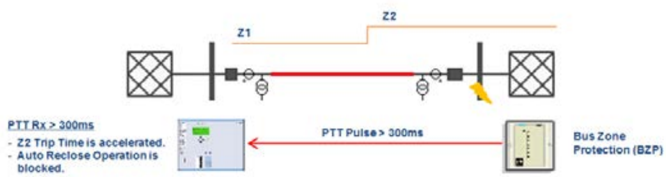

Figure 5: PLC Implementation of Zone Acceleration and AR Blocking Channel from BZP

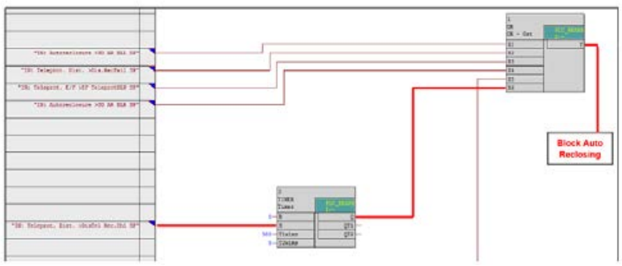

Figure 6: PLC Block AR Logic

4 Traditional Approach to End-to-End Testing

4.1 Point to Point

Historically, end-to-end testing was limited to functional testing by 'pinging' the respective PTT Tx channel and observing the IED response. The commissioning engineer would ensure that this tele-protection transmit signal was received at the remote line protection IED(s) and that zone acceleration occurred. Following experience gained over a number of years, this approach was found to have several shortcomings.

To test correct and reliable operation of the auto reclosing on both the main and duplicate protection at both ends of the line, it is important for the commissioning engineer to ensure that PTT pulses are << 300ms, for line faults as a PTT Rx >300ms will block the auto reclose cycle.

Using the point to point 'pinging' technique, it is not possible to reliably and repeatedly test the auto reclose functionality due to the tight time tolerances involved.

4.2 Steady State

Due to the challenges outlined in 4.1 above and with the advent of a readily available and easily implementable global timing reference (GPS), tele-protection testing evolved into synchronised end-to-end testing.

End-to-end testing uses two or more time synchronised test-sets at multiple locations to simulate a fault on a transmission line simultaneously. The responses from the IEDs are automatically evaluated against predefined pass/fail metrics using automated test routines. This method enabled a more holistic test on the interaction of all components of a distributed protection system.

Initially, GPS end-to-end testing was performed on individual protection IED pairs, e.g., Main1 to Main 1, and the test repeated for Main 2 to Main 2, however, this later evolved to injecting both Main 1 and Main 2 protection simultaneously.

Steady state GPS testing involves calculating pertinent test points on the power system in order to challenge the protection scheme response. The test points are derived from the feeder specific settings as applied to the protection relays.

For a typical permissive scheme, such as POTT, it is important to prove protection scheme dependability and security, in other words, that the local relay will not only issue a PTT Tx for a fault within the overreaching zone, but also that it will not issue a PTT Tx for a fault behind the local protection relay or outside the over-reaching zone.

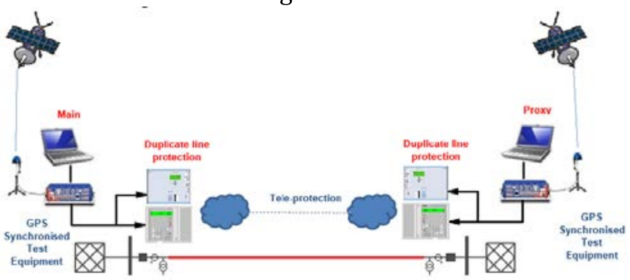

Figure 7: Steady State GPS End to End Test Setup

Figure 8 below illustrates typical steady state GPS tests that would be carried out to functionally prove that a POTT scheme is working as intended.

An initial test (Position 1) would be carried out as a sanity check to ensure the test setup at either end is connected correctly, and that the tele-protection media are operational. An initial test involves injecting a zone 1 fault into both local and remote protection relays simultaneously and observing that the circuit breakers trip and reclose in zone 1 time.

Once the initial test has proved successful, the commissioning engineer at station A would then pick a fault value outside zone 1, but within the overreaching zone (Position 2). The commissioning engineer at station B would pick a fault inside zone 1. Both relays should receive the permissive signal from the respective remote end. Relay(s) B should trip and reclose in zone 1 time and relay(s) A should trip and reclose in an accelerated time approximately equal to zone 1 time, plus the tele-protection propagation delay.

This test is then repeated for position 3, i.e., the commissioning engineer at station B picks a fault outside zone 1 but within the overreaching zone, the commissioning engineer at station A picks a fault within zone 1.

Further testing would be performed to examine the security of the scheme (Position 4), this entails simulating a reverse fault on relay(s) A and applying a forward fault on relay(s) B within the overreaching zone. Relay A should receive a PTT Rx signal from Relay B and not accelerate its zone timers. Relay B should trip and reclose, relay A should trip and not reclose.

This test is then repeated for the opposite side (Position 5).

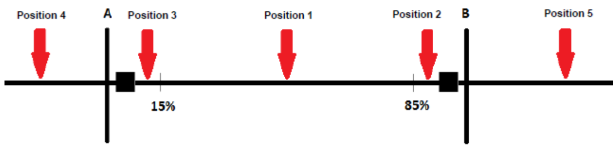

Figure 8: Typical Test Points for Steady State End to End Testing

Some disadvantages with this method of steady state GPS testing are:

- Commissioning engineers at either end of the protected line pick arbitrary fault locations based on the parameters that have been applied to the local distance relay(s) only
- The protection settings could have incorrect zone reaches applied but the tests may still record a pass
- The fault may not correspond to the same location when viewed from station A and station B, i.e., commissioning engineer at station A may pick a fault at 70% of the line length when viewed from A and station B may pick 70% of line length when viewed from B
- Fault magnitudes are idealised and not realistic
- The commissioning engineers are in communication with each other via telephone while the testing is in progress, should a test

fail, troubleshooting can be difficult and slow as diagnosis requires test information from the remote laptop for a complete picture of the issue
- More a functional test than a system test

A real-world example of where auto reclosing has not operated correctly for a transient fault on the line was where it was discovered through analysis of the fault records (see Figure 9) that the PTT Rx pulse was maintained in excess of 300ms, resulting in the blocking of an auto reclose cycle within the relay.

It was revealed that this was as a result of the tele-protection echo function having been enabled on both the main and duplicate protection relays while sharing the same PLC carrier channel. The solution to this particular problem was to switch off the echo function on the duplicate protection IED.

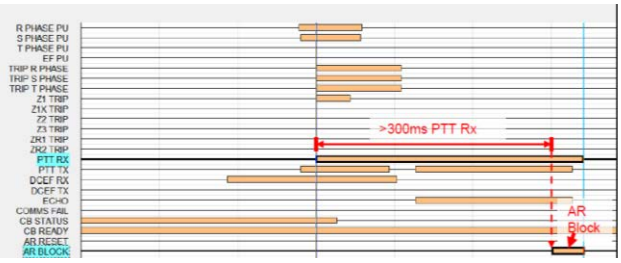

Figure 9: Fault Records Following a Prolonged PTT Rx which Blocked AR

5 Evolution to System-Based End-to-End Testing

5.1 System-Based End-to-End Testing

System-based end-to-end testing is a system test that focuses on testing of protection schemes independently of relay type and settings. With this test method, fault points and values are calculated independently of relay settings, therefore, more realistic fault voltages and current levels are presented to the protection scheme. This ensures the commissioning engineer has a more accurate picture of how the protection will behave under actual fault conditions.

Fault values are based on actual system parameters such as source impedances and line impedance data. The behaviour of the protection system is the only thing that is examined with this method.

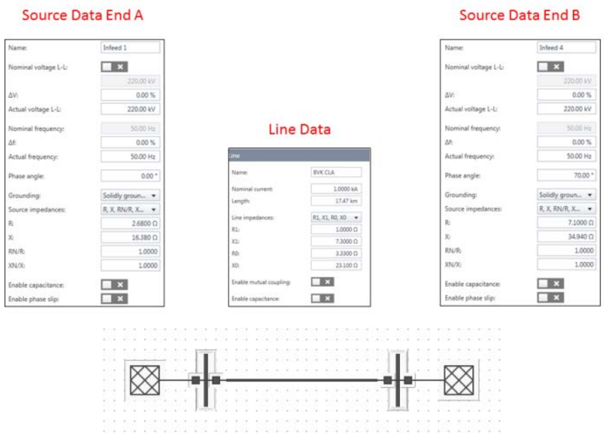

Figure 10: Source and Line Data Required for A Single Line Model

5.2 Benefits

The main benefits of system-based testing are that fault quantities for testing of the protection scheme are calculated outside of relay type, settings and configuration. This method also provides a more simplistic approach to testing of advanced functions such as:

- Power swings
- Transient ground faults
- Mutual coupling on parallel lines
- Complex tele-protection
- Sequential tests such as a failed auto reclose cycle or a circuit breaker fail situation using the iterative closed loop feature

An important feature is the simulation of current transformer saturation which can be used to examine the direct effects of CT saturation during fault conditions on the protection scheme. CT data can be entered directly into the software or results from CT fingerprinting tests can be imported. One useful application of this could be for analysing the effects of mismatched CTs on protection, e.g., P class CTs at one end and TPZ CTs at the opposite end of the line.

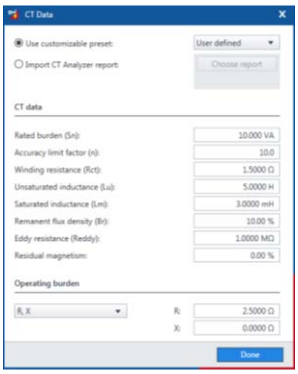

Figure 11: Input/Import Realistic CT Data Directly from CT Analyser

Another advantage over steady state GPS testing is that the system also controls multiple test devices from a single location provided there is some form of internet connection (3G was used in this application). This reduces trouble shooting time significantly and one commissioning engineer can immediately see the protective relay response from all devices under test on a single computer. This provides additional security as there is no reliance on information passing between commissioning engineers over telephone to perform a pass/fail evaluation of the protection scheme.

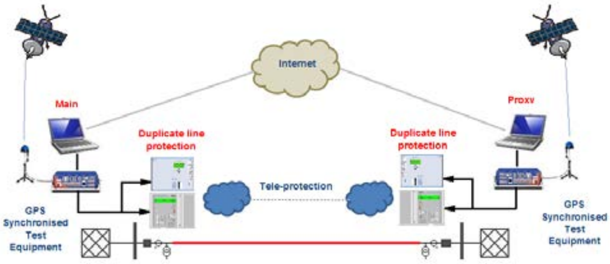

Figure 12: Duplicate Line Protection System-Based Test Setup

6 Practical Experience of System-Based Testing

Figure 13 shows the south west stations 220kV model. Line data for the various sections includes modelling of 2 no. Kilpaddoge - Moneypoint Submarine cables and significant HTLS and ACSR overhead conductor.

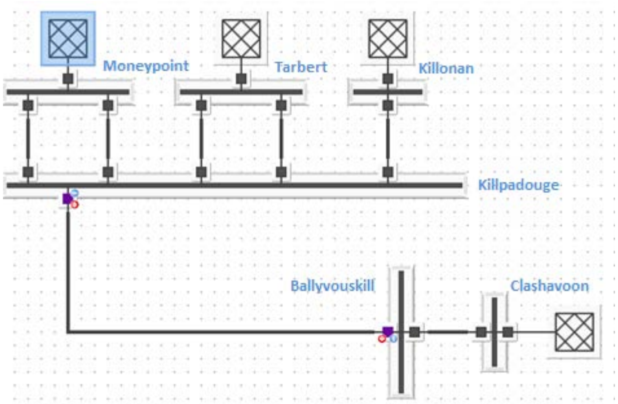

Figure 13: South West 220kV System Model

Station	Bay	Voltage	Circuit	Length (km)	R+ (Ohms)	X+ (Ohms)	R0 (Ohms)	X0 (Ohms)	Source Resistance RSA (Ohms)	Source Reactance XSA (Ohms)	Source Resistance RSB (Ohms)	Source Reactance XSB (Ohms)
Ballyvouskill	Clashavoon	220	1	17.47	1.0	7.3	3.33	23.1	6.12	37.86	7.1	34.94
Ballyvouskill	Knockanure	220	1	65.69	3.73	27.5	13.26	91.27	7.83	37.78	3.78	24.21
Knockanure	Kilpaddoge	220	1	21.48	1.37	8.86	4.6	29.26	7.69	43.61	2.64	17.17
Kilpaddoge	Killonan	220	1	67.79	3.95	28.37	13.67	93.02	2.79	18.2	4.83	23.4
Kilpaddoge	Tarbert	220	1	2.48	0.27	0.91	0.64	2.11	2.67	16.3	2.74	16.87
Kilpaddoge	Tarbert	220	2	2.43	0.26	0.9	0.61	2.1	2.68	16.4	2.74	16.88
Kilpaddoge	Moneypoint	220	1	5.02	1.44	1.02	2.84	0.58	2.68	16.32	2.68	16.38
Kilpaddoge	Moneypoint	220	2	4.93	1.42	1.0	2.79	0.57	2.68	16.32	2.68	16.38

Figure 14: South West Line and Source Impedance Models

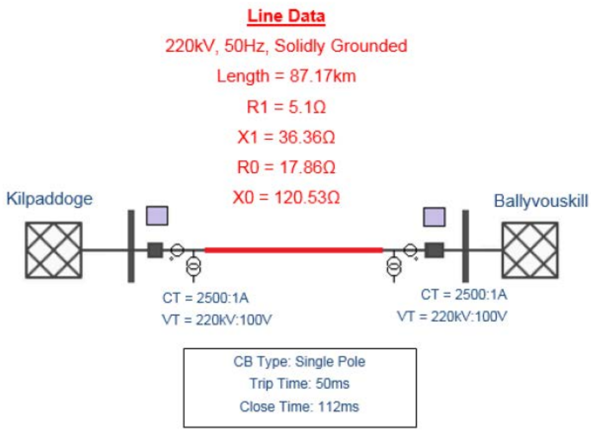

Figure 15: Kilpaddoge – Ballyvouskill 220kV Line Data

6.1 Test Cases

6.1.1 Test 1: Load Flow

The purpose of this test is to confirm the stability of the protection scheme under normal load conditions. Here it is confirmed that:

- The entire protection scheme remains stable
- No differential current is present. (A facility to measure line/cable charging current is available)
- Power flow direction measured is correct on all IEDs within the scheme

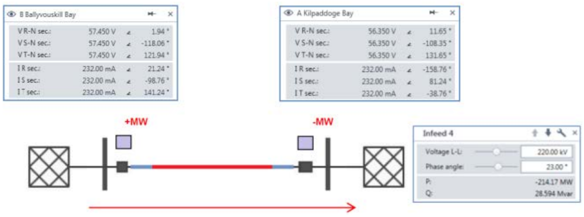

Figure 16: Load Flow Stability Case

6.1.2 Test 2: Fault on 50% Line

Transient fault on the centre of the line which will be cleared by a successful trip reclose operation.

- The fault is picked up by zone 1 of the distance protection at each end and differential protection
- No zone acceleration is required for fast tripping
- No blocking of reclosing for any faults picked up on cable sections or prolonged PTT pulse present
- In this instance a successful trip/reclose operation should be observed at both ends

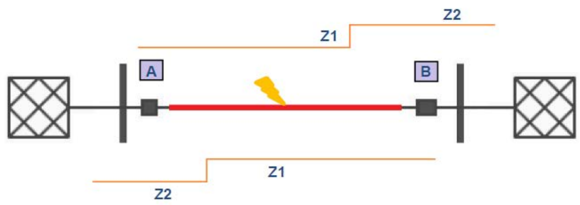

Figure 17: Fault Position 50% of Line

6.1.3 Test 3: Fault in First/Last 20% of the Line (Outside Cable Section)

This test is to prove the correct zone acceleration; a transient fault is played in turn at the first, and then to the last 20% of the line. The fault is selected outside the reach of the controlled zone used to block the AR for the cable section.

- The local relay to the fault picks up and trips in zones 1 and differential protection trips
- The remote relay will see the fault in zone 2 but the trip time will be accelerated by a PTT Rx from the local relay
- No blocking of reclosing for any faults picked up on cable sections or prolonged PTT pulse should be present
- In this instance a successful trip/reclose operation should be observed at both ends

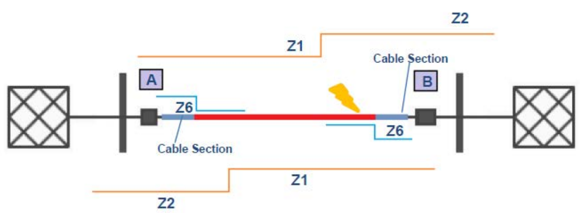

Figure 18: Fault on Last 15% of Line (Outside Cable Section if Possible)

6.1.4 Test 4: Fault on Cable Section

A fault is simulated on the cable section in turn at either end.

- The local relay to the fault picks up and trips in zone 1 and differential protection trips
- The remote relay will see the fault in zone 2 but the trip time will be accelerated by a PTT Rx from the local relay
- The fault should also be picked up on the controlled zone covering the cable section which will:
- Issue an internal auto reclose block to the auto reclose function.
- Issues an auto reclose cross block to the duplicate protection device via a binary output
- No auto reclose operation should occur

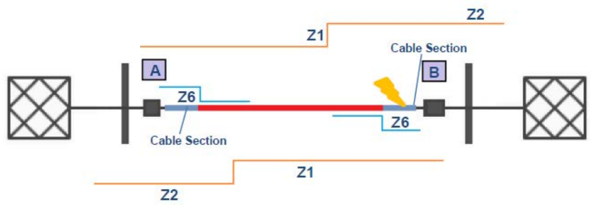

Figure 19: Fault on Cable Section

6.1.5 Test 5: Fault on Next Line

For this test, a fault is simulated on the next line and is cleared by the protection on the next line. In this instance, the protection on the line under test should remain stable.

- The differential protection should remain stable
- The DCEF protection should pick up in the forward direction in end A but have picked up in the reverse direction on end B so no DCEF trip will occur
- The impedance protection should pick up at end A in Zone 2 and in the reverse direction at end B
- As the fault is picked up in reverse at end B no PTT pulse will be sent to end A to accelerate tripping
- Protection on the next section of line should clear before impedance zone timers expire on the protection under test

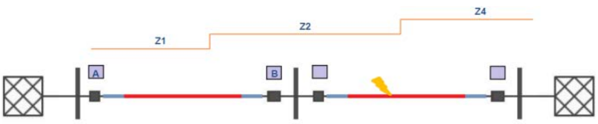

Figure 20: Fault outside the Primary Protection of Line

6.1.6 Test 6: Unsuccessful Auto Reclose (Fault Failed to Clear)

In this situation a permanent fault is simulated again at approximately 50 % of the line. This time though, the fault is still present after a trip/reclose cycle, and a three pole final trip should be issued after this fault is, once again, picked up.

- The fault is picked up by zone 1 of the distance protection at each end and differential protection
- No zone acceleration is required for fast tripping
- No blocking of reclosing for any faults picked up on cable sections or prolonged PTT pulse present
- In this instance a trip/reclose operation should be observed at both ends
- As the fault is still present all protection should again trip permanently and the circuit breaker should remain open

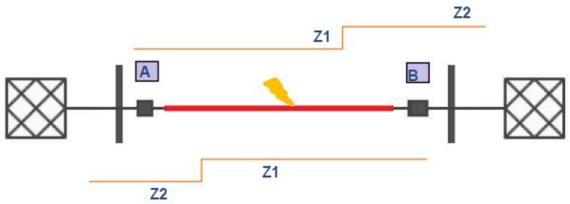

Figure 21: Sustained Fault

7 Results

7.1 Issues Identified

7.1.1 Three Pole Trip after a Block Duplicate AR Command was Received for a Single Phase Fault

An R phase fault was simulated and R phase CB pole tripped at both ends as expected.

As the differential protection had the shorter dead time, before it issued a close command to the circuit breaker the following occurred:

- The differential protection issued an auto reclose cross block to the distance device as expected.
- This should have aborted the auto reclose cycle in the distance protection so as to prevent an additional close command to the circuit breaker been issued.

It was found during this operation, that on receipt of an auto reclose cross block command from the differential relay that a 3 pole trip was issued from the distance protection before the circuit breaker close command is issued by the differential protection.

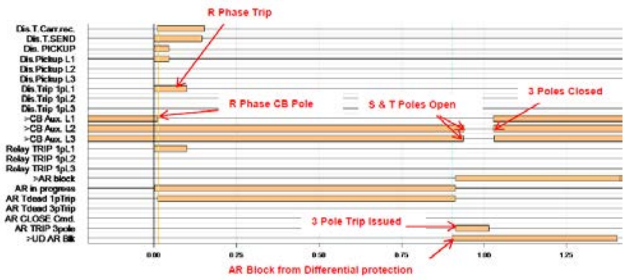

Figure 22: 3 Pole Trip on Receipt of a Block Duplicate Input from Duplicate Differential Protection

The cause of this was found to be as a result of an incorrect setting in the distance protection relay which caused a three pole trip upon receipt of a local auto reclose block from the duplicate protection relay, See Figure 23.

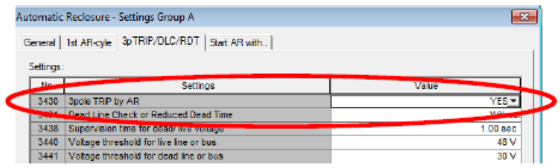

Figure 23: Incorrect Setting Identified

7.1.2 Prolonged Circuit Breaker Close Command from the Differential Protection Following an Unsuccessful Auto-reclose Cycle

During an unsuccessful auto-reclose test where there was a sustained R-E fault present on the line and a trip/reclose operation failed to clear the fault, It would have been expected that, upon detection of the fault following a reclose operation, the protection would:

- Abort the auto reclose cycle and the circuit breaker close command would drop off
- Issue a three pole final trip

However, it was observed from the trace recording following tests that the circuit breaker close command did not drop off and remained held on for an additional 300ms after the relay picked up for the fault again.

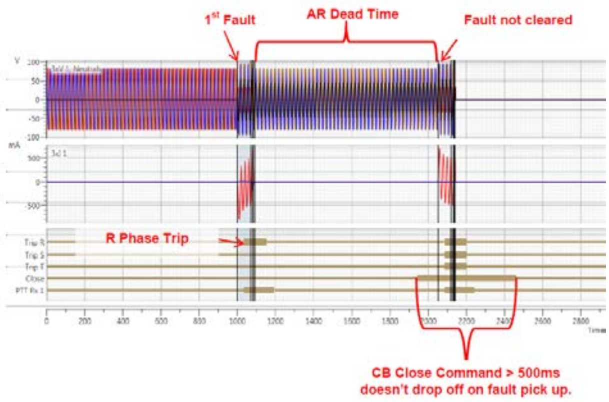

Figure 24: Prolonged CB Close Command

- The circuit breaker close command from the differential protection did not drop off upon second pick up of the R-E fault. The relay correctly issued a three phase final trip but the circuit breaker close command was maintained following this
- The anti-pumping circuit of the 220kV circuit breaker blocked the additional close operation while the circuit breaker close command was maintained
- The cause of this was found to be an extended pulse timer marshalled in circuit breaker close command binary output

8 Conclusion

In this paper, the authors have outlined how an electrical power utility has incrementally adapted its approach to the testing of distributed protection schemes following experience gained through their lifecycles.

The paper outlines utility experience of using an system-based testing approach and details how this test methodology has detected several protection scheme and parameter setting anomalies where traditional test methods have failed.

As protection systems have grown increasingly complex, this presents completely new challenges for commissioning engineers to prove the correct functionality of these schemes. Conventional functional tests, which verify that the parameters set in the relay are correct, are no longer sufficient in many cases, and legacy protection setting errors may not be detected.

The main advantage of system-based testing is that actual system parameters, such as line length, line impedance, K-factor, and S.I.R., are used to verify the correct functionality of the scheme independently of the derived protection settings. It also allows even more complex scenarios to be tested under various system conditions, for example, two ended infeed, weak infeed, load flow, power swing, effects of CT saturation and mutual coupling.

System-based testing examines the protective performance in the electrical power system using highly realistic scenarios. This allows the commissioning engineer to satisfy themselves to a high degree of certainty that the protection scheme will perform as intended, irrespective of the tele-protection medium, protection relay vendor, number of protection devices or complexity of the schemes.

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