SP ENERGY NETWORKS

LV ENGINE

LV Engine Solution Integration and Regression Testing

LV ENGINE

About Report

Report Title	:	LV Engine Deliverable #4 – Integration Testing
Report Status	:	Final
Date	:	12/04/24

Contents

List of Figures

Take care of the environment.
Printed in black and white and only if necessary.

Take care of the environment.
Printed in black and white and only if necessary.

Take care of the environment.
Printed in black and white and only if necessary.

List of Tables

Take care of the environment.
Printed in black and white and only if necessary.

List of Abbreviations

AC	Alternating Current
CT	Current Transformer
DC	Direct Current
LCS	Local Control System
LV	Low Voltage
MCCB	Moulded Case Circuit Breaker
PNDC	Power Networks Demonstration Centre
RCM	Residual Current Monitor
RMU	Ring Main Unit
SCADA	Supervisory Control and Data Acquisition
SST	Solid State Transformer
THD	Total Harmonic Distortion
UoS	University of Strathclyde
UPFC	Unified Power Flow Controller

This document satisfies the fourth deliverable for the LV Engine project “Complete network integration tests” as described in the LV Engine Network Innovation Competition (NIC) proposal presented in 2017. The document provides evidence in detail that LV Engine solution has been tested successfully, improved based on learnings gathered during the tests, and passed all the tests prior to live network trial.

1 Introduction

LV Engine, an innovation project funded through NIC mechanism and led by SP Energy Networks (SPEN), aims to deploy power electronic technology to significantly enhance the functions delivered by a secondary substation. LV Engine is targeting the provision of a smart hybrid LV AC and LV DC supply offering a more efficient and improved quality of supply. As an LV Engine project partner, the University of Strathclyde worked closely with SPEN to carry out number of desktop studies simulating the performance of the LV Engine solution, in normal and fault operating conditions [1, 2]. The overall performance of the LV Engine solution was then demonstrated in a controlled laboratory environment, replicating real network conditions. The lab-based testing enabled the validation of desk-based studies and de-risked key LV Engine schemes prior to live trials. This document outlines the learning outcomes, and test setup carried out at the Power Networks Demonstration Centre (PNDC), using all equipment manufactured for LV Engine project.

The lab-based testing was completed in two phases, with initial integration testing completed on first LV Engine solution (S1) and subsequent regression testing was completed on version 2 (S2). In each phase of testing, the AC and DC output of the LV Engine solution was investigated, over a range of different test cases. A summary of the final test status of the LV Engine solution following the conclusion of lab testing is outlined in Table 1, showing all test criteria was met by the power electronic hardware.

Table 1: LV Engine solution Integration Test status following the conclusion of lab based testing

ID	Name of test	Test Status	ID	Name of test	Test Status
4.1	System start up	PASS	4.6.4	Resistive pole to earth fault	PASS
4.2	System shut down	PASS	4.8	Operation outside statutory limits	PASS
4.3	LVDC Switchboard MCCB position	PASS	4.9	Reactive power compensation	PASS
4.4	Inter-Trip Test	PASS	4.10	Leakage relay tuning	PASS
4.5	Functional Test	PASS	4.11	Enspec (extra LV DC fault detection solution) tuning	PASS
4.6.1	Solid Pole to Pole Fault	PASS	4.12	Voltage regulation	PASS
4.6.2	Solid Pole to Earth Fault	PASS	4.13	Power Sharing	PASS
4.6.3	Solid pole to neutral fault	PASS	4.14	AC fault testing	PASS

2 Safety Risk Assessment

Prior to the test programme commencing, a comprehensive risk assessment was compiled by the team at PNDC. This encompassed the delivery, installation, commissioning, testing and removal of the equipment. Prior to any physical work being completed for the project, PNDC staff and external visitors reviewed and signed on to the associated risk assessment. Visitors were then inducted into the test area and were made aware of any concurrent projects. The test schedule was executed as outlined in the test plan [3]. All testing was be conducted in the presence and supervision of the PNDC technical team.

All attendees for testing were required to wear safety footwear when working in the PNDC LV bay. Any additional safety measures are outlined in the aforementioned risk assessment.

3 Test Setup

The test setup will be introduced in this section, consisting of the equipment under test, the test circuit and the measurement apparatus. The test plan was developed prior to start of the test to confirm the procedures that LV Engine and PNDC team will follow during the test.

3.1 Equipment Under Test

The following key components are part of the tests:

- **Solid State Transformer/Unified Power Flow Controller (UPFC)** – This is Topology 1 of SST/UPFC, designed and manufactured by ERMCO-GridBridge as part of LV Engine project (see Figure 1 for the general arrangement of the UPFC). The UPFChas a DC output rating of 167 kW and a DC output voltage of ±475 Vdc. The UPFC is a power electronics-based converter, designed to supply Low Voltage Direct Current (LVDC) circuits or infrastructure. This arrangement is planned to be trialled live as part of LV Engine, to supply an ultra-rapid 150 kW electric Vehicle (EV) charger. A particular area of interest, in this test, is the suitability of the protection strategy for the LVDC trial prior to installation and commissioning the LV Engine substation. The UPFC also has an LVAC supply; however, the functionalities delivered on the AC supply will not be tested in this phase of the project.

Figure 1 – UPFC (left) and LVDC distribution board (middle), LCS (Right)

- **LVDC switchboard** – This is manufactured by Schneider Electric. The switchboard accepts the DC output from the UPFC. The main function of the switchboard is to distribute power to DC customers.

Take care of the environment.
Printed in black and white and only if necessary.

Additionally, the switchboard houses protection and isolation equipment. The LVDC distribution board is fitted with disconnectors, Moulded Case Circuit Breakers (MCCB) and under-voltage release relays. Furthermore, an earth leakage protection relay is installed in the distribution board measuring current through the earth-neutral link. The Bender RCMB301 earth leakage protection relay has been selected to deliver this function. The suitability of this relay has been confirmed previously following tests carried out PNDC [2]. See Figure 1 for the general arrangement of the LV Switchboard.

- **Local Control System (LCS)** - This is an Alarm Display Panel and Telecoms cabinet, designed specifically for LV Engine. The aim of this Alarm Panel is to provide an overview about the status of the various devices in the substation. The router, communicating the monitored data, can also be fitted in this cabinet.

- **Ring Main Unit (RMU)** – This is a typical Schneider RN2C RMU, fitted with a Shunt Trip Coil (STC), to enable the disconnection of the HV supply in case fault occurs in the LVDC small zone (between UPFC DC Terminal and LVDC switchboard). Additionally, the customer (EV charger Operator) may trip the RMU via an emergency push button located in the customer premises.

- **150 kW DC EV charger** – This is a Tritium PKM150 DC Electric Vehicle (EV) charger. The charger can have a mix and match of EV charger connectors (CHAdeMO/CCS1/CCS2), with dual outputs of CCS or CCS and CHAdeMO. The charger to be tested, will have CCS (200 A) and CHAdeMO (125 A) outputs. The charger can provide 150 kW on a single charge connector, providing this rate of charge is accepted by the car, or 2x75 kW on the two output connectors simultaneously.

The interconnection and interactions between the key hardware is detailed in Figure 2 for a typical LV Engine solution. Numbers 1 to 7 shows the points of isolation considered in the final design.

LV ENGINE

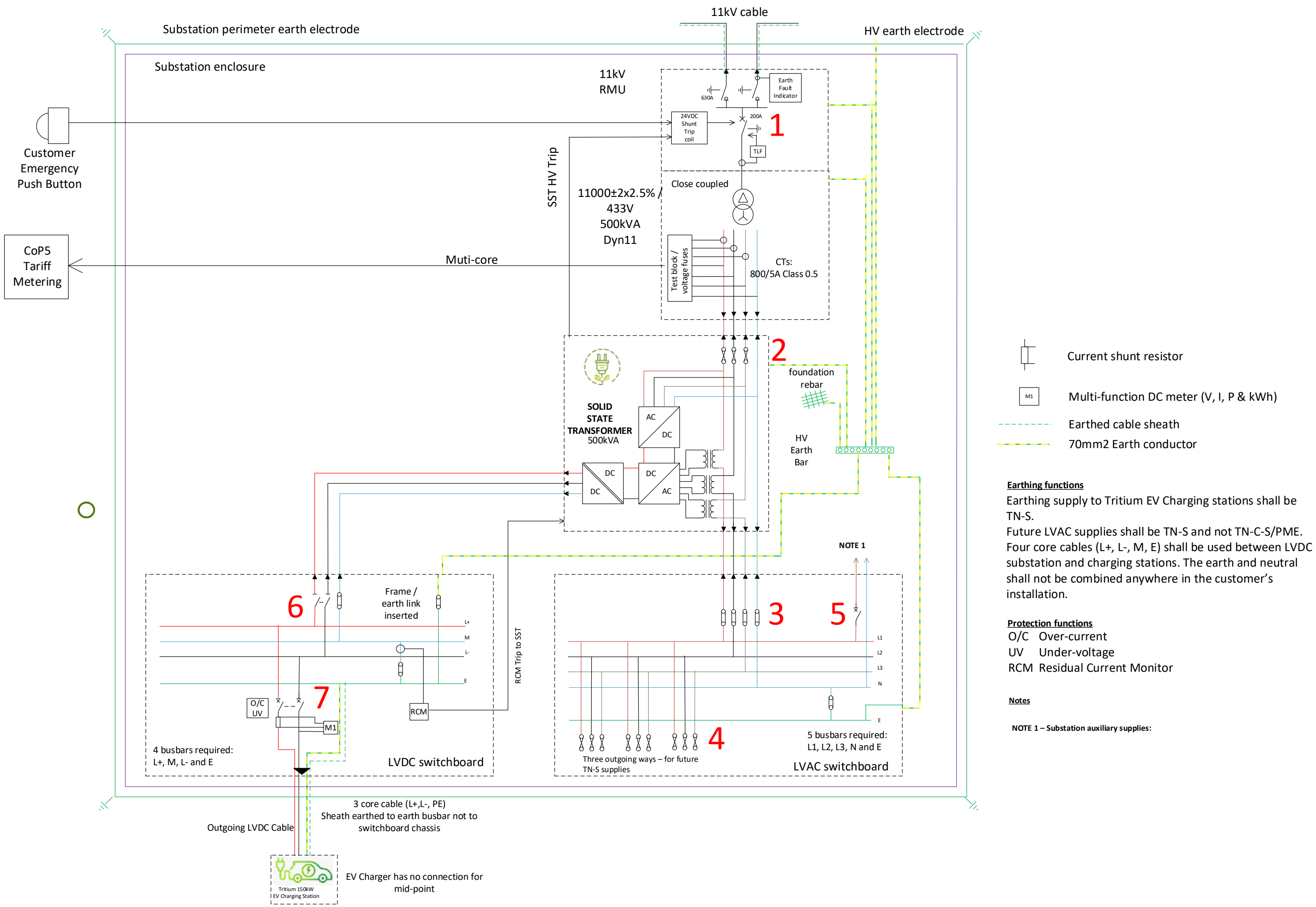


Figure 2 – Trial network diagram illustrating the key hardware and interconnections [2].

3.2 Circuit Setup

The test programme considers the deployment of the ERMCO-GridBridge UPFC, in the lab environment, to enable testing to be conducted on both and AC and DC output of the device. The general test setup is shown in Figure 3. The DC output of the UPFC is rated at 167 kW, which for the Falkirk trial (first LV Engine trial site) will power a 150 kW Tritium PKM DC EV charger. The AC output of the UPFC is rated at 500kVA and was used to power loadbanks on the PNDC test network. The UPFC is supplied from a 500kVA 11/0.4 kV AC distribution transformer. All equipment from the UPFC and downstream will be tested indoors. The intention of the testing was to replicate the same conditions (circuit arrangement and network impedance) as will be experienced at the first LV Engine installation site in Falkirk.

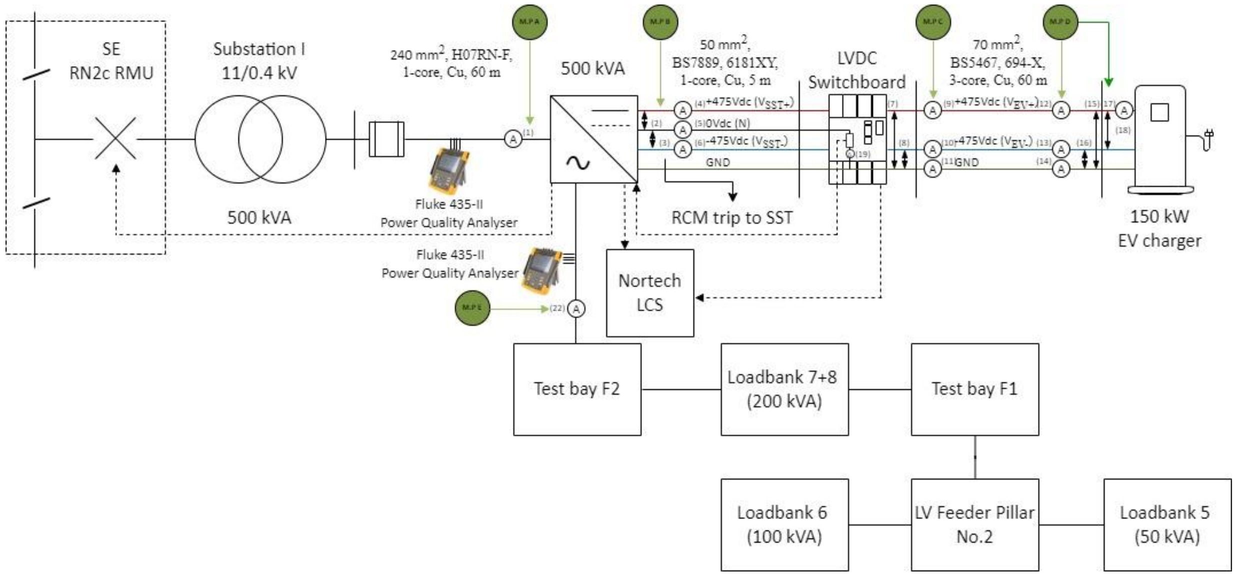


Figure 3 – Test circuit employed for AC and DC testing on the LV Engine equipment

An LVDC switchboard was installed between the UPFC and the DC EV charger. The switchboard is used to distribute the DC power to the downstream DC loads and provides protection functionality. The LVDC switchboard is fitted with disconnectors, an MCCB, under-voltage release relays and an earth leakage protection relay.

The UPFC was fed by four 240 mm^2 H07RN-F single core cables (AC side): three phases and neutral. The earth was cabled separately, using a more flexible, smaller, diameter cable. At the output side of the UPFC, three 50 mm^2 6181XY single core cables were employed for the two pole connections and the neutral connection to the LVDC switchboard. The total resistance of this cable was 60 mΩ, which is equivalent to that used in the aforementioned simulation studies [2]. At the output of the LVDC switchboard, a 3-core 70 mm^2 Single Wire Armour (SWA) cable (167 A rating), was used to supply the EV charger (this same cable will be employed in the Falkirk trial). The total resistance of this cable was 16 mΩ.

DC voltage and current measurement were taken at the LVDC switchboard and EV charger input, using a suitable measurement system. AC measurements at the UPFC input/output were recorded, using the same measurement system or using a Fluke 435-II power quality analyser. The weight and dimensions of the large pieces of equipment are summarised in Table 2.

Table 2: Equipment weights and dimensions.

Item	Weight (kg)	Dimensions (WxDxH mm)
UPFC	1600	1300 x 1200 x 1600
LVDC switchboard	150	1000 x 1000 x 1800

Item	Weight (kg)	Dimensions (WxDxH mm)
EV charger	266	850 x 309 x 1998
Nortech LCS	<20	400 x 400 x 20

Equipment for the testing is sourced from multiple vendors and is provided by both SPEN and PNDC. Table 3 lists the items that are supplied by SPEN.

Table 3: Items to be supplied by SPEN.

Item	Part number	Quantity/Length
ERMCO-GridBridge UPFC	TBC	1
24 V battery system	-	1
Nortech LCS	CAB-1260	1
Cables UPFC to distribution board	50 mm^2 BS7889 6181XY, 1 core cable	Roll of cable to be supplied. Will then be cut to length by PNDC as required and remaining roll returned to SPEN
Terminations for 6181XY cables	BLMT-25/95-17 [Tyco Catalogue EPP-2003-4_16]	6
Cables distribution board to EV charger	Seval Kablo BS 5467, 694-X, 70 mm^2, 3 core SWA cable	1x 60 m length (70 mm^2) required but a 100m roll to be supplied
LVDC Switchboard	TBC	1

The test environment was the PNDC Low Voltage (LV) bay. It is an industrial building, with minimal insulation, but is wind and water tight. The LV bay is accessed via a roller door. A general image of the LV bay is shown in Figure 4.

Figure 4 – General view of LV bay.

The delivery vehicle for the UPFC and LVDC switchboard must allow the unit to be received at ground level. A pallet truck (3000 kg capacity) is available onsite for final positioning in the LV test bay. The route for delivery vehicles when on the PNDC site is detailed in Figure 5.

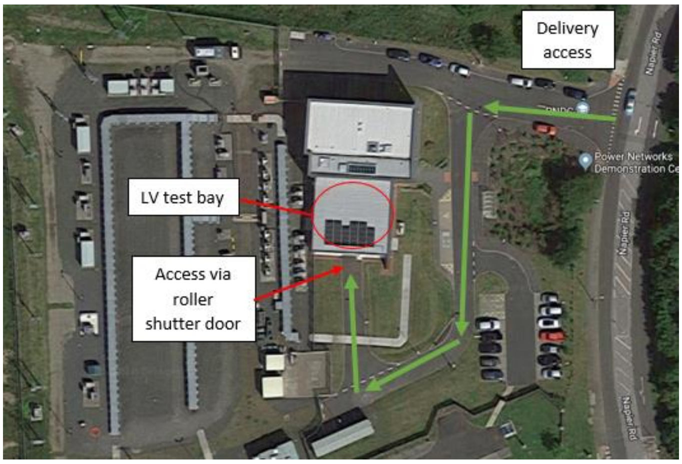


Figure 5 – Delivery route on plan view of PNDC site.

3.3 Measurement Setup

The PNDC measurement setup will record voltage and current data during the applied fault conditions. Figure 6 details the general test circuit, where the specific measurement points (MP) will be and fault locations (red numbered points).

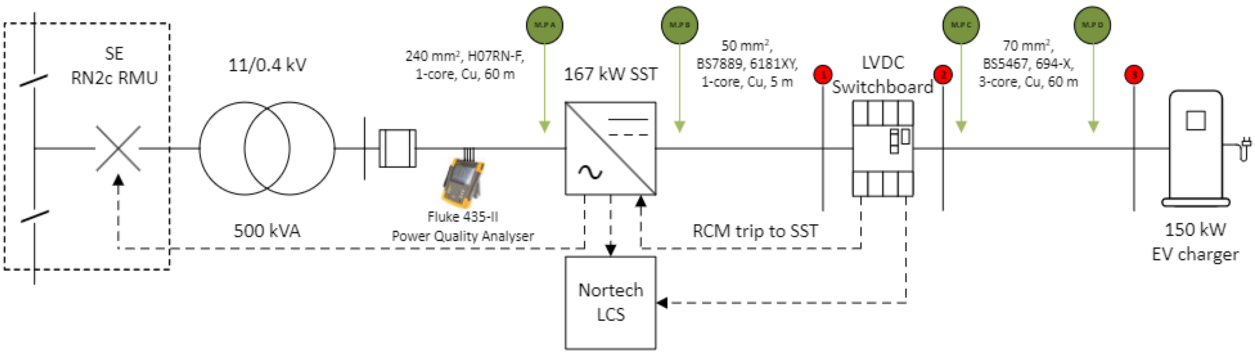


Figure 6 – Simplified test circuit with measurement points (M.P) and fault locations (red numbered circles).

Measurement point A (MP A) is an AC measurement point. Data will be captured using the PNDC's fast Data Acquisition (DAQ) system, based on Beckhoff hardware. The PNDC fast DAQ consists of a Beckhoff measurement system and oversampling cards for voltage and current.

The AC side measurements (three phases and neutral) will be captured with Fluke i1000s current clamps, which will be interfaced to 5 kHz measurement cards, to allow capturing transient waveforms. The three-

Take care of the environment.
Printed in black and white and only if necessary.

phase voltages will be measured using the Beckhoff EL3783 three-phase measurement card. These measurements will be trialled in advance of final testing to ensure measurement quality. A Fluke 435-II power quality analyser will also be used on the AC-side for measuring the voltages and currents and will present another means of capturing and assessing waveforms, i.e. to evaluate harmonics. The Fluke will continuously log voltage and current data at 4 Hz and voltage/current triggers will be set for wave event capture (4 kHz sampling rate). The voltage measurement will be made directly by the Fluke via fused terminals for safety. Fluke i1000s Current Transformers (CTs) will be used for the measurement of AC-side currents. The Fluke and Beckhoff systems are both timestamped, with the Fluke timestamped by GPS, which will permit post-processing to align captured waveforms.

Measurement points B, C and D (MP B, MP C and MP D) are on the DC-side of the UPFC and will be performed by the PNDC fast DAQ system. The oversampling cards, for voltage measurements, will be interfaced with the Verivolt Isoblock V-1C voltage transducer, to enable the DC voltage to be stepped down to the ±10 V differential input for the EL3702 cards. Hall Effect current sensors (ATO-CUS-20000ACDC) with a range of ±8 kA will be interfaced with the EL3702 oversampling card to capture DC-side currents. Additional Flukes could be deployed at measurement points B, C and D; however, there will be limitations in the current magnitude that can be detected by the i1000s CTs (2 kA max) and possible bandwidth limitations, making the Hall Effect sensors the preferred choice.

Based on the LVDC protection study [2], each DC measurement point requires:

- Pole to neutral voltage - 2 voltage measurements at each measurement point (i.e. V_{SST+} and V_{SST-}) for an operating voltage of ±475 Vdc with potential for deviations of up to 1000 Vdc (noted during P-E faults).
- Applied fault current - 3 current measurements (i.e. I_{SST+}, I_{SST-} and I_N) performed by a Hall effect current sensor, an 8 KA rated sensor should cover the following fault currents from the study:
  - Pole to Pole: Expected fault range = 1.38-6.48 kA (locations 2 and 3)
  - Pole to Ground: Expected fault range for faulted pole = 6.48 kA, non-faulted pole ~= 500 A
  - Pole to Neutral Expected fault range = 1.2-5.5 kA
  - Resistive pole to ground 10 Ω = 200 A (max)

In addition to the defined measurement points, two other sets of measurements have been considered to conform with the simulation study. These additional measurements are: the voltage and current at the EV charger terminals and the earth leakage current as measured inside the LVDC switchboard.

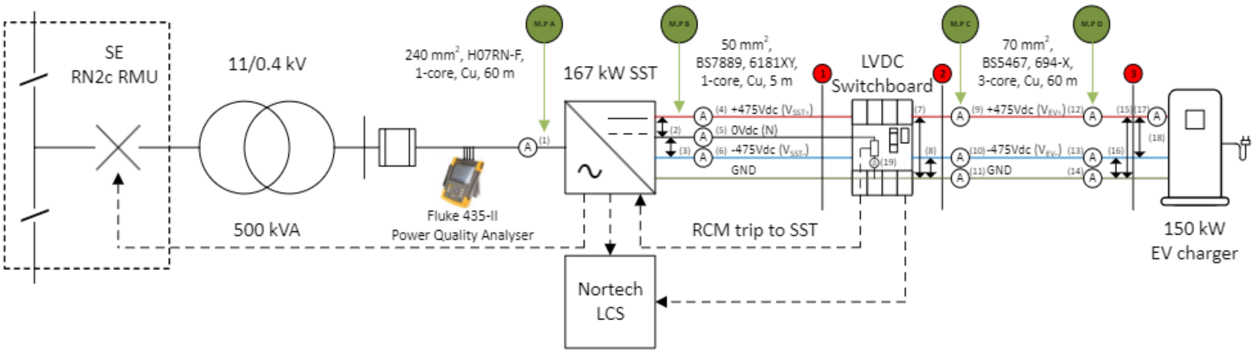


Figure 7 – Annotated test diagram with measurements. Measurement names and sensors are given in Table 3.

An annotated diagram of the testing setup is shown in Figure 7, with the corresponding measurements and tools listed in Table 4.

Table 4: Measurements as shown in Figure 6.

Measurement Point	Measurement Number on Figure 6	Measurement	Measurement Solution
MP A	(1)	Three-phase voltage	EL3783 measurement card
	(1)	Three-phase currents and neutral	Fluke i1000s
MP B	(2)	V_{SST+} to V_N	Isoblock V-1C
	(3)	V_{SST-} to V_N	Isoblock V-1C
	(4)	I_{SST+}	ATO-CUS-20000ACDC
	(5)	I_{SST-}	ATO-CUS-20000ACDC
	(6)	I_N	ATO-CUS-20000ACDC
MP C	(7)	V_{EV+} to GND	Isoblock V-1C
	(8)	V_{EV-} to GND	Isoblock V-1C
	(9)	I_{EV+}	ATO-CUS-20000ACDC
	(10)	I_{EV-}	ATO-CUS-20000ACDC
	(11)	I_{GND}	ATO-CUS-20000ACDC
MP D	(12)	I_{EV+}	ATO-CUS-20000ACDC
	(13)	I_{EV-}	ATO-CUS-20000ACDC
	(14)	I_{GND}	ATO-CUS-20000ACDC
	(15)	V_{EV+} to GND	Isoblock V-1C
	(16)	V_{EV-} to GND	Isoblock V-1C
EV charger terminals	(17)	I_{EV+}	ATO-CUS-20000ACDC
	(18)	V_{EV+} to V_{EV-}	Isoblock V-1C
LVDC switchboard	(19)	RCM current	ATO-CUS-20000ACDC

Take care of the environment.
Printed in black and white and only if necessary.

3.4 LVDC Protection Strategy

The UPFC DC rating (167 kW or 175 A) is very close to the EV charger rating (150 kW), so the typical overcurrent protection relays may not be suitable for this application. The UPFC will automatically switch off the DC supply if it experiences any current beyond its rating. This behaviour of the power electronics provides opportunity to rely on undervoltage/loss of supply protection.

The LVDC switchboard contains a MCCB, a DC Residual Current Monitor (RCM) and two under-voltage release coils. The LVDC switchboard supplies the customer's EV charger via four single core cables, which carry the supply positive, negative, neutral and earth. One under-voltage relay is connected between the positive pole and the mid-point, and the other under-voltage relay is connected between the negative pole and the mid-point. When either pole voltage falls below a given threshold, the MCCB is tripped. The EV charger does not have a mid-point input, so the system mid-point goes no further than the LVDC switchboard. The DC RCM measures the current between the mid-point and earth, and any current flowing above a given threshold sends a trip signal to the UPFC. This is shown diagrammatically in Figure 8.

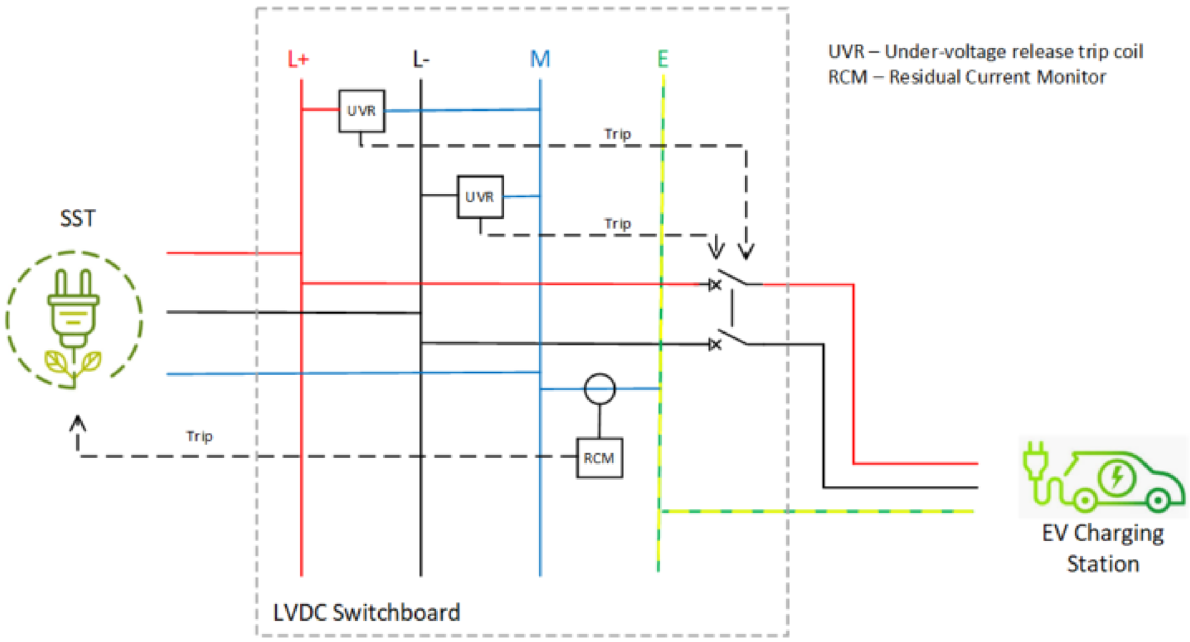


Figure 8 – LVDC Switchboard protection arrangement

The initial LVDC protection strategy, proposed by SPEN, is as follows:

1- During any fault occurs between UPFC LVDC terminal and the EV charger, the UPFC switches off in less than 1.0 ms if the fault current is greater than UPFC rating. This will result in an under-voltage on either the positive pole, the negative pole or both. This will be detected by one or both under-voltage release coils, which will trip the MCCB.

2- After a period (5 s which is configurable), the UPFC will attempt to re-start and energise its output to an extra DC low voltage (48.0 V).

   a. If UPFC sees any current at DC terminal (even a small value), the fault is therefore upstream of the MCCB, so the UPFC will send a trip signal to RMU's shunt trip coil. This condition suggests that fault is within the substation.

   b. If no current is seen, when energised at extra DC low voltage, then the UPFC will be ramped up to its nominal voltage (±475 V), and the LVDC switchboard will be re-energised, but the MCCB is already open i.e. no supply to the customer. This condition suggests that fault is outside the substation and within customer zone.

After ensuring the fault no longer exists, an operator will be required to manually re-close the MCCB and re-energise the circuit to the EV charger. If the MCCB does not trip, the fault is likely to have been of a transient nature. If the MCCB trips, the fault will be permanent and located downstream of the MCCB. If the MCCB and RMU trips, the fault is within the substation.

Figure 9 shows the expected time sequence of various events when any LVDC fault occurs between UPFC LVDC terminal and EV charger.

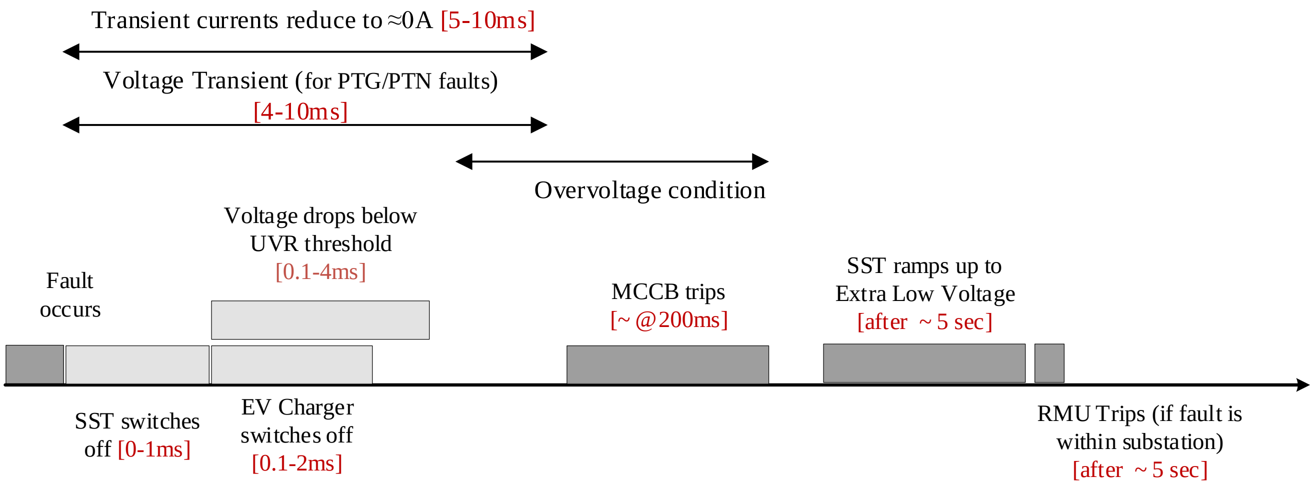


Figure 9 – Time sequence of various events from fault inception.

3.5 System Shutdown and Restart Procedure

This section outlines the procedure of a system shutdown and system restart under normal and fault conditions. The purpose of this section is to outline what a typical operator would do when shutting the system down and restarting it on-site, which will be emulated by PNDC personnel.

In both normal operation and operation with a fault applied, only the primary equipment (i.e. power hardware) will be affected. This means that the 24 Vdc supply and the Nortech LCS will not be turned off.

Take care of the environment.
Printed in black and white and only if necessary.

3.5.1 Normal Operation

Shutdown under normal operation entails turning the primary equipment off without a fault present. This will be done without an EV plugged in to charge.

When turning the system off, the procedure will be:

1. Switch UPFC to Bypass operation
2. Open the RMU (removes power to UPFC)
3. Confirm the MCCB is tripped/open (disconnects UPFC from EV charger)

The EV charger and UPFC should be de-energised by this procedure. This must be verified before proceeding.

As no fault is present, no further investigations are required and the system will be turned back on with the following procedure:

1. Close the RMU (provides power to the UPFC)
2. Switch on AC and DC services on the UPFC (energises the LVDC switchboard)
3. Close the MCCB (connects UPFC to EV charger – with no EV load present)

With the MCCB closed and the UPFC energised, the EV charger should become energised again and will be ready for operation.

3.5.2 Under Fault: Upstream of MCCB ("Substation")

Section 3.4 introduced the protection strategy of the system under test, which relies on several means of detecting faults and tripping various components as a part of the fault handling procedure. The operator will be required to make several checks before re-energising the system. The procedure outlined assumes that the fault was on the DC-side, it was not temporary (i.e. it will remain before, during and after the UPFC attempts to ramp its voltage up) and that the fault will be removed by PNDC personnel after ensuring the system is de-energised.

The location of the fault is important for the behaviour of the protection. Upon application of a DC fault upstream of the MCCB, the following will occur:

1. UPFC will go to Bypass operation and DC supply will switch off
2. The EV charger will switch off
3. The MCCB will be tripped, disconnecting the UPFC from the EV charger
4. The UPFC will attempt to ramp up its voltage. Because the fault will create a short circuit and a voltage will be applied across it, a current will be detected and the RMU will be tripped. This will de-energise the UPFC

Once the automated fault shutdown procedure is complete, the system will be de-energised. It is at this time that the operator will check the DC-side for faults. In the case of testing at PNDC, the known fault will be removed. The PNDC technical team will safely isolate the test circuit and confirm via monitoring equipment that no voltage is present. A voltage indictor/proving device will be employed in conjunction with PPE (visor, insulated gloves and clothing) to check for dead. This will enable the reset of the fault thrower to be completed safely. In the field, SPEN operatives will complete a safe isolation and fault finding exercise. This full process will not be considered in this test programme, as the fault type and location are known.

With the fault removed, the system will be turned back on with the following procedure:

1. Close the RMU (provides power to the UPFC)
2. Switch on AC and DC services on the UPFC(energises the LVDC switchboard)
3. Close the MCCB (connects UPFC to EV charger – with no EV load present)

3.5.3 Under Fault: Downstream of MCCB ("Customer Zone")

Upon application of a DC fault downstream of the MCCB, the following will occur:

1. The UPFC will switch off
2. The EV charger will switch off
3. The MCCB will be tripped, disconnecting the UPFC from the EV charger
4. The UPFC will attempt to ramp up its voltage. Because the fault is downstream of the MCCB, the UPFC will be able to ramp back up to its nominal output voltage.

Once the automated fault shutdown procedure is complete, the EV charger will be de-energised, but the UPFC will not be. Therefore, the system must be de-energised by switching off the UPFC. The PNDC technical team will safely isolate the test circuit and confirm via monitoring equipment that no voltage is present. A voltage indictor/proving device will be employed in conjunction with PPE (visor, insulated gloves and clothing) to check for dead. This will enable the reset of the fault thrower to be completed safely. In the field, SPEN operatives will complete a safe isolation and fault-finding exercise. This full process will not be considered in this test programme as the fault type and location are known.

With the fault removed, the system will be turned back on with the following procedure:

1. Close the RMU (provides power to the UPFC)
2. Turn on the UPFC (energises the LVDC switchboard)
3. Close the MCCB (connects UPFC to EV charger – with no EV load present)

3.5.4 Under Fault: Earth Fault

When an earth fault occurs, the procedure is different. In this case, the following will occur:

1. The UPFC's output voltage will fall below the undervoltage threshold, opening the MCCB
2. The MCCB will be tripped, disconnecting the UPFC from the EV charger
3. If the earth fault is highly resistive and the undervoltage protection was not triggered then the back-up protection of the DC RCM will detect a current and trip the RMU
4. The UPFC will not attempt to ramp its voltage up as the RMU trip signal has de-energised it

Once the automated fault shutdown procedure is complete, the system will be de-energised. It is at this time that the operator will check the DC-side for faults. The PNDC technical team will safely isolate the test circuit and confirm via monitoring equipment that no voltage is present. A voltage indictor/proving device will be employed in conjunction with PPE (visor, insulated gloves and clothing) to check for dead. This will enable the reset of the fault thrower to be completed safely. In the field, SPEN operatives will complete a safe isolation and fault finding exercise. This full process will not be considered in this test programme as the fault type and location are known.

With the fault removed, the system will be turned back on with the following procedure:

1. Close the RMU (provides power to the UPFC)
2. Turn on the UPFC (energises the LVDC switchboard)
3. Close the MCCB (connects UPFC to EV charger – with no EV load present)

4 S1 UPFC Integration Test Procedure

In this section the test procedure that was executed on the PNDC test network during integration testing is summarised. In each subsection the test is discussed and the test outcome is detailed. The summary and test status for the UPFC integration testing at PNDC is detailed in Table 5.

In general, the S1 UPFC passed all tests with the exception of the AC power sharing this was not attempted based on manufacturer guidance (completed in S2 integration testing see section 5.7). Tests, 4.8, 4.9, 4.10, 4.11, 4.12 and 4.14 were tests added to the programme during the execution of testing.

Table 5: Test summary, test number ID, focused equipment of test, status of each test and notes

ID	Name	Description	Relevant Test Number IDs	Focused Equipment	PASS/ Status	Notes
4.1	**System start up**	With all the primary equipment de-energised (does not include the 24V DC supply and Nortech LCS), and no faults present on the system, energise the equipment sequentially. This test demonstrates start-up under normal conditions.	1, 2, 3,4, 6, 7 10, 11 and 69	UPFC, LVDC switchboard, PKM150	PASS	The overall system was shown to start up multiple times under control of ERMCO-GridBridge and also via the SPEN team.
4.2	**System shut down**	With all equipment energised, and no faults present on the system, the primary equipment will be de-energised (does not include the 24 V DC supply and Nortech LCS). This test demonstrates shutdown under normal conditions.	8	UPFC, LVDC switchboard, PKM150	PASS	The overall system was shown to shut down in a controlled manner on multiple occasions when controlled by both ERMCO-GridBridge and SPEN team.
4.3	**LVDC Switchboard MCCB position**	Turn the LVDC MCCB on and off and check that the MCCB position indicator on the Nortech LCS illuminates correctly.	Observation no data record	LVDC switchboard	PASS	MCCB was manually switched and the status indication was shown to change on the Nortech LCS.
4.4	**Inter-Trip Test**	To verify the Schneider RN2c is tripped successfully, dedicated inter-trip testing will be undertaken. The inter-trip will be independently tested to ensure the Schneider RN2c is tripped successfully. To further validate operation before going live, inter-trip functionality will also be trialled through applying trip conditions to the UPFC protection circuits (i.e. fault in the small zone) or by applying a 24 Volt inter-trip command to the Schneider Electric (SE) RN2c RMU.	Observation no data record	RN2C RMU and UPFC	PASS	Intertrip demonstrated at the UPFC and via the GUI in the presence of ERMCO-Gridbridge and SPEN team.
4.5	**DC Functional Test**	Initial functional testing of the UPFC to verify overall operation and facilitate any test setup debugging. The control/communications will be setup to ensure normal operation. In the functional test, an EV with a CHAdeMO/CCS2 charging port will be connected to the Tritium EV charger which will provide the DC load on the UPFC/LVDC switchboard. Data will be collected to show start-up, operation and shutdown procedures.	9, 11, 12, 13, 36, 48, 71, 72, 75	UPFC, LVDC switchboard, PKM150	PASS	Reliable and stable operation was observed the only operational issue was the auto restore function on the UPFC.

ID	Name	Description	Relevant Test Number IDs	Focused Equipment	PASS/ Status	Notes
4.6.1	**Solid Pole to Pole Fault**	This fault connects the positive pole (i.e. VSST+) to the negative pole (i.e. VSST-) using the DC fault thrower. This test simulates the sorting of the two poles energised at +/-475 Vdc.	14, 15, 16, 17, 18, 35, 39, 52, 64, 82, 85, 91, 92, 93	UPFC, LVDC switchboard, PKM 150 (partial), 14.5 ohm resistive load (complete)	PASS - Auto restore in question	No auto restore was available but UPFC operated fine after re-energisation. EV charger failed after 5 pole to pole faults and was replaced by a resistive load.
4.6.2	**Solid Pole to Earth Fault**	The solid pole to earth fault tests are low resistance, as the connection is made by a solid copper bus bar. Due to asymmetry in the under-voltage relay protection scheme in the LVDC switchboard, the solid pole to earth test must be undertaken with a fault connecting the positive pole to earth and the negative pole to earth. The test will confirm the trip time and to check whether the asymmetry has a material impact on the operation of the protection scheme.	40, 41, 42, 43, 44, 45, 46, 49, 50, 51,54, 55, 62,63, 83, 86, 87, 88, 89, 90, 94, 97, 98, 99, 100	UPFC, LVDC switchboard, 14.5 ohm resistive load (complete)	PASS	No auto restore but unit operated fine after re-energisation.
4.6.3	**Solid pole to neutral fault**	The solid pole to neutral fault will place a short from the positive/negative rail to the neutral connection, where it is available.		UPFC	Not complete	Test conditions were not applied during integration testing. Test was completed in the regression testing on the S2 UPFC.
4.6.4	**Resistive pole to earth fault**	The resistive pole to neutral fault will be achieved with a 10 Ω resistor in series with the fault thrower. The resistance will trigger an earth fault warning but will not trip the protection due to the reduced fault current.	56, 57, 58, 59, 60, 61	UPFC, LVDC switchboard, 14.5 ohm	PASS	High resistive fault was permanent so UPFC seen a short, shut the output down and the Bender RCM detected this condition.

ID	Name	Description	Relevant Test Number IDs	Focused Equipment	PASS/ Status	Notes
				resistive load (complete)		
4.7	**Witness tests**	As a part of the system demonstration and testing, members of the LV Engine team will be present to witness some of the functional and fault testing being undertaken.		Walk round of all key items and SPEN representative onsite for all testing	PASS	A large number of key stakeholders were hosted during the test programme, SP Energy Networks, OFGEM, Falkirk Council, University of Strathclyde and where possible testing was demonstrated to attendees.
4.8	**215 V AC output on UPFC**	Provide a phase voltage of 215 V AC from the UPFC whilst subject to a balanced AC load.	Extra 1	UPFC	PASS	UPFC provided the requested regulated AC phase voltage at the output of the UPFC.
4.9	**Reactive power compensation**	Use the UPFC to inject reactive power whilst regulating the phase voltage at 230 V on the AC output. This will enable the UPFC to appear as a unity power factor load at the transformer.	Extra 2	UPFC	PASS	UPFC injected 45 kVAR capacitance for power factor correction at the input to UPFC. The UPFC appeared as a unity power factor load.
4.10	**Bender tuning**	Perform tests at the start up and during EV charging to ensure that the selected Bender settings do not cause spurious/nuisance tripping of the RMU.	78, 79, 80, 81, 82, 83	Bender RCM	PASS	The Bender relay was tested independently using an omicron amplifier to confirm trip behaviour. A fault was evident with the Bender relay originally installed in the LVDC

Take care of the environment.
Printed in black and white and only if necessary.

ID	Name	Description	Relevant Test Number IDs	Focused Equipment	PASS/ Status	Notes
						switchboard and this was replaced. Extensive trip and load based testing whilst housed in the LVDC switchboard. Suggested revised trip threshold of 150 mA and warning of 90% to prevent spurious tripping during the UPFC start up.
4.11	**Enspec tuning**	Perform trial for tuning the detection threshold of the Enspec protection unit for an onsite trial.	97, 98, 99, 100	Enspec external protection unit	PASS	Extensive range of trip testing to ensure both pole to pole and pole to earth faults could be detected. Initial voltage threshold of 7.5 V (160 A in the primary circuit) suggested revision to 4 V (40 A) to ensure the fault current can be detected.
4.12	**Voltage regulation**	The Voltage regulation function of the UPFC enables voltage control on a per phase basis. Testing will be conducted under the three scenarios; the presence of a balanced AC load, a DC load and an imbalance on a selected phase (phase A)	65, 67, 73,74, 76, 77, 78,79, 80, 81, 114, 115, 116, Extra 3	UPFC	PASS	UPFC voltage control was demonstrated on a per phase basis. Additionally, the phase voltage was controlled to ensure the end customer (load bank) received the required voltage under unbalanced load conditions.

ID	Name	Description	Relevant Test Number IDs	Focused Equipment	PASS/ Status	Notes
4.13	**Power Sharing**	The power sharing function enables load to be shared between the UPFC and a neighbouring transformer on the same feeder. The UPFC version being tested will not have the final power sharing control function enabled. However, power sharing can be verified by manually adjusting the AC voltage set point. This test case will demonstrate the adjustment of LV voltage setpoint at the UPFC so that the overall LV load can be shared between UPFC and the neighbouring transformer.	20,21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31	UPFC	Function not available on S1 UPFC completed in section 5.7 on S2 UPFC	Not attempted based on manufacturer guidance - has not been trialled in the ERMCO-GridBridge lab.
4.14	**AC fault testing**	Apply AC faults to the output of the UPFC under bypass and regulated voltage conditions. Applied AC faults consider the variation of LV AC feeder fuses (100, 200 and 315 A) and fault orientation (phase to phase, phase to earth, 3 phase, 3 phase to earth). The unit will pass the test if following the renewal of fuses it can power up and perform all necessary functions. The fuse size was varied to control the duration that the fault current was applied to the output of the UPFC (final application=315 A).	102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112	UPFC	PASS	Unit survived all faults and was proven operationally after the AC fault testing.

Take care of the environment.
Printed in black and white and only if necessary.

4.1 System Start-up

With all the primary equipment de-energised (i.e. not the 24V DC supply and Nortech LCS), and no faults present on the system, energise the equipment sequentially. This test demonstrates start-up under normal conditions.

After start-up, the following will be verified:

- No alarms present on the UPFC
- No alarms present on the Bender earth fault leakage relay
- No alarms present on the LVDC switchboard
- No alarms present on the Nortech LCS
- Voltages at DC and AC terminals are at acceptable levels

Outcome: The system powers up successfully with no alarms/fault indicators. The overall system was shown to start up multiple times under control of ERMCO-GridBridge and also via the SPEN team.

4.2 System Shutdown

With all the equipment energised, and no faults present on the system, the primary equipment will be de-energised (i.e. do not de-energise the 24 V DC supply and Nortech LCS). This test demonstrates shutdown under normal conditions.

After shutdown, the following will be verified:

- No alarms present on the UPFC
- No alarms present on the Bender earth fault leakage relay
- No alarms present on the LVDC switchboard
- No alarms present on the Nortech LCS
- No voltage at DC terminal

Outcome: The system powers down successfully with no alarms/fault indicators. The overall system was shown to shut down in a controlled manner on multiple occasions when controlled by both the ERMCO-GridBridge and SPEN team.

4.3 LVDC Switchboard MCCB Position

Turn the LVDC MCCB on and off and check that the MCCB position indicator on the Nortech LCS illuminates correctly.

Outcome: MCCB was manually switched and the status indication was shown to change on the Nortech LCS. The Nortech LCS LVDC switchboard MCCB position switch is ON when the LVDC MCCB is ON and OFF and then LVDC MCCB is OFF.

4.4 Inter-Trip Test

To verify the Schneider RN2c is tripped successfully, dedicated inter-trip testing will be undertaken. The inter-trip will be independently tested to ensure the Schneider RN2c is tripped successfully. To further validate operation before going live, inter-trip functionality will also be trialled through applying trip conditions to the UPFC protection circuits (i.e. fault in the small zone) or by applying a 24 Volt inter-trip command to the Schneider Electric (SE) RN2c RMU.

Outcome: The inter-trip successfully trips the Schneider RN2c RMU. Inter-trip demonstrated at the UPFC and via the GUI in the presence of ERMCO-GridBridge and SPEN team.

4.5 DC Functional Test

Initial functional testing of the UPFC to verify overall operation and facilitate any test setup debugging. Figure 10 shows the circuit diagram for the functional testing. The control/communications will be setup to ensure normal operation. In the functional test, an EV with a CHAdeMO/CCS2 charging port will be connected to the Tritium EV charger which will provide the DC load on the UPFC/LVDC switchboard. The PNDC measurement system will be operational throughout and data will be collected to show start-up, operation and shutdown procedures. This may enable correlations between the UPFC/LVDC switchboard measured quantities and the PNDC measurement apparatus.

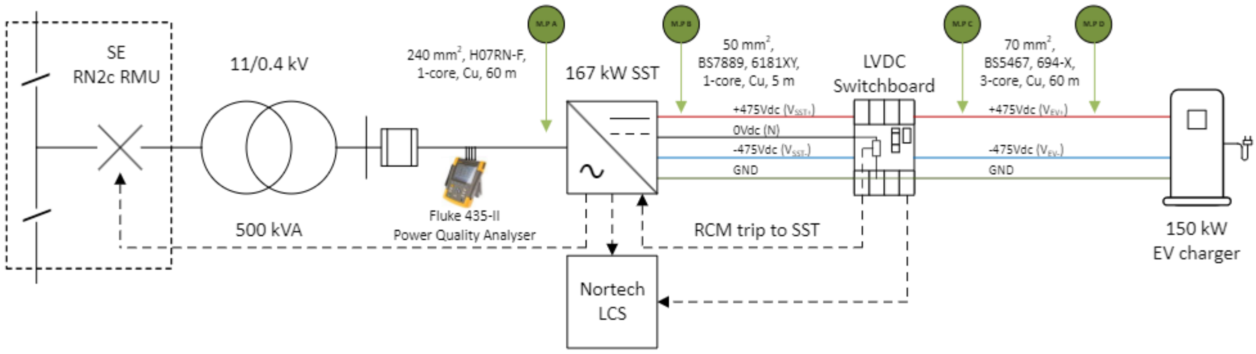


Figure 10 – Test arrangement for functional testing.

The DC functional tests involved the supply of DC voltage to the Tritium PKM 150 EV charger, via the Grid Bridge UPFC. A variety of EVs were connected to the charger, the testing mainly used a PNDC owned 30 kWh Nissan Leaf, which connects to the charger via the CHAdeMO outlet of the PKM 150. Two electric vehicles (Tesla Model 3 and Hyundai Kona), which charge via a CCS connection were also connected to the PKM 150. The PKM 150 has one CHAdeMO and one CCS outlet so this permitted the dual charging of a Nissan leaf and a Tesla Model 3 as well as the Nissan Leaf and Hyundai Kona. Figure 11 shows charging rates recorded on the PKM 150 during one such session.

Figure 11 – Charging session with Nissan Leaf (45.1 kW) and Hyundai Kona (56 kW)

The Nissan Leaf and Hyundai Kona were charged simultaneously over a number of charging sessions. The simultaneous start of a charge session is shown in Figure 12 with the DC current demand on the positive and negative poles.

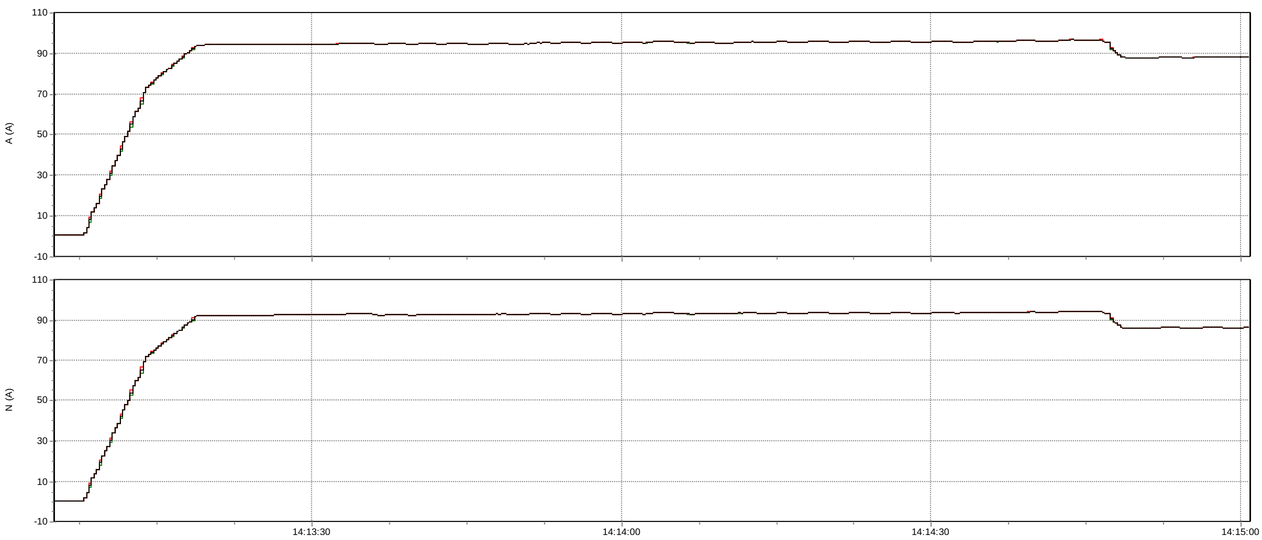


Figure 12 – Current on positive pole (A) and negative pole (N) at the start of Nissan leaf and Hyundai Kona charging session.

The trace shows several minutes charging at 95 A, then a drop in current below 90 A. This drop was a tapering of the charge rate of the Kona. The trace in Figure 13 shows the current on the positive pole whilst the Nissan leaf and Hyundai Kona were charged. At 12:14, the charge rate of the Kona dropped at 12:20 the Kona was disconnected. At 12:27 the Nissan leaf was taken off charge and at 12:29 the Kona was reconnected. There were no abnormal responses observed from the UPFC whilst the loading and charge sessions were varied.

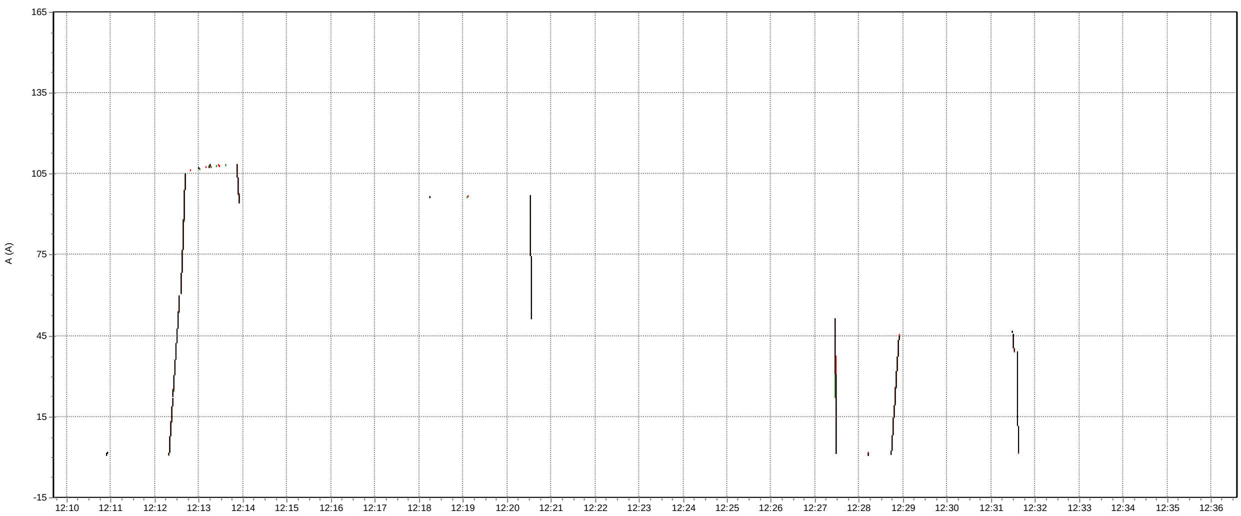


Figure 13 – Nissan leaf and Hyundai Kona on charge.

Outcome: The test circuit can be energised, communications were established, the inter-trip operation was proven end to end and the charging of an EV on the Tritium charger could be demonstrated. The UPFC provided a reliable supply to the Tritium PKM 150 EV charger and the charger was demonstrated to charge three different EVs. No issues were evident during repeated vehicle connection and disconnection. However, the UPFC manufacturer advised that there is a thermal constraint in one of the UPFC components, which currently limits the charging duration depending on the DC loading level.

4.6 Fault Tests

Faults are introduced using a fault thrower, developed as part of the SP Energy Networks transition to LVDC - phase 2 NIA project [4]. There are three fault locations, which are indicated in Figure 15, with the numbered red circles. The response of the UPFC, and downstream protection, will be monitored to verify the functionality and performance of the protection strategy in accordance with the findings of the simulation studies. Faults will be applied by a mechanical fault switch as detailed in Figure 14.

Figure 14 – DC fault thrower.

The fault thrower has a firing pin, activated by the pull of a cord, allowing the spring-loaded contacts to drop onto the busbars, producing a short between the connections at the two busbars. The busbars of the fault thrower will be connected to the two connections of interest in each fault (positive pole, negative pole, neutral and earth). The four faults of interest are:

- Solid pole to pole fault (positive to negative)
- Solid pole to earth fault (positive to earth, negative to earth)
- Solid pole to neutral fault (where a neutral connection is available)
- Resistive pole to ground faults (10 Ω fault resistance)

The one fault configuration that has a difference in setup is the resistive pole to ground faults. The 10 Ω (6 kW rated) Cressall resistor will be included in the fault path to emulate a fault of higher resistance. Each fault configuration will be applied at the three fault locations as detailed in Figure 15.

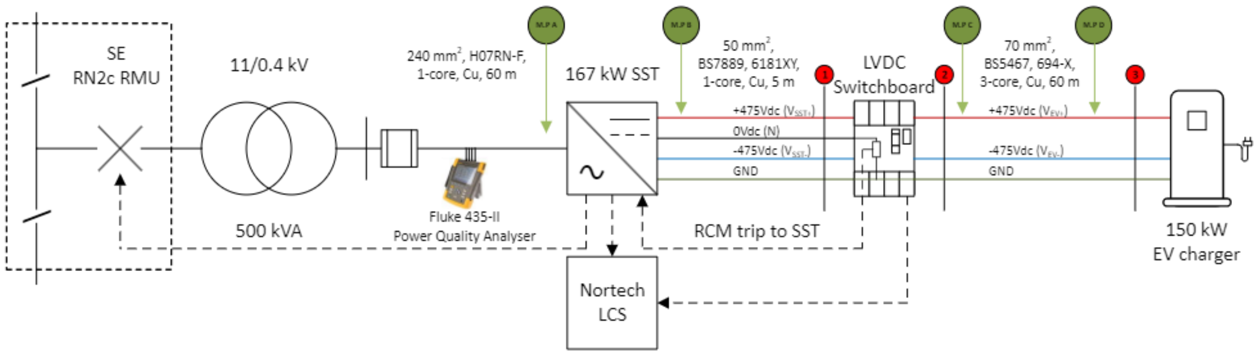


Figure 15 – Fault locations on the DC side of the test circuit.

The expected outcomes based on a fault on the DC side of the UPFC [2]:

1. Fault between the UPFC DC terminal and the EV charger (including the EV charger itself)
    - The UPFC will see increased fault current or reduced DC voltage and will shut down to protect the power electronic devices.
2. Loss of DC voltage supply after the UPFC is switched off
    - The under-voltage relay unit will trip with a fixed time delay response.
3. Following a fault, the UPFC starts ramping up the voltage to a fixed low value reference to check if there is still a fault current in the system.
    - If there is current circulation, it means that there is a DC fault within the small zone between the UPFC DC terminal and the LVDC switchboard. In this case, a 24V inter-trip command will be sent to the RMU from the UPFC protective circuits.
    - Otherwise, the converter continues ramping up to the nominal DC voltage.

The majority of DC fault testing employed the 14.5 Ω resistive load in place of the Tritium PKM 150 EV charger. This substitution was made because the charger experienced issues following the initial application of pole-to-pole faults at location 3.

4.6.1 Solid Pole to Pole Fault

This fault connects the positive pole (i.e. V_{SST+}) to the negative pole (i.e. V_{SST-}) using the DC fault thrower shown in Figure 14.

After application of the fault, the system restart procedure (as detailed in section 3.5) will be completed and the following will be verified:

- The DC fault indicator illuminates on the UPFC, with the status of the DC ON and DC OFF indicators noted
- The LVDC MCCB switch goes to the tripped position
- No warning or fault indicators are illuminated on the Bender earth leakage relay
- On the Nortech LCS, the LVDC switchboard MCCB tripped indicator is illuminated
- On the Nortech LCS, the earth leakage warning and tripped indicators shall not be illuminated

Pole to pole faults were applied at the three locations shown in Figure 15. An example of the current profile recorded at the output terminals of the LVDC switchboard during pole-to-pole faults is detailed in Figure 16.

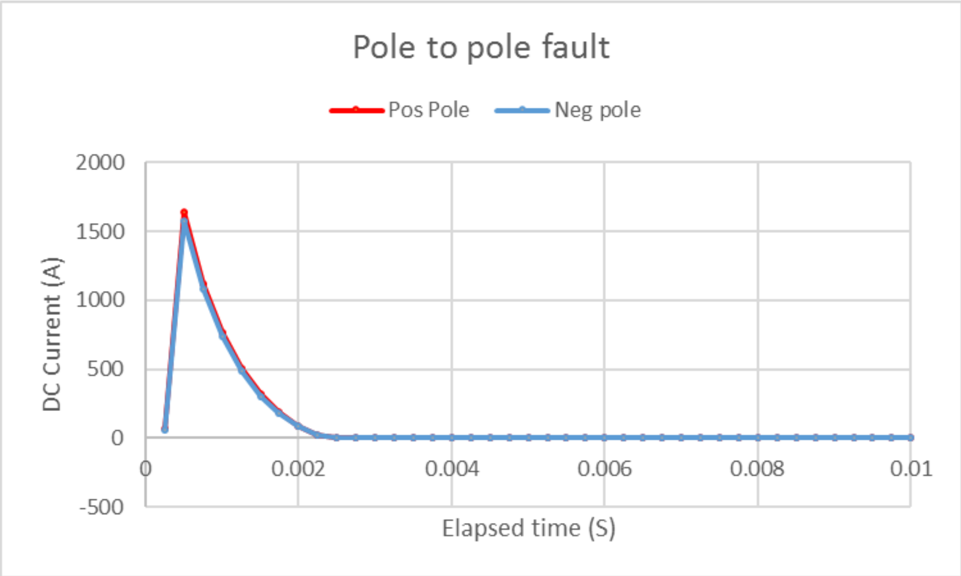


Figure 16 – Pole to pole fault current profile [FB_meas84]

The resulting peak fault currents, UPFC and MCCB status during the pole-to-pole faults in each location is summarised in Table 6.

Table 6: Fault current measured at the output of the LVDC switchboard during pole-to-pole faults

Test No	Location	Charger or resistive load present (Y/N)	Current positive pole (A)	Current negative pole (A)	Time Constant (s)	Total duration (s)	UPFC status	MCCB status
53	1	N	1638	1576	0.00025	0.00325	Output shut down and auto restore attempted	Trip
52	2	N	1557	1581	0.0005	0.00375	Output shut down and auto restore attempted	Trip
14	3	Y	1108	1103	0.000375	0.00375	Output shut down	Trip
15	3	Y	1123	1118	0.0005	0.004	Output shut down	Trip
17	3	N	841	822	0.0005	0.00375	Output shut down	Trip
35	3	Y	1106	1104	0.0005	0.004	Output shut down	Trip
39	3	N	885	707	0.00025	0.00375	Output shut down	Trip
64	3	N	1134	1126	0.00075	0.00375	Output shut down and auto restore attempted	Trip
82	3	N	1074	1052	0.00025	0.0035	Output shut down	Trip
85	3	N	1165	1174	0.00025	0.004	Output shut down – manual restart	Trip
91	3	N	822	823	0.00025	0.0035	Output shut down – manual restart	Trip
92	3	N	1047	1049	0.003	0.00025	Output shut down – manual restart	Trip
93	3	N	821	823	0.000375	0.004	Output shut down – manual restart	Trip

The inter trip from the UPFC to the RMU was employed for several the pole-to-pole faults and the UPFC was shown to reliably shunt trip the RMU. In repeated tests the shunt trip was disabled to reduce downtime between pole-to-pole fault tests.

Take care of the environment.
Printed in black and white and only if necessary.

4.6.2 Solid Pole to Earth Fault

The solid pole to earth fault tests is low resistance, as the connection is made by a solid copper bus bar. Due to asymmetry in the under-voltage relay protection scheme, in the LVDC switchboard, the solid pole to earth test must be undertaken, with a fault connecting the positive pole to earth and the negative pole to earth. The test will confirm the trip time and to check whether the asymmetry has a material impact on the operation of the protection scheme.

After application of the fault, the following will be verified:

- The DC fault indicator is not illuminated on the UPFC, with the status of the DC ON and DC OFF indicators noted
- The UPFC has shut down its LVDC output
- The LVDC MCCB switch goes to the tripped position
- The earth leakage indicator on the Bender earth leakage relay should not be illuminated as it is non-latching
- On the Nortech LCS, the LVDC switchboard MCCB tripped indicator is illuminated
- On the Nortech LCS, the earth leakage tripped indicator is illuminated

Once the fault has been removed and the MCCB is closed, the system restart procedure (as detailed in section 3.5) will be completed and the following will be verified:

- The DC fault indicator is not illuminated on the UPFC, with the status of the DC ON and DC OFF indicators noted
- The LVDC switchboard MCCB tripped indicator on the Nortech LCS is still illuminated
- Pressing the reset button on the Nortech LCS turns the LVDC Switchboard MCCB tripped indicator off

4.6.2.1 Positive pole to ground

The positive pole to ground faults were applied whilst the resistive load was in circuit. The resulting current trace for a positive pole to ground fault is shown in Figure 17.

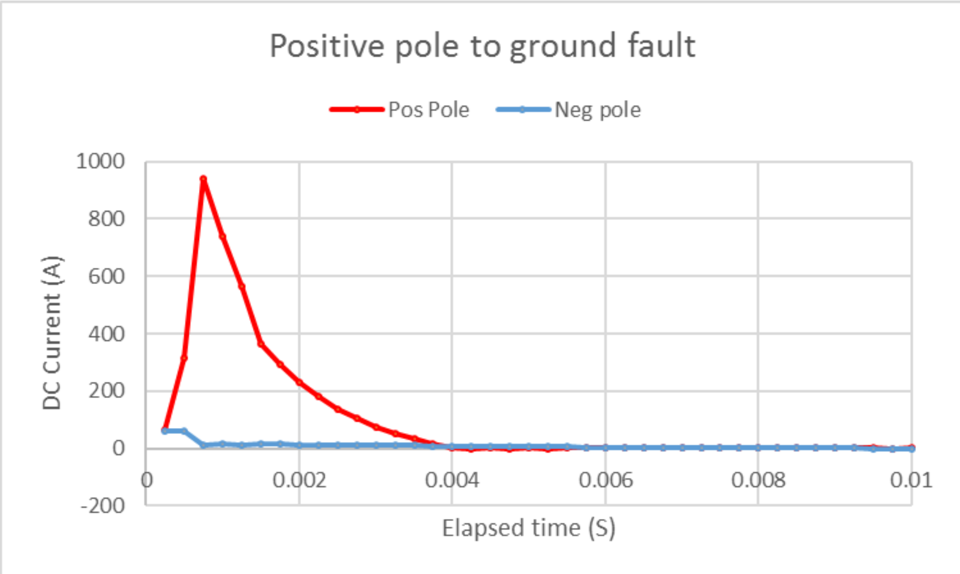


Figure 17 – Positive pole (red trace) to ground fault [FB_meas85_ifault]

Positive pole to ground faults were applied at the three locations (Figure 15). The resulting peak fault current, UPFC and MCCB status is detailed in Table 7.

Table 7: Fault current measured during positive pole to earth faults

Test No	Location	Current positive pole (A)	Time Constant (s)	Total duration (s)	UPFC status	MCCB status
54	1	941.086	0.0005	0.005	Output shut down	Trip
51	2	897.217	0.0005	0.00375	Output shut down	Trip
40	3	513.84	0.00075	0.0075	Output shut down and auto restore attempted	Trip
62	3	577.164	0.0005	0.00825	Output shut down	Trip
90	3	571.06	0.0005	0.00875	Output shut down	Trip
94	3	502.014	0.00075	0.00875	Output shut down	Trip
97	3	513.077	0.0005	0.009	Output shut down	Trip

The UPFC to RMU inter trip was demonstrated to operate reliably for several the positive pole to earth faults then the inter trip was disabled to aid testing (reduced downtime).

4.6.2.2 Negative pole to ground

The negative pole to ground faults were applied whilst the resistive load was in circuit. The DC fault study also considered negative pole to ground faults as illustrated in Figure 18.

Take care of the environment.
Printed in black and white and only if necessary.

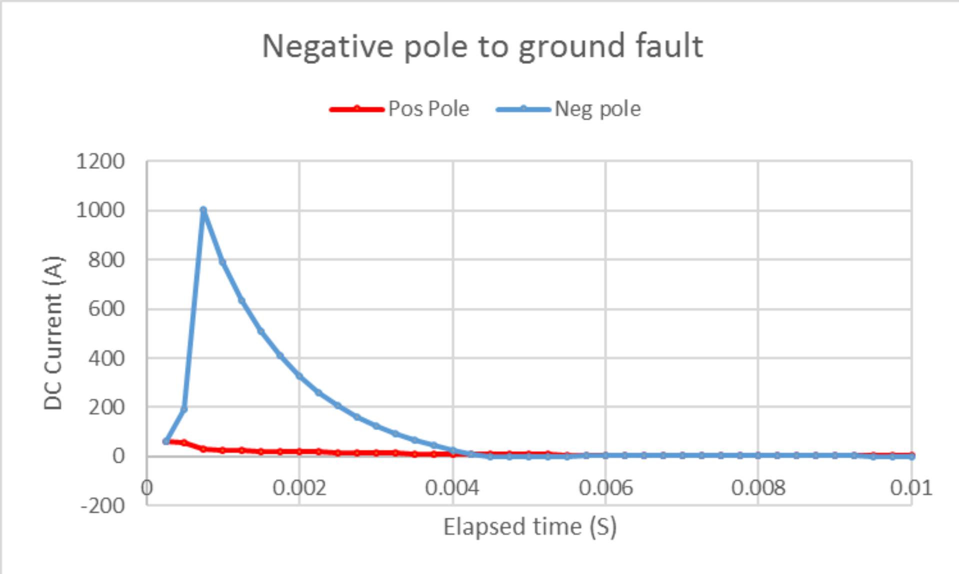


Figure 18 – Negative pole (blue trace) to ground fault [FB_meas86_ifault]

Faults were applied between the negative pole and ground at the three locations. The peak value of the resulting fault current, UPFC and MCCB status is shown in Table 8.

Table 8: Fault current measured during negative pole to earth faults

Test No	Location	Current negative pole (A)	Time Constant (s)	Total duration (s)	UPFC status	MCCB status
55	1	1002.884	0.00075	0.02475	Output shut down	Trip
63	1	606.537	0.0005	0.00925	Output shut down	Trip
49	2	995.255	0.0005	0.01025	Output shut down	Trip
50	2	1028.442	0.0005	0.01025	Output shut down	Trip
83	3	547.409	0.00075	0.00925	Output shut down and auto restore attempted	Trip
86	3	551.224	0.000875	0.009	Output shut down	Trip
87	3	646.973	0.000625	0.00825	Output shut down	Trip
88	3	558.09	0.00075	0.007	Output shut down	Trip
89	3	585.938	0.00075	0.0075	Output shut down	Trip
99	3	558.853	0.0005	0.007	Output shut down	Trip
100	3	560.76	0.00075	0.0075	Output shut down	Trip

The UPFC to RMU inter trip was demonstrated to operate reliably for a number of the positive pole to earth faults then the inter trip was disabled to aid testing (reduced downtime).

4.6.3 Solid Pole to Neutral Fault

The solid pole to neutral fault will place a short from the positive/negative rail to the neutral connection, where it is available. This fault can be applied directly at the red circled number 1 in Figure 15. For fault

Take care of the environment.
Printed in black and white and only if necessary.

points 2 and 3, this will be performed by connecting a flying lead to the neutral cable between the UPFC and the LVDC switchboard.

After application of the fault, the following will be verified:

- The DC fault indicator is not illuminated on the UPFC, with the status of the DC ON and DC OFF indicators noted
- The UPFC has shut down its LVDC output
- The earth leakage indicator on the Bender earth leakage relay is not illuminated
- On the Nortech LCS, the LVDC switchboard MCCB tripped indicator is illuminated
- On the Nortech LCS, the earth leakage tripped indicator is not illuminated

Once the fault has been removed, the system restart procedure (as detailed in section 3.5) will be completed and the following will be verified:

- The earth leakage indicator on the Bender earth leakage relay is not illuminated
- The earth leakage tripped indicator on the Nortech LCS is illuminated
- Pressing the reset button on the Nortech LCS turns the earth leakage tripped indicator off

4.6.3.1 Pole to neutral

These fault conditions were not applied during the integration testing.

4.6.4 Resistive Pole to Earth Fault

The resistive pole to earth fault will be achieved with a 10 Ω resistor. This fault will be applied at the red circled number 1 in Figure 15. The high resistor value will trigger an earth fault warning but will not trip the protection.

After application of the fault, the following will be verified:

- The DC fault indicator illuminates on the UPFC, with the status of the DC ON and DC OFF indicators noted
- The UPFC has shut down its LVDC output
- The earth leakage indicator on the Bender earth leakage relay is not illuminated
- On the Nortech LCS, the LVDC switchboard MCCB tripped indicator is illuminated
- On the Nortech LCS, the earth leakage tripped indicator is not illuminated

Once the fault has been removed, the system restart procedure (as detailed in section 3.5) will be completed and the following will be verified:

- The earth leakage warning indicator on the Bender earth leakage relay is not illuminated
- The earth leakage warning indicator on the Nortech LCS is illuminated
- Pressing the reset button on the Nortech LCS turns the earth leakage warning indicator off

In each location a high impedance (10 Ω) fault was applied to the positive and negative pole separately. The reduced fault current magnitude, under these conditions, cannot be detected by the UPFC and the MCCB. The Bender, relay which is installed at the earth connection in the LVDC switchboard, can detect the elevated current flowing to earth, under these fault conditions. An example of the current profile for a negative pole to ground high impedance fault is shown in Figure 19.

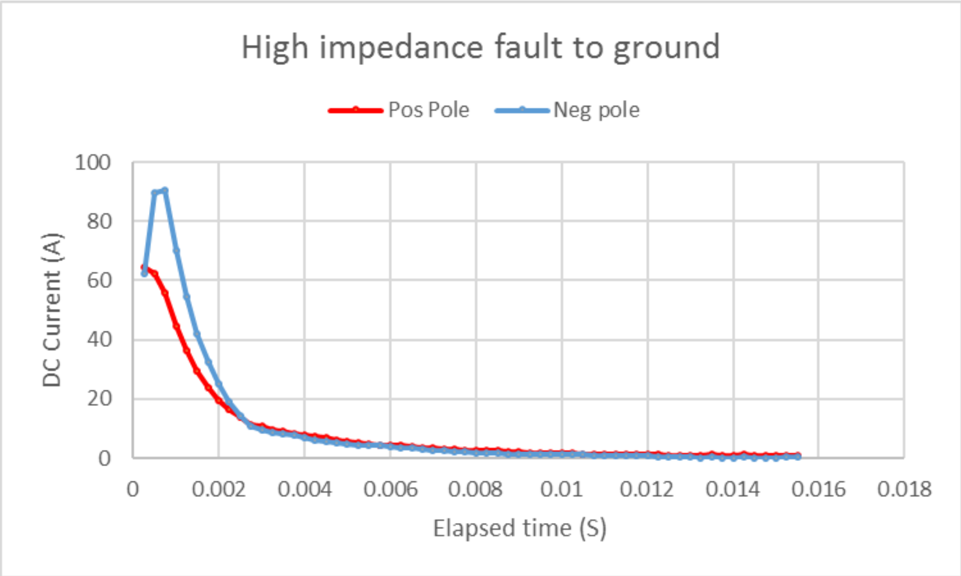


Figure 19 – High impedance fault to ground

The high impedance faults were applied whilst the resistive load was in circuit. The summary of the faults is shown in Table 9.

Table 9: Fault current apparent during high impedance faults to ground

Test No	Location	Current positive pole (A)	Current negative pole (A)	Time Constant (s)	Total duration (S)	Bender status
56	1	55	90	0.0005	0.01	Trip
57	1	101	57	0.0005	0.00975	Trip
58	2	92	54	0.0005	0.0095	Trip
59	2	62	107	0.0005	0.0105	Trip
60	3	56	93	0.0005	0.0095	Trip
61	3	105	61	0.0005	0.00925	Trip

Outcome (all DC faults): Following the application of each DC fault, the operation of the UPFC was verified and once the faults were completed, comprehensive functional tests confirmed that the unit was fully operational. Generally, under fault conditions, when excessive current was drawn from the UPFC (pole to pole and pole to earth), the UPFC stopped injecting current and subsequently the MCCB tripped on under voltage. The UPFC then attempts an auto restore whereby the extra DC low voltage (48 Vdc) and if current is apparent then the UPFC shunt trips the RMU. The auto restore function of the UPFC was shown to successfully operate on several occasions but was not reliable and ultimately the user had to perform a manual reset on the front panel of the UPFC.

In the case of resistive earth faults, the fault current was relatively low so the excessive current in the earth path was detected by the Bender earth leakage relay which acted to trip the RMU. The EV charger experienced hardware issues following the application of pole-to-pole faults at location 3, the EV charger load was substituted by a 14.5 Ω resistor for the majority of fault tests. As such the fault contribution of the EV charger was not fully realised due to these hardware issues with the charger.

4.7 Witness Tests

As a part of the system demonstration and testing, members of the LV Engine team were present to witness some of the functional and fault testing being undertaken. The demonstration mainly covered the system start up, charger operation and the application of DC faults.

Outcome: A large number of key stakeholders were hosted during the test programme, SP Energy Networks, OFGEM, Falkirk Council, University of Strathclyde and where possible testing was demonstrated to attendees.

4.8 215 V Output on UPFC

An additional test performed during the test programme was to request a setpoint of 215 V. Initially the setpoint was 238 V, then the setpoint was changed to 215 V (12:10:44) and finally a setpoint of 231 (12:13:53) was selected by the operator. The voltage output from the UPFC (Fluke C) is detailed in Figure 20.

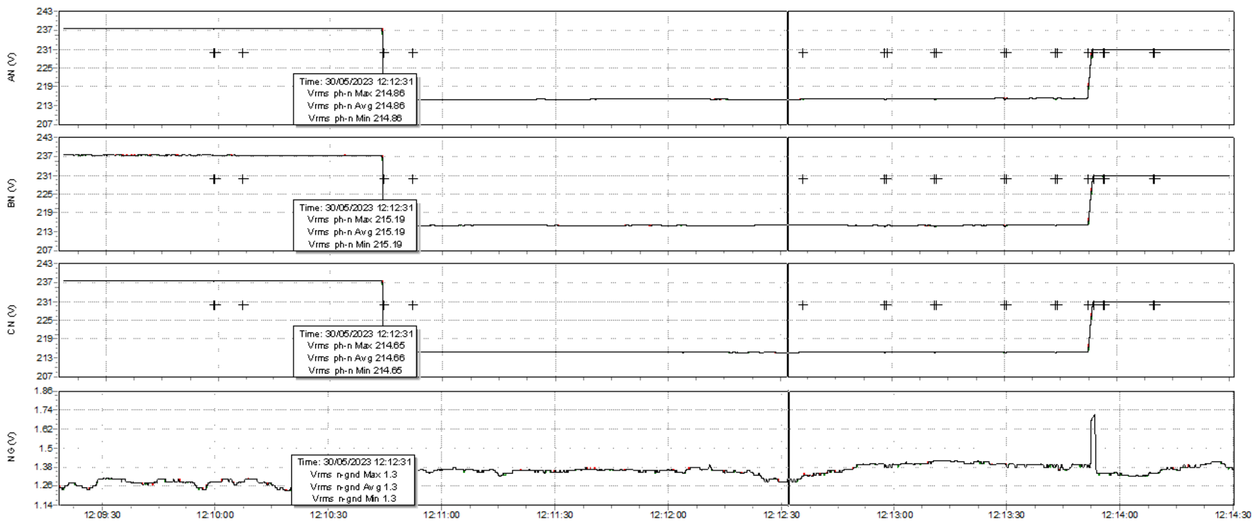


Figure 20 – 215 V output on the UPFC AC output [FC_meas63]

In order to study the control of the UPFC AC output, the distribution of the three phase to neutral voltages was investigated. Figure 21 shows the number of events recorded over the phase voltage range of interest.

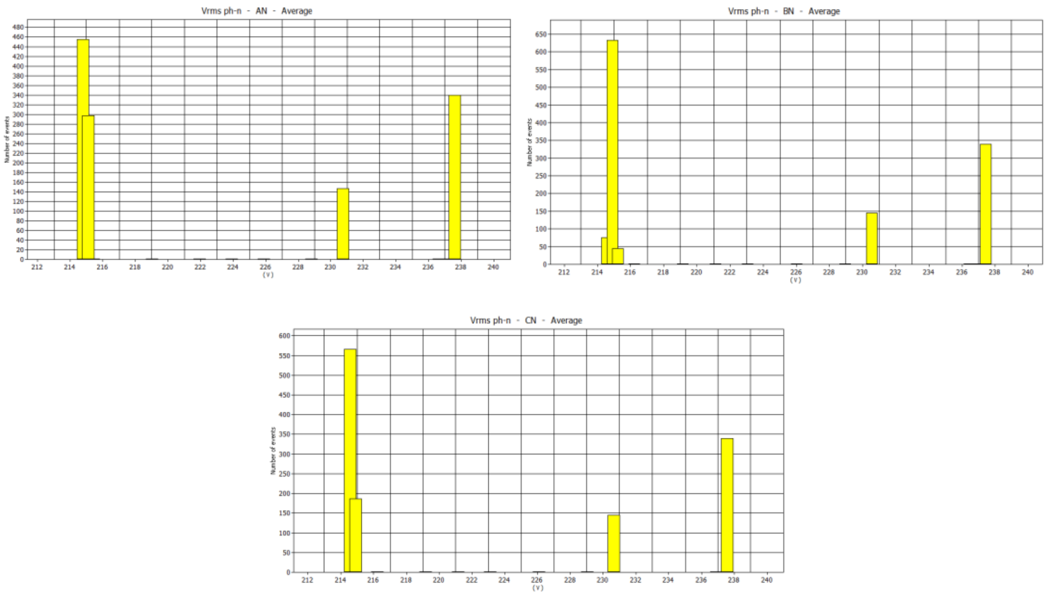


Figure 21 – Phase to neutral voltage distributions

The plots show three clusters for the distributions around the three set points requested by the operator (215, 230 and 238 V). No outliers are present demonstrating that the set point of the UPFC is effective.

Outcome: The UPFC was shown to regulate the AC voltage to 215 V with the max and min voltage being 215.38 (+0.176%) and 214.58 V (-0.195%), whilst this setpoint was applied to the UPFC control. This level of AC voltage control will be useful for network operations and offers finer control than transformer tap changes (potential for reduced wear and tear on existing assets).

4.9 Reactive Power Compensation

The reactive power compensation of the UPFC was demonstrated by the Grid Bridge representative. The UPFC used alternative operating mode, whereby the capacitor bank inside the unit was used for power factor correction. The PNDC load bank was set as a balanced 96.6 kVA load with a lagging power factor if 0.84 (Figure 22).

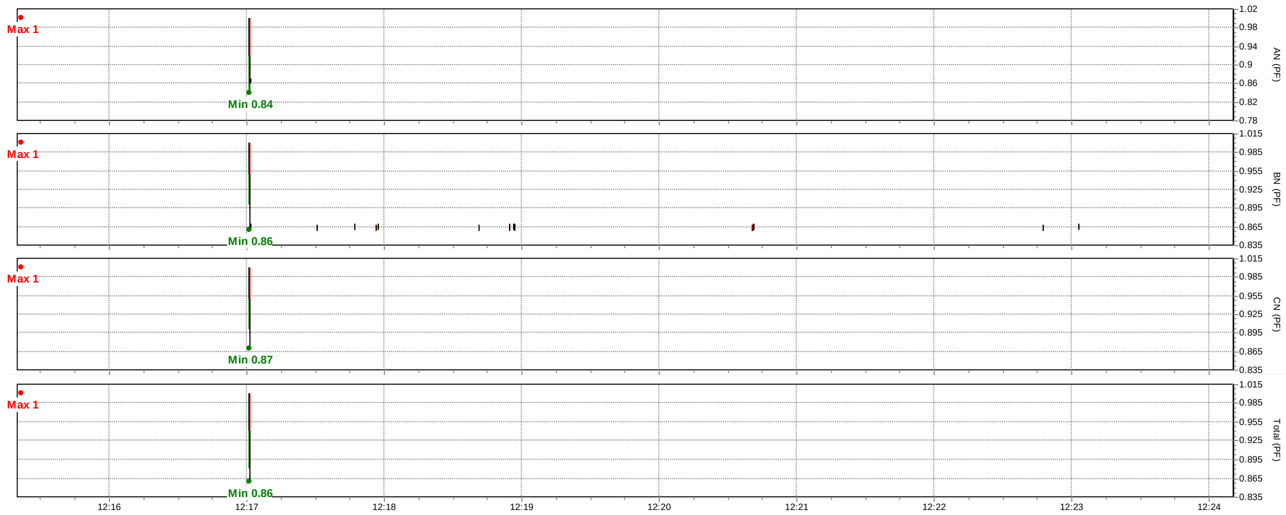


Figure 22 – Power factor at UPFC AC output terminals [FC_meas64]

At 12:17:03, 45 kVAR of reactive power was requested on the UPFC control, this was recorded as 48.3 kVAR on the Fluke power quality analyser. The reactive power consumed by the UPFC is illustrated in Figure 23.

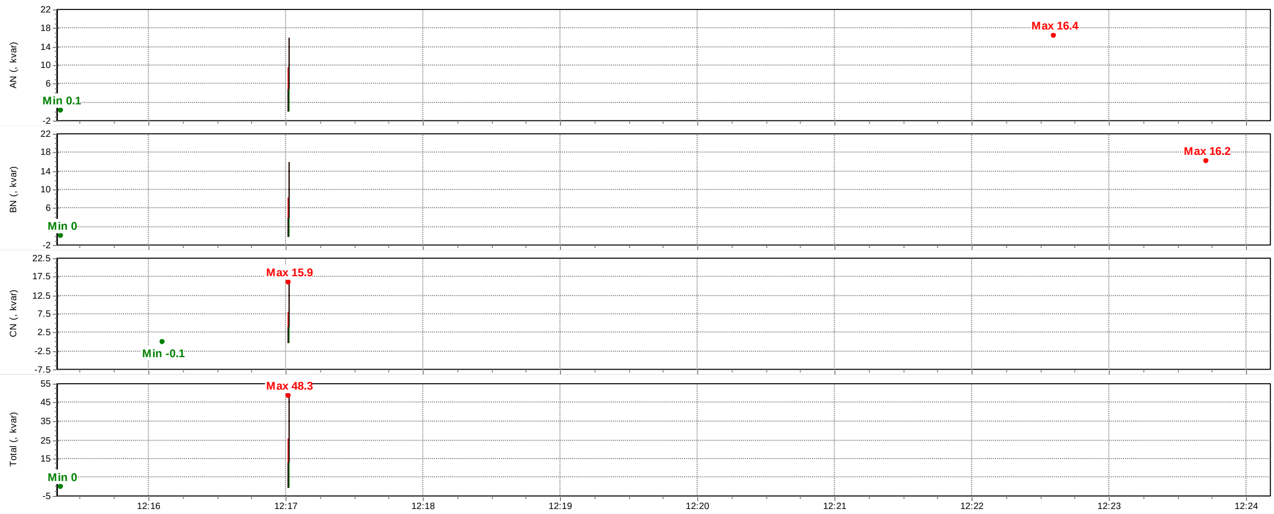


Figure 23 – Reactive power compensation [FC_meas64_kvar]

The reactive power compensation is shown across the AC input terminal of the UPFC (Figure 24) with the power factor returning to 1 at 12:18:18 despite the load still being 85 kW with a lagging power factor of 0.84.

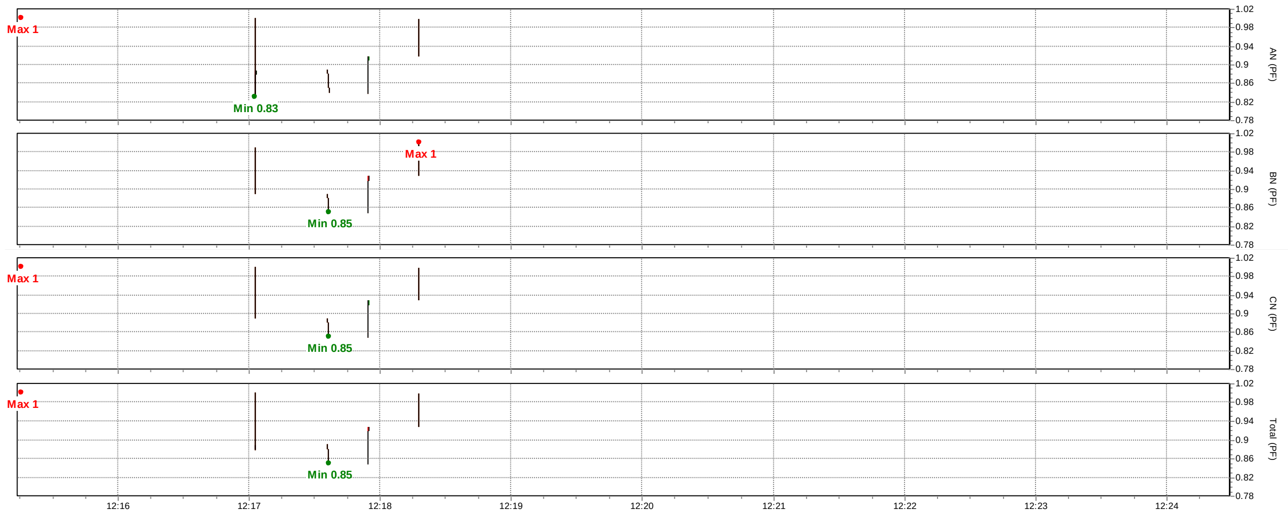


Figure 24 – Reactive power compensation and power factor at UPFC input terminals [FA_meas63]

Outcome: The reactive power compensation of the UPFC was demonstrated for a load of 85 kW with a lagging power factor of 0.84. This enabled the UPFC to appear to the feeder as a unity power factor load. This additional functionality could be beneficial in some challenging network scenarios.

4.10 Bender Relay Tuning

An earth leakage relay manufactured by Bender (RCMB301) was installed in the LVDC switchboard between the midpoint and the earth connection from the 11/0.4 kV transformer feeding the UPFC illustrated in Figure 2. It was not possible to connect to the existing RCMB301 evaluation unit (serial number: 2105541108) to read or write Modbus commands. The evaluation unit was replaced and initially the RCMB301 [5] had the settings shown in Table 10.

Table 10: Initial bender RCMB301 settings

Device parameter	Modbus register value [5]	Value
Limit value alarm (mA)	16012	50
T_{on} alarm (ms)	16018	50
DC Limit value prewarning (%)	16014	60
Relay 1 fault memory	16055	ON

During the execution of the test plan it became apparent that the RCMB301 was continually tripping as such it was decided to perform specific tests to review the settings on the RCMB301. The start-up on of the UPFC was repeated for different current trip settings. In order to investigate the duration that the trip/limit value alarm setting was exceeded the fault memory setting was turned off (Modbus register value 16055). In this mode, the LED indicator on the RCMB301 would light up when the trip value was exceeded and turn off again when the current was below the value. The observations for a range of trip settings are outlined in Table 11.

Table 11: Bender RCMB301 behaviour during UPFC start up

RCM301 trip setting/limit value alarm (mA)	LED observation
50	Initial trip with 3 bounces
60	Trip and no bounces
80	Trip and no bounces
100	Trip and no bounces
110	Trip and no bounces
120	Trip and no bounces
130	No trip signal
150	No trip signal

Based on the findings above the Bender RCMB301 settings were revised as illustrated in Table 12.

Table 12: Revised Bender RCMB301 settings

Device parameter	Modbus register value	Value
Limit value alarm (mA)	16012	150
T_{on} alarm (ms)	16018	50
DC Limit value prewarning (%)	16014	90
Relay 1 fault memory	16055	ON

A trip threshold of 150 mA avoided any spurious operation during the start-up of the UPFC or during functional testing with AC and DC loading applied to the UPFC. The RCMB301 was shown to reliably trip for pole to earth faults but not for pole to pole faults as specified in the protection scheme.

Outcome: The operation of the Bender was fully trialled on the expected test setup for the Falkirk trial site. PNDC suggests revisions to the Bender RCMB301 settings based on the start-up observed for the Grid Bridge UPFC. The trip threshold/limit value alarm has a recommended value of 150 mA (default = 50 mA), the time delay/T_{on} alarm was set to the minimum value of 50 ms (default), the alarm threshold/ DC Limit value prewarning was set to 90 % (default = 60%) and the Relay 1 fault memory was set to on (default). With these settings the RCMB301 was shown to operate as required and detect pole to earth faults. If spurious tripping is apparent the method outlined above should be completed to confirm whether a permanent earth fault is present or if the start-up of the UPFC is causing an earth leakage relay trip.

4.11 Enspec Tuning

An Enspec DC fault detection system was trailed on the LV Engine test setup at PNDC. The Enspec system had a central measurement unit and two CTs which were connected at the output of the LV distribution board. The measurement system had a HMI which indicated if a fault had been detected. Initially the factory settings on the Enspec were employed for testing and the unit could reliably detect the presence of DC faults. The Enspec unit has a voltage detection threshold in the secondary circuit that is set via a potentiometer on the main board inside the measurement unit. Initially this voltage threshold was at 7.5 V which provided a current measurement range of 160 A in the primary circuit. It must also be noted that the CTs employed in this testing were a temporary stand in due to a component delay.

During fault testing it was evident that the Enspec unit was missing some of the DC fault events. Following discussions with the Enspec team the polarity of the CT and the voltage detection threshold were varied in a series of tests whilst the overall scheme was operating under realistic load conditions (EV charging on the

Tritium PKM 150). Changing the polarity of the CT had an adverse effect on the detection of faults and effectively blinded the system from detecting DC faults. The voltage detection threshold in the secondary circuit was varied by altering the setting on the potentiometer whilst measuring the voltage with a multimeter.

A summary of the voltage threshold changes on the secondary circuit on the main board of the Enspec unit and associated observations are outlined in Table 13.

Table 13: Observations from testing the Enspec fault detection system

Voltage threshold in secondary (V)	Current threshold in primary (A)	Observation
7.5	160	Apparent that some faults could not be detected
3	64	Consistently detecting the faults and no false detections during normal load conditions
5	106.67	Apparent that some faults could not be detected
4	85.33	Consistently detecting the faults and no false detections during normal load conditions

Following the revision to the voltage detection threshold in the secondary circuit the Enspec unit was able to reliably detect DC faults.

Outcome: The Enspec unit was proven to detect DC faults during the full suite of testing with the exception of the high impedance faults that the Bender relay I designed to detect. The HMI interface made it easy to determine if a fault had been recorded. The voltage threshold for the detection system may need to be fine-tuned (most likely the threshold value reduced) in the field if repeated faults are not detected. PNDC suggests that a voltage threshold of 4 V is employed initially based on the findings from the full scale integration testing. The 4 V threshold voltage equates to a primary current threshold of 85 A.

4.12 Voltage Regulation

This test case extends the hardware to cover AC loads on the UPFC. Of particular interest is balanced and unbalanced loads. The balanced 3 phase load was provided by Froment Loadbanks on the PNDC test network. The loadbanks are accessed by the LV test bays and powersafe connectors. The imbalance was introduced on the selected phase(s) using up to six 10 Ω resistors (each rated at 6 kW) and through removing fuses in the loadbanks to produce further imbalance. An illustration of the test circuit is shown in Figure 25.

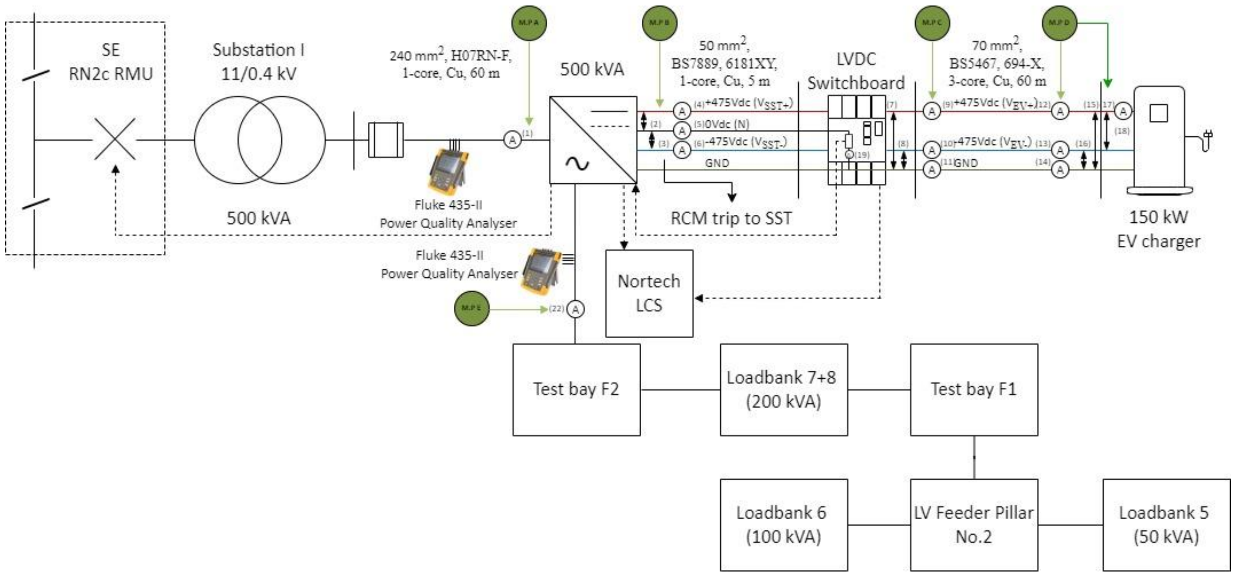


Figure 25 – SPEN-030 test setup with AC load

Two different functions of the UPFC will be trialled with AC and DC loads present on the UPFC, the specific functions and test cases will be introduced in the following sections.

The Voltage regulation function of the UPFC enables voltage regulation on a per phase basis. Testing was conducted under the three scenarios outlined in Table 14. The cases cover the presence of a balanced AC load, a DC load and an imbalance added to a selected phase (phase A). Care was taken to ensure that the current rating of the 240 mm^2 H07RN-F single core cable is not exceeded (471 A) [6] during testing of the voltage regulation function.

Table 14: Voltage regulation test cases

DC load (kW)	Balanced AC load (kVA)	Unbalanced load added to phase A at test bay F2 (kW)	UPFC target phase voltage (V)		
			L1	L2	L3
0	200	0	230		
0	200	6-36	230		
50-150	200	6-36	230		
50-150	200	6-36	230	240	248

The UPFC has two operating modes, the AC output bypass mode and voltage regulation. Each mode will be introduced and the findings will be outlined in the following subsections.

4.12.1 Voltage Regulation

Whilst in voltage regulation the operator of the UPFC can control the voltage at the output of the UPFC across the three phases. The voltage output was varied between 230, 240, 250 and 254 V. During this test the total load on the UPFC ranged between 73.2-110.1 kVA. The voltage at the input terminals of the UPFC is shown in Figure 26 and the output is shown in Figure 27 (whilst regulating the AC output voltage of the UPFC).

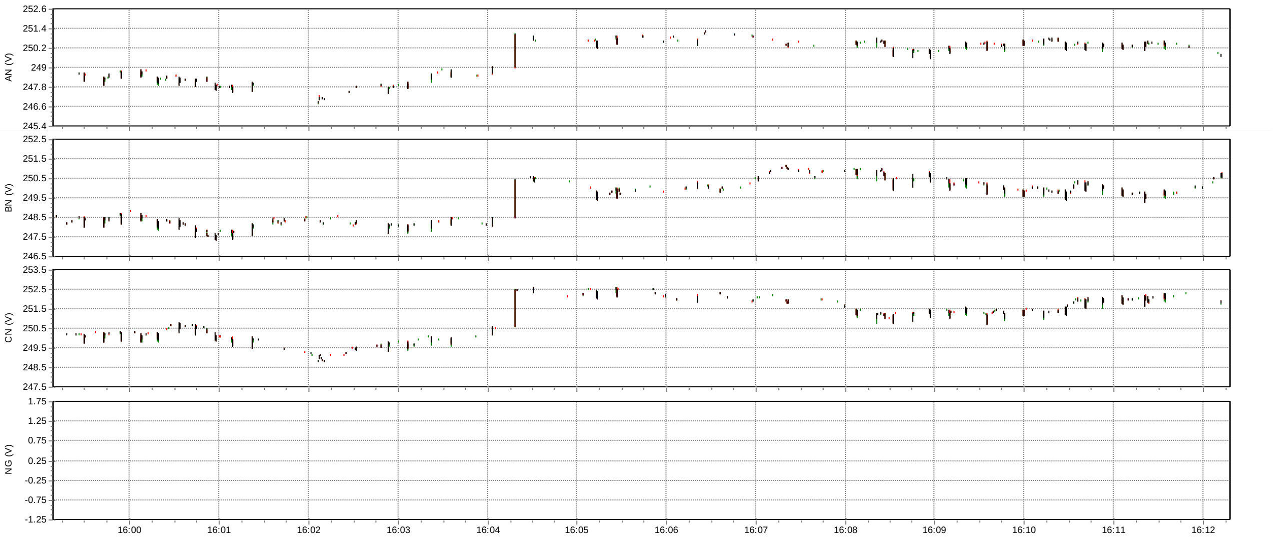


Figure 26 – Voltage at the input of the UPFC (regulation mode) [FA_meas53]

Figure 27 – Voltage at the output of the UPFC (regulation mode) [FC_Meas54]

The power factor of the AC load on the UPFC was varied between 1, 0.9 and 0.87. The variation in the power factor on the PNDC loadbanks is shown in Figure 28.

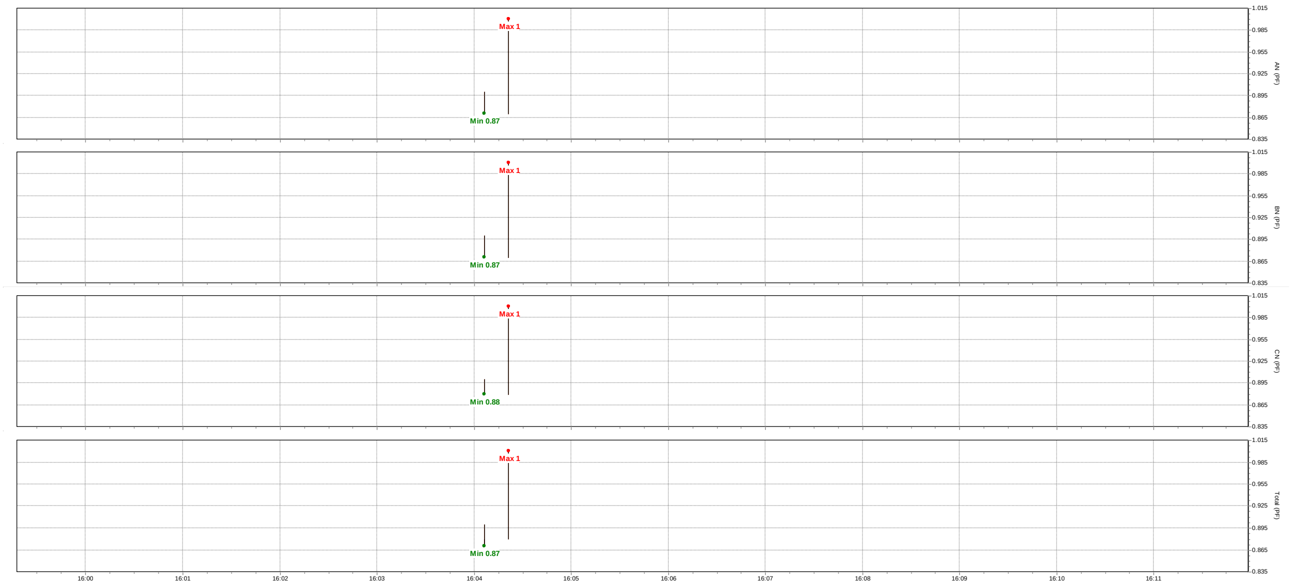


Figure 28 – Variation in power factor at UPFC output (regulation mode) [F_C_Meas54_PF]

An imbalanced load and the EV charger loads were employed as loads on the UPFC whilst changes were made to the AC voltage set point as outlined in Table 15.

Table 15: Voltage setpoint and load conditions

Time	AC voltage set point			Loadbank loading (kVA)	EV charger load (kW)
	Phase A	Phase B	Phase C		
14:31	Bypass			0	0
14:37	230			372	0
14:38	230			278	0
14:40	230			278	88
14:42	240			308	88
14:42:30	250			334	88
14:48	240			307	82
14:49	240	250	230	307	82
14:51:22	240	250	230	307	72
14:54:30	240	250	230	0	72

The voltage and current at the input of the UPFC are shown in Figure 29 and Figure 30.

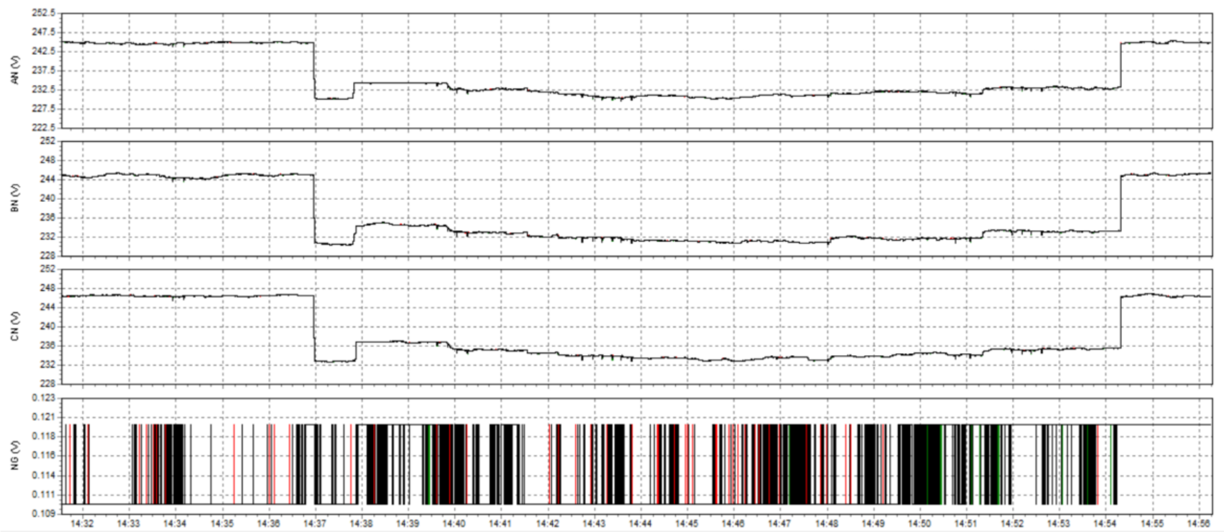


Figure 29 – Voltage at the input of the UPFC [FA_Meas106]

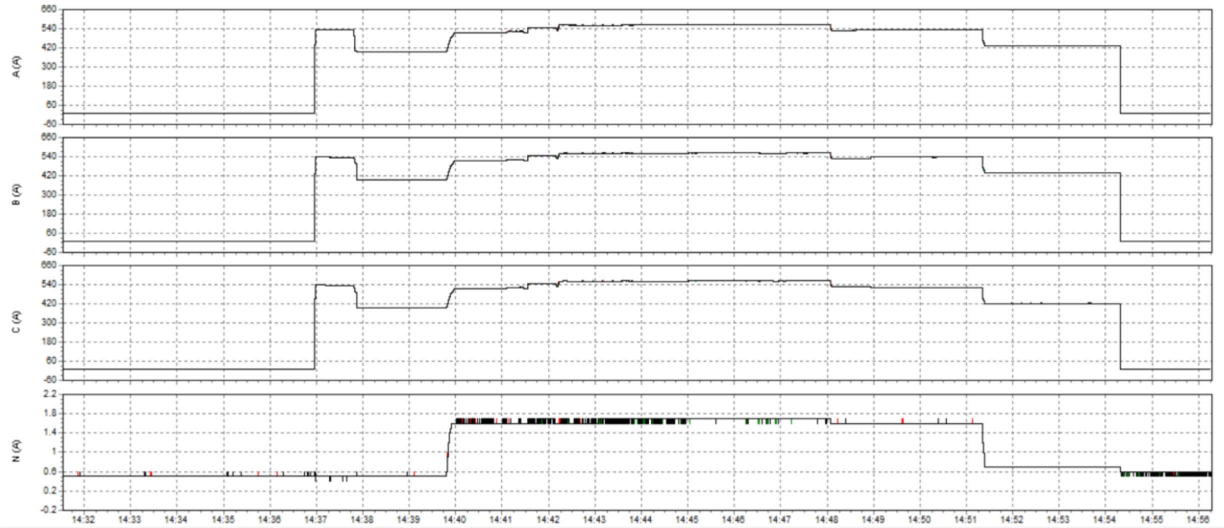


Figure 30 – Current at the input of the UPFC [FA_Meas106]

The total load on the UPFC ranged from 277.8 kVA to 375.6 kVA. The voltage and current at AC the output of the UPFC are shown in Figure 31 and Figure 32.

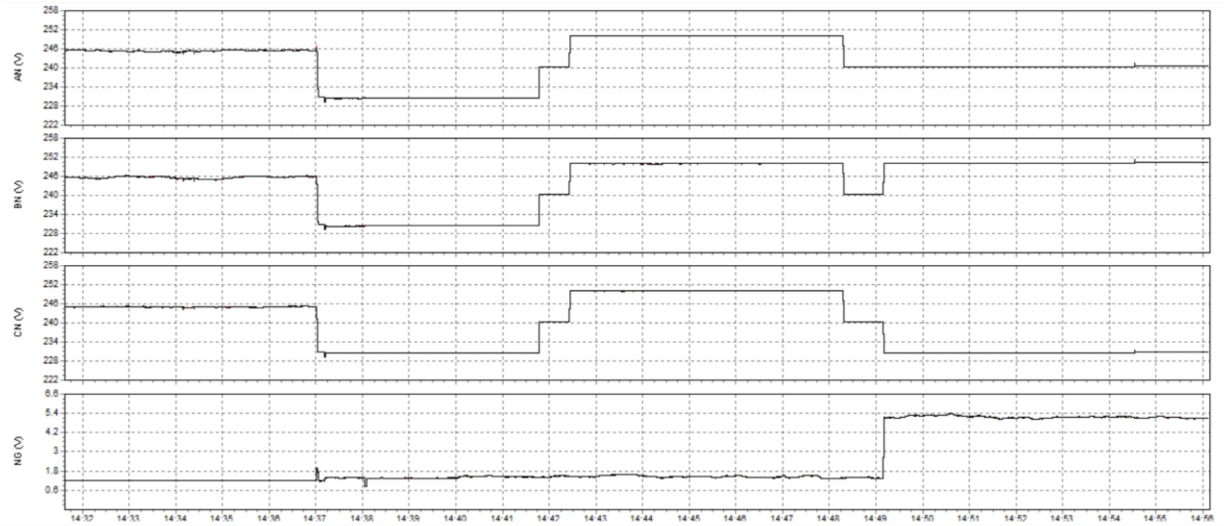


Figure 31 – AC voltage output from the UPFC [FC_meas109]

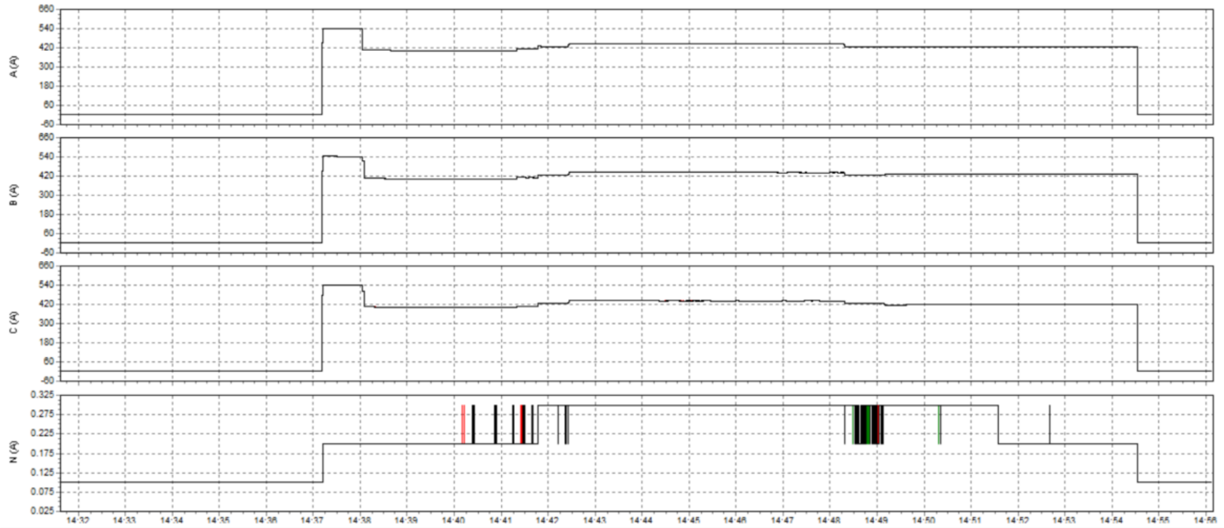


Figure 32 – AC current at the output of the UPFC [FC_meas109]

The DC loading was applied by the Tritium PKM150 EV charger whilst charging a 30 kWh Nissan leaf and 64 kWh Hyundai Kona. The EV charging session was started at 14:40, then tapering of the charging rate on the Kona was evident at 14:48 and 14:51.

Outcome: Whilst in regulation mode the UPFC was shown to regulate the voltage output from 230 V to 254 V whilst under a range of different loading conditions up to a maximum combined load of 376.5 kVA. The lockout/warning if the operator tried to exceed the upper voltage limit (+10% =253 V) and the lower limit (-6%=216.2 V) was also successfully implemented via a firmware update by ERMCO-GridBridge. The variation in the power factor of the load had no impact in the voltage regulation function of the UPFC.

4.12.2 Independent Voltage Control

Whilst in voltage regulation the operator of the UPFC can independently control the voltage of each phase. The total load on the UPFC ranged from 86.1 to 106.2 kVA. The setpoint changes requested are outlined in Table 16.

Table 16: Set point changes during independent voltage control testing

Time	Voltage set point		
	Phase A	Phase B	Phase C
16:07	244	244	244
16:09	230	240	250
16:15	231	231	230
16:22	240	250	230

Figure 28 shows the output of the UPFC whilst independent voltage regulation was trailed.

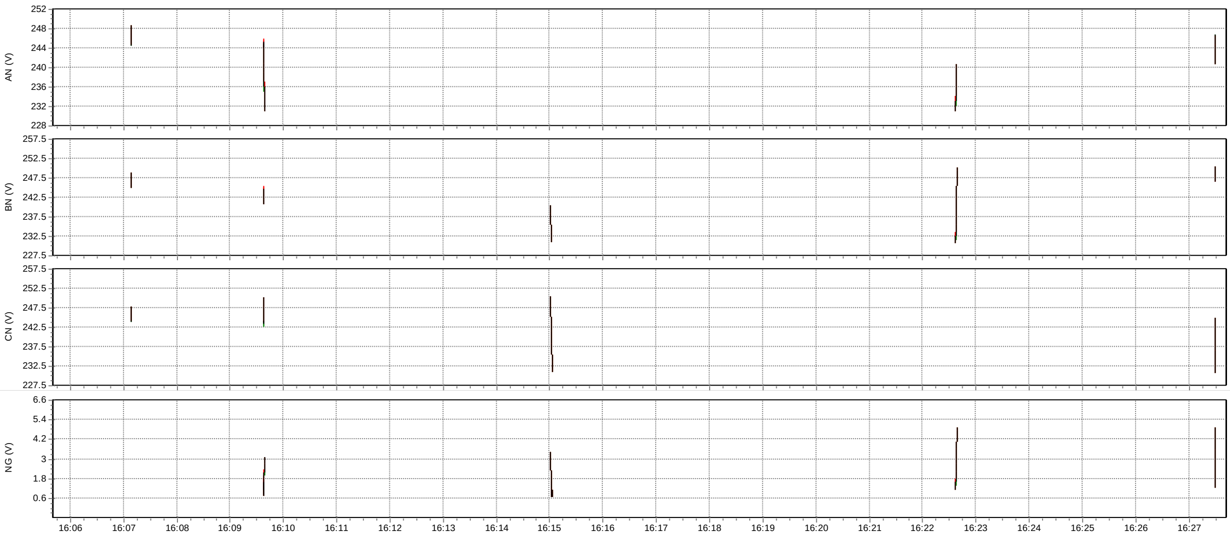


Figure 33 – Voltage at the output of the UPFC (independent voltage regulation) [FC_Meas96]

Outcome: With the UPFC in voltage regulation mode independent control of the three phase voltages was demonstrated for a range of voltages (230-250 V). The operator was able to readily change the setpoint on each phase separately. Such control would be beneficial in a system with unbalanced feeders or if tap changes are too coarse.

4.13 Power Sharing

The power sharing function enables load to be shared between the UPFC and a neighbouring transformer on the same feeder. The S1 UPFC did not have the final power sharing control function enabled and nor lab based testing had been completed by ERMCO-GridBridge. In phase 1 of integration testing the project team decided to dedicate available PNDC test days to higher priority test objectives (Bender tuning, Enspec tuning and auto restore tests). The power sharing tests were successfully completed at the conclusion of the regression testing on the S2 UPFC and are detailed in section 5.7.

4.14 AC Fault Testing

Faults were applied on the AC output of the UPFC whilst supplying the PNDC AC loadbanks. The AC faults were applied by the PNDC fault thrower (Figure 34). Faults considered were phase to phase, phase to earth, 3 phase and 3 phase to earth.

Figure 34 – PNDC AC fault thrower

The setup of the fuse ways from the AC output of the UPFC in the final application environment was replicated with 315 A fuses included in the test setup. Initially 100 and 200 A fuses were employed to confirm the UPFC could withstand the applied fault current over the shorter blow time of these fuses. The 315 A fuses were used in the final round of AC fault testing to ensure that the UPFC could withstand the fault current for the extended blow time of the 315 A fuses. In all AC fault tests, the voltage regulation set point across the three phases was 240 V. The Summary of AC fault conditions and the peak fault current detected are in Table 17.

Table 17: Summary of AC faults

Test No	Fault type	UPFC volt regulation (y/n)	Fuse size (A)	Fluke A observed fault current (A)			
				L1	L2	L3	N
102	L2 to GND	n	100		1920.32		1928.33
103	L2 to GND	y	100		1954.27		1968.00
104	3PH to GND	y	100	3934.86	2994.92	3243.26	2173.23
105	L2 to GND	y	200		5262.38		5237.58
106	3PH to GND	y	200	5596.92	8226.01	4373.19	
110	L2 to GND	y	315		5818.18		5842.97
111	L2 to L3	y	315		7904.43		7950.21
112	3 PH	y	315	8858.87	7661.82	9054.95	

The fault current waveforms for the faults with the 315 A fuses are illustrated in Figure 35, Figure 36 and Figure 37.

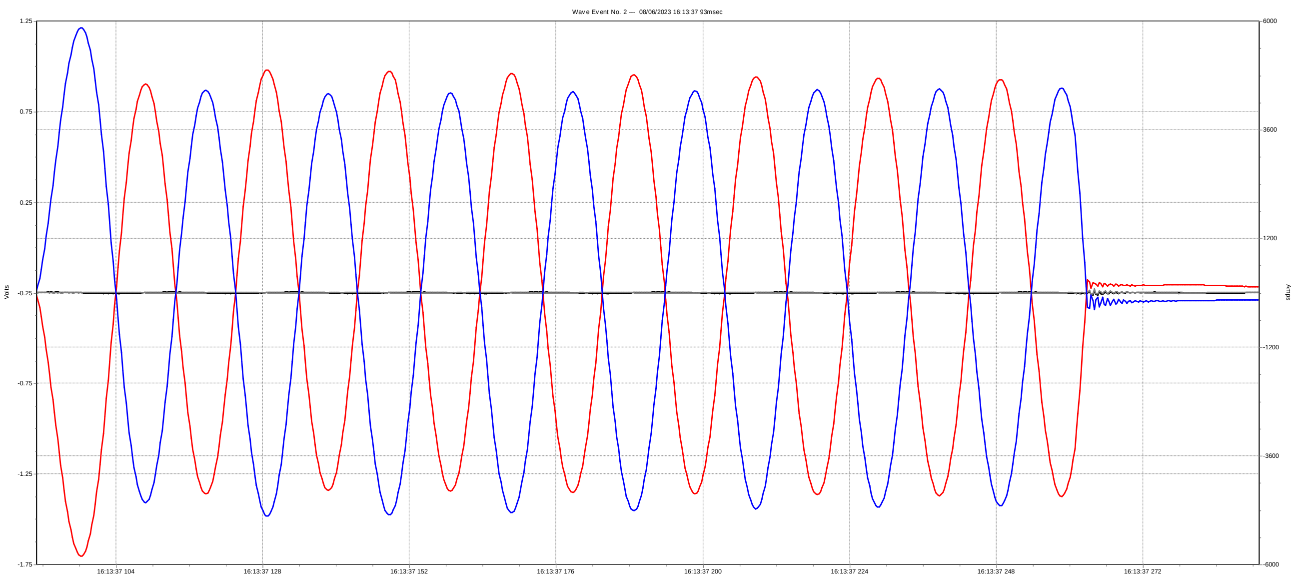


Figure 35 – Phase to ground fault (L2-GND) and resulting fault current for a 315 A fuse [FA_meas 133]

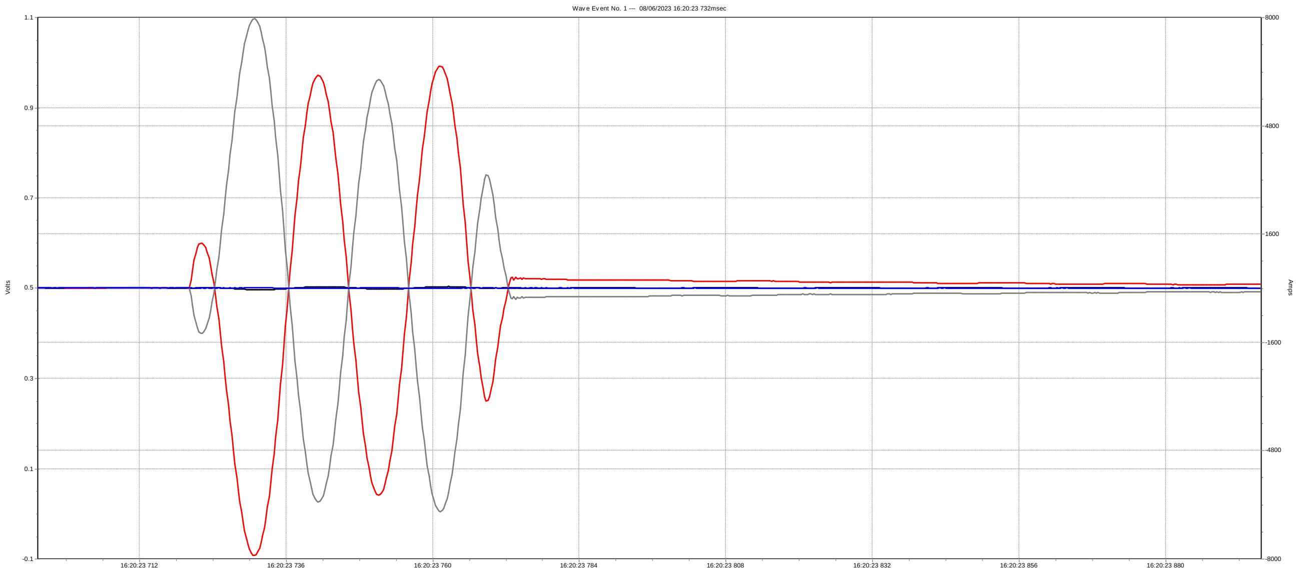


Figure 36 – Phase to phase (L2-L3) fault and resulting current with a 315 A fuse [FA_Meas134_ifault]

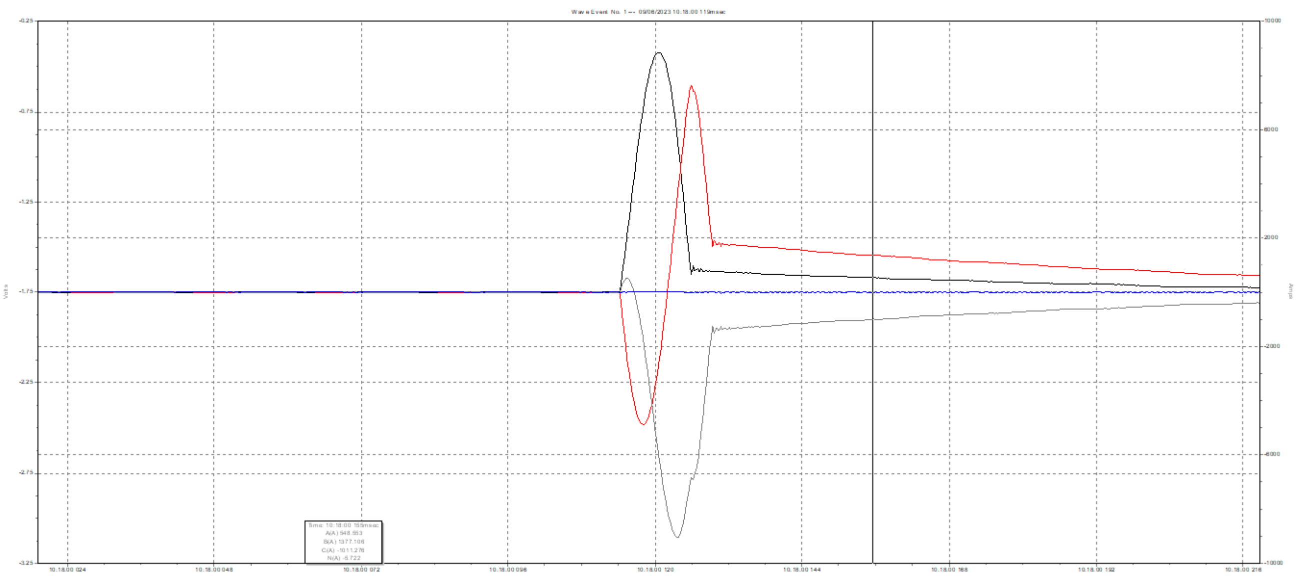


Figure 37 – 3 phase fault and resulting current with 315 A fuses [FA_Meas135_ifault]

Outcome: Following the completion of AC faults, the UPFC was tested under AC and DC load conditions to verify the functionality of the UPFC. In the majority of AC fault tests the UPFC was operating in regulation mode prior to the fault. The UPFC went into bypass mode when the fault was detected and voltage regulation was returned (by user selection) following each fault. The UPFC was fully operational after the applied AC fault conditions.

5 S2 UPFC Regression Test Procedure

A revised version of the ERMCO-GridBridge UPFC (termed the S2 unit) was issued to the project with a number of hardware and software refinements. The main revision was in relation to the thermal rating of the components associated with the DC output of the UPFC. Extensive testing was completed by ERMCO-GridBridge in an environmental chamber at a temperature of 40 °C whilst applying the rated AC and DC loading simultaneously. Revisions of the software included a new Graphical User Interface (GUI) and an upgrade to the auto restart function of the UPFC. This section demonstrates that the S2 UPFC meets and exceeds the test capabilities of the S1 UPFC through a full suite of regression tests.

A summary of the S2 UPFC regression tests is outlined in Table 18, the ID number is derived from the integration test carried out in the first phase of the project reported on in section 4.

Table 18: S2 UPFC regression testing summary

ID	Name	Description	Relevant Test Number IDs	Relevant Equipment	PASS/ Status	Notes
4.1	**System start up**	With all the primary equipment de-energised (does not include the 24V DC supply and Nortech LCS), and no faults present on the system, energise the equipment sequentially. This test demonstrates start-up under normal conditions.	1	UPFC, LVDC switchboard, PKM150	PASS	The overall system was shown to start up multiple times under control of the SPEN team. The Nortech LCS panel was fully operational.
4.2	**System shut down**	With all equipment energised, and no faults present on the system, the primary equipment was de-energised (does not include the 24 V DC supply and Nortech LCS). This test demonstrates shutdown under normal conditions.	2	UPFC, LVDC switchboard, PKM150	PASS	The overall system was shown to shut down in a controlled manner on multiple occasions when controlled by the SPEN team.
4.3	**LVDC Switchboard MCCB position**	Turn the LVDC MCCB on and off and check that the MCCB position indicator on the Nortech LCS illuminates correctly.	3	LVDC switchboard	PASS	MCCB was manually switched and the status indication was shown to change on the Nortech LCS.
4.4	**Inter-Trip Test**	To verify the Schneider RN2c is tripped successfully, dedicated inter-trip testing was undertaken. The inter-trip was independently tested to ensure the Schneider RN2c is tripped successfully. To further validate operation before going live, inter-trip functionality was also trialled through applying trip conditions to the UPFC protection circuits (i.e. fault in the small zone) or by applying a 24 Volt inter-trip command to the Schneider Electric (SE) RN2c RMU.	4	RN2C RMU and UPFC	PASS	Intertrip demonstrated at the UPFC and via the customer emergency switch on the Nortech LCS in the presence of the SPEN team.
4.5	**DC Functional Test**	Initial functional testing of the UPFC to verify overall operation and facilitate any test setup debugging. The control/communications was setup to ensure normal operation. In the functional test, an EV with a CHAdeMO/CCS2 charging port was connected to the Tritium EV charger which provides the DC load on the UPFC/LVDC switchboard. Data was collected to show start-up, operation and shutdown procedures.	5, 6, 9	UPFC, LVDC switchboard, PKM150	PASS	Reliable and stable operation was observed and there were no thermal constraints while charging three different electric vehicles (Tesla Model 3, Nissan Leaf and Hyundai Kona).

4.6.1	**Solid Pole to Pole Fault**	This fault connects the positive pole (i.e. VSST+) to the negative pole (i.e. VSST-) using the DC fault thrower. This test simulates the shorting of the two poles energised at +/-475 Vdc.	13, 14, 19, 25, 26, 38, 43, 44,47	UPFC, LVDC switchboard, PKM 150 (partial), 14.5 ohm resistive load (complete)	PASS	Auto restore was available throughout the pole to pole fault tests. For faults at location 1 auto restore was attempted then the UPFC shunt tripped the RMU. Location 2 and 3 faults led to an MCCB trip on under voltage which isolated the UPFC output terminals and allowed auto restore to operate.
4.6.2	**Solid Pole to Earth Fault**	The solid pole to earth fault tests are low resistance, as the connection is made by a solid copper bus bar. Due to asymmetry in the under-voltage relay protection scheme in the LVDC switchboard, the solid pole to earth test must be undertaken with a fault connecting the positive pole to earth and the negative pole to earth. The test confirms the trip time and to check whether the asymmetry has a material impact on the operation of the protection scheme.	12, 15, 16, 17, 18, 23, 24, 28, 29,30,31,32,33, 34,35,36,37, 38	UPFC, LVDC switchboard, 14.5 ohm resistive load (complete)	PASS	The full suite of pole to earth faults were applied in the three defined locations. Faults at location 1 led to an attempted auto restore then shunt trip. Faults in location 2 and 3 led to an MCCB trip on under voltage which enabled auto restore to operate on the UPFC. The PKM 150 EV charger was included for 2 pole to earth faults at location 1 and one fault at location 2. With the EV charger in circuit the pole which did not experience a fault had a rise in voltage >1000 Vdc and this takes some time approx. 1 minute to decay to a point where auto restore can be attempted. Grid Bridge successfully

						implemented a firmware update for the fault at location 2 to demonstrate successful auto restore.
4.6.3	**Solid pole to midpoint fault**	The solid pole to midpoint fault places a short from the positive/negative rail to the neutral connection, where it is available.	21, 22	UPFC	PASS	The pole to midpoint faults were applied at the incomer on the LVDC switchboard. Following the fault, auto restart was attempted but due to the fault still present the RMU was shunt tripped.
4.7	**Witness tests**	As a part of the system demonstration and testing, members of the LV Engine team was present to witness some of the functional and fault testing being undertaken.	No data recorded	Walk round of all key items and SPEN representative onsite for all testing	PASS	A large number of key stakeholders were hosted during the test programme, SP Energy Networks, site installation contractors, OFGEM, Falkirk Council, University of Strathclyde and where possible testing was demonstrated to attendees.
4.10	**Bender tuning**	Perform tests at the start up and during EV charging to ensure that the selected Bender settings do not cause spurious/nuisance tripping of the RMU.	Operational throughout testing	Bender RCM	PASS	The behaviour of the Bender relay was monitored throughout the regression testing on the S2 UPFC no adverse behaviour was apparent.

4.11	**Enspec tuning**	Perform trial for tuning the detection threshold of the Enspec protection unit for an onsite trial.	28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38	Enspec external protection unit	PASS	Extensive range of trip testing to ensure both pole to pole and pole to earth faults could be detected. The Enspec unit required that the threshold be set by the user every time that the unit was re-powered (SPEN and user login required). Threshold set at 85 A. There was an issue with detecting pole to earth faults on the negative pole. The resolution was to install the CTs on the positive and negative poles facing the load. Installer guidance document will need revised to match this orientation.
4.12	**Voltage regulation**	The Voltage regulation function of the UPFC enables voltage control on a per phase basis. Testing was conducted under the three scenarios; the presence of a balanced AC load, a DC load and an imbalance on a selected phase (phase A)	7, 8, 10, 12, 40, 41, 48	UPFC	PASS	UPFC voltage control was demonstrated on a per phase basis. Additionally, the phase voltage was controlled to ensure the end customer (load bank) received the required voltage under unbalanced load conditions. It was possible for the user to set the voltage setpoint outside the (-6%/+10%) operational limits for UK DNOs.

4.13	**Power Sharing**	The power sharing function enables load to be shared between the UPFC and a neighbouring transformer on the same feeder. The UPFC version being tested did not have the final power sharing control function enabled. However, power sharing can be verified by manually adjusting the AC voltage set point. This test case demonstrates the adjustment of LV voltage setpoint at the UPFC so that the overall LV load can be shared between UPFC and the neighbouring transformer.	50, 51, 52, 53, 54, 55	UPFC	PASS	Full suite of testing conducted with the UPFC fed by a 500 kVA transformer and sharing and AC load with a 315 kVA transformer. Tests were initially conducted in bypass mode then voltage regulation was applied. The voltage setpoint was varied to alter the contribution of each transformer to the AC load. DC loading was also applied to the UPFC. The power sharing function was successfully demonstrated.

With the S2 UPFC meeting the operational standards of the S1 UPFC, focus in this section will be placed on the upgraded capabilities and revisions to the S2 UPFC. The following subsections focus on the upgrades and areas of further investigation highlighted in the first phase of testing the S1 UPFC. Additional functionality was explored in the form of power sharing tests on the S1 version of the UPFC.

5.1 Bypass Mode

The bypass mode behaviour was explored in a range of test cases in order to investigate the behaviour of the UPFC. The test cases explore behaviour under imbalanced and balanced AC load. Throughout this investigation the load on the AC output of the UPFC was the resistive loadbanks (350 kVA) on the PNDC test network. A load imbalance was created by removing associated fuses from each of the loadbanks.

5.1.1 Bypass Mode with Balanced Load

A balanced AC load was introduced via loadbanks with a maximum load of 227.4 KVA. The load applied by the resistive loadbanks was varied between 84 and 227.4 kVA through the test. The phase voltages at the input and output of the UPFC whilst supplying a balanced AC load is shown in Figure 38.

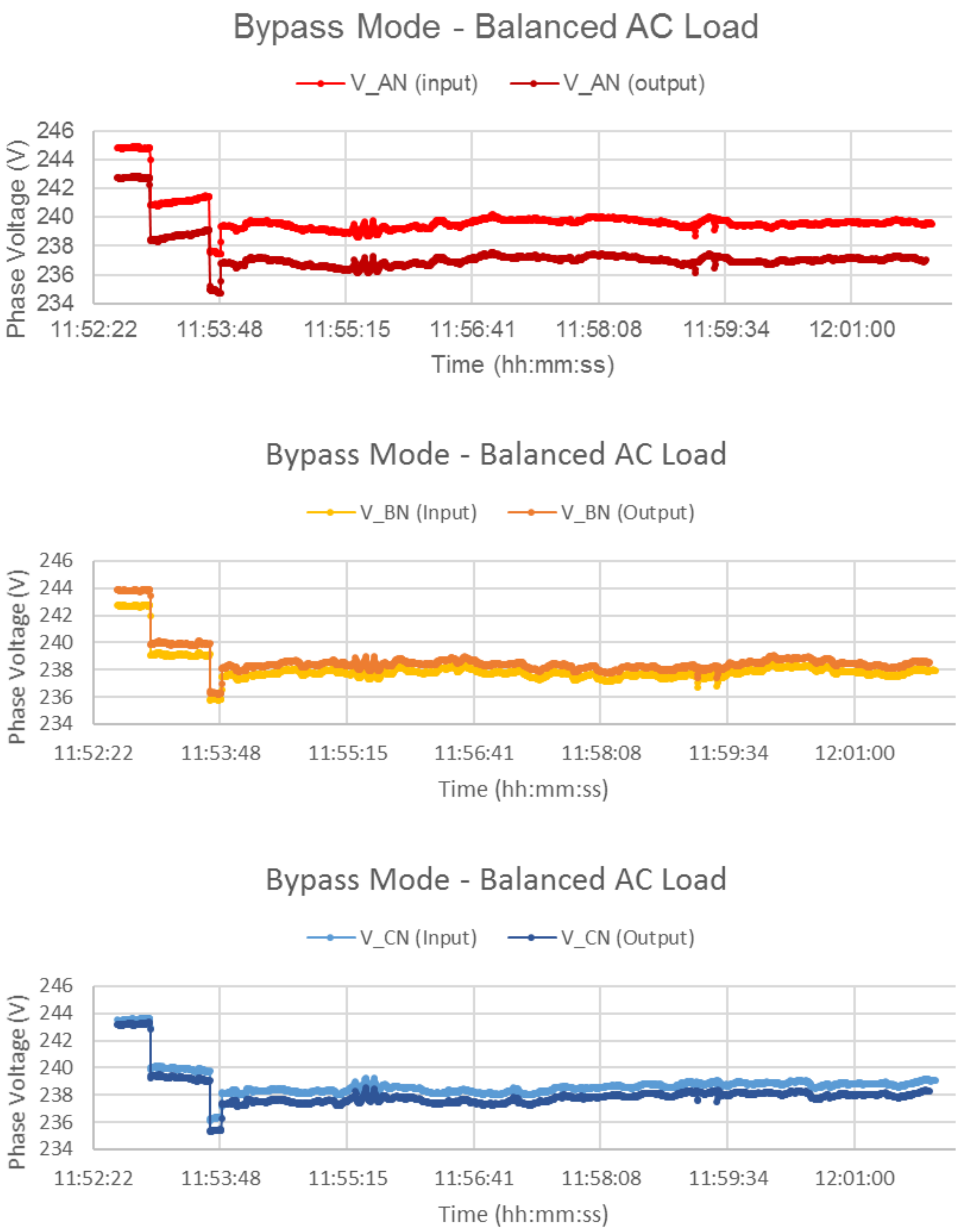


Figure 38 – Phase voltages for bypass mode with a balanced AC load

On phase A the UPFC output was on average 2.52 V lower than the input voltage. The phase voltage on phase B at the UPFC output was 0.66 V higher than the input. On phase C the output voltage was 0.72 V lower than the input voltage.

The THD on the output voltages of the UPFC whilst supplying a balanced AC load is shown in Figure 39.

Take care of the environment.
Printed in black and white and only if necessary.

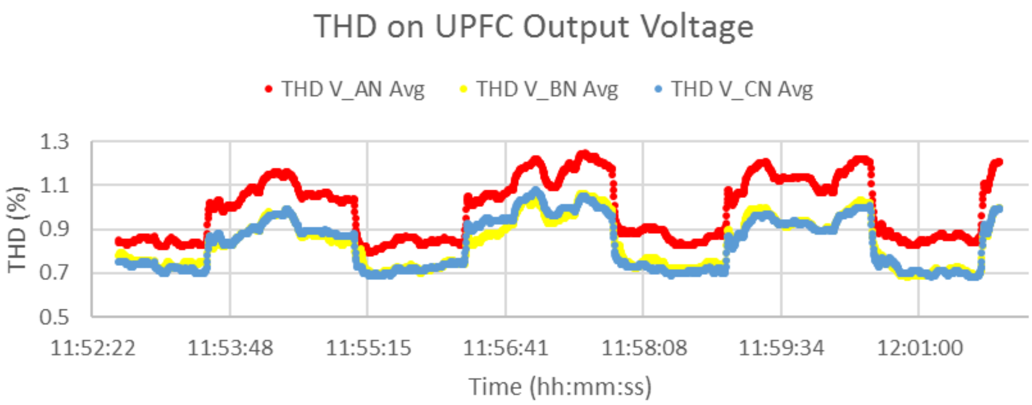


Figure 39 – THD on the output voltage of the UPFC in bypass mode with a balanced AC load

The THD at the output of the UPFC was shown to be below 1.3%.

5.1.2 Bypass Mode with Unbalanced Load

Fuses were removed from the 4 loadbanks used to ensure that the UPFC experienced an unbalanced load. The phase currents at the input of the UPFC are shown in Figure 40.

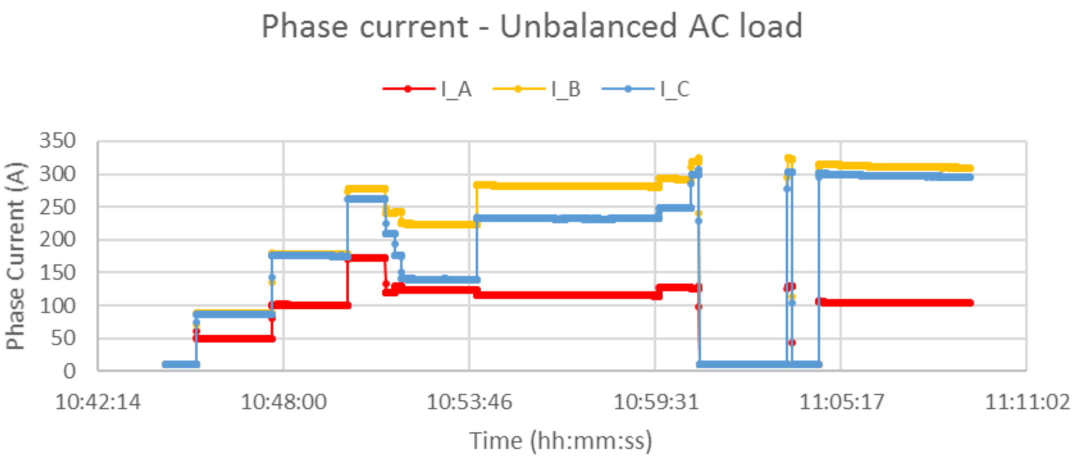


Figure 40 – Phase currents at the input of the UPFC whilst in bypass mode with an unbalanced load

The phase voltages were compared to determine the relative difference between the input and output of the UPFC whilst operating in bypass mode (Figure 41).

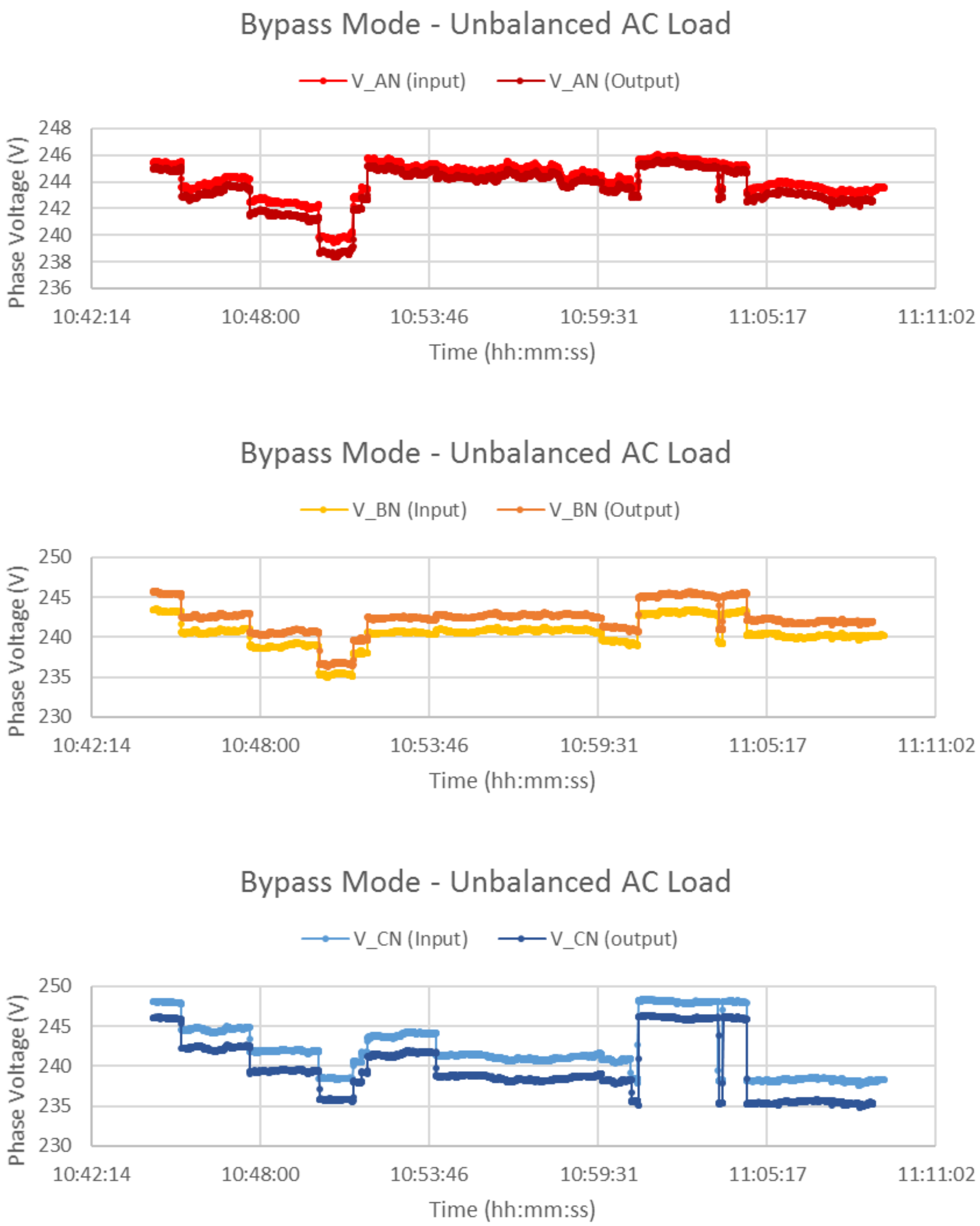


Figure 41 – Phase voltage comparison between the input and output of the UPFC whilst in bypass mode with an unbalanced load

The voltage output on phase A was on average 0.63 V lower than the input voltage. On phase B the output voltage was 1.86 V higher and on phase C the output was 2.47 V lower than the input voltage to the UPFC. The THD on the output voltage of the UPFC whilst in bypass mode and supplying an unbalanced load is shown in Figure 42.

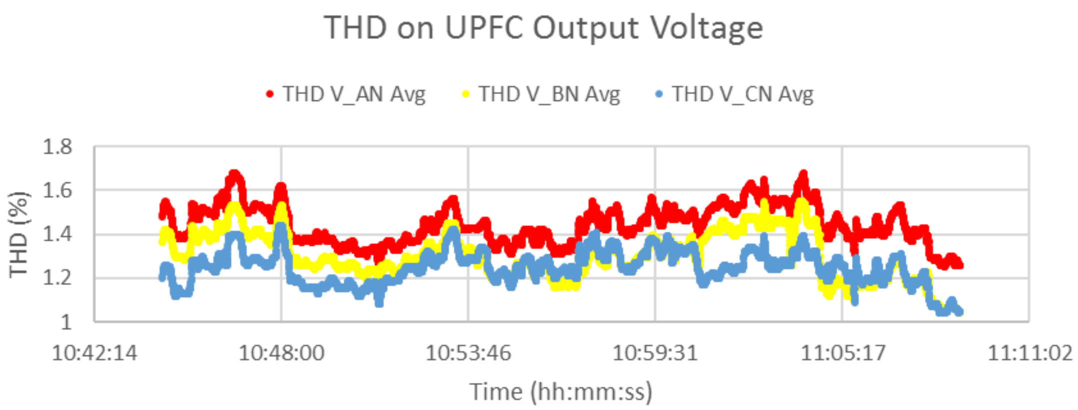


Figure 42 – THD on the UPFC output voltage whilst in bypass mode and when supplying an unbalanced AC load

Throughout the test THD remained below 1.7% well below the threshold of 5%.

Outcome:

The behaviour of the UPFC was considered in more detail, whilst in bypass mode, based on some observations from the testing on the S1 UPFC. Through a range of load conditions the input and output phase voltages were different across the three phases. There was some variability in the voltage difference based on the load applied (marginal change). It must be noted that the polarity of the voltage difference between the input and output remained consistent (Table 19). Both Phase A and Phase C consistently had an output voltage lower than the input. The output voltage on phase B of the UPFC was consistently higher than the input. It can be concluded that when the UPFC was in bypass mode the output voltage of the UPFC does not match that of the input (not a straight through connection). Bypass should be considered as a control mode whereby no voltage regulation is being attempted based on user control but there is a consistent internal voltage variation between the input and output. Knowledge or a note of this behaviour will assist field operation of the UPFC. The THD of the output voltage from the UPFC was also considered when the UPFC was in bypass mode with no load, balanced AC load and unbalanced AC load. THD remained below 1.7% well within the 5% limit from G5/4-1 [7].

Table 19: Voltage difference between the output and input voltage on the UPFC whilst in bypass mode

Scenario	Average voltage difference between UPFC output and the input (V)		
	Phase A	Phase B	Phase C
No Load	-1.69	1.52	-0.05
Balanced Load	-2.52	0.66	-0.73
Unbalanced load	-0.63	1.86	-2.47

5.2 Auto Restore Function

Auto restore was fully demonstrated and operated reliably through the regression testing. There was only 1 glitch during Enspec testing (29/9/23), a positive pole to earth fault was applied at location 3. The expectation was for auto restore to operate but the UPFC shunt tripped instead in test 35.

An example of a successful auto restore following a negative pole to earth fault at location 2 (LVDC switchboard outgoing MCCB) whilst supplying a resistive load (14.5 Ω) is illustrated in Figure 43. During this fault the MCCB trips on under voltage so the DC output of the UPFC is isolated at the LVDC switchboard which removes the fault condition and allows auto restore to be completed successfully.

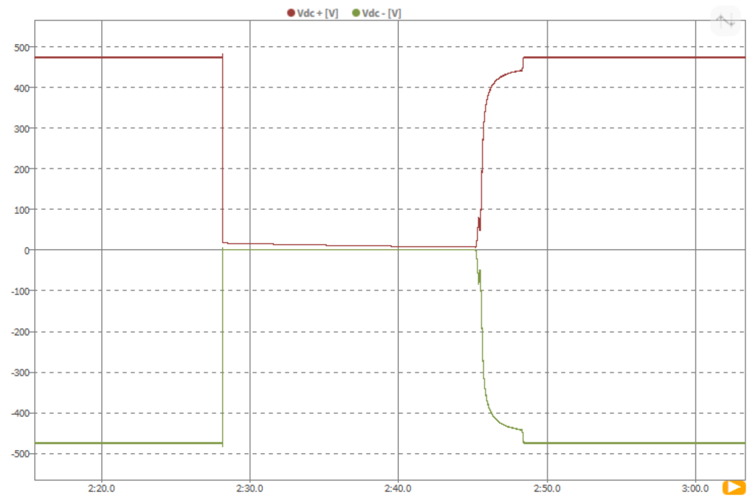


Figure 43 – Pole voltages for a negative pole to earth fault with resistive load (14.5 Ω) with a 10 second auto restore

The plot shows the decay in the positive pole voltage following the application of the negative pole fault. The bleed resistors at the output of the UPFC are employed to drop the voltage on the pole which did not experience a fault. The positive pole voltage had dropped to 7.2 V when auto restore was attempted. The trace also shows the operation of the low voltage check of the UPFC at 48 Vdc, a more detailed view of this event is shown in Figure 44. The voltage of the positive and negative poles then returns to +/-475 Vdc.

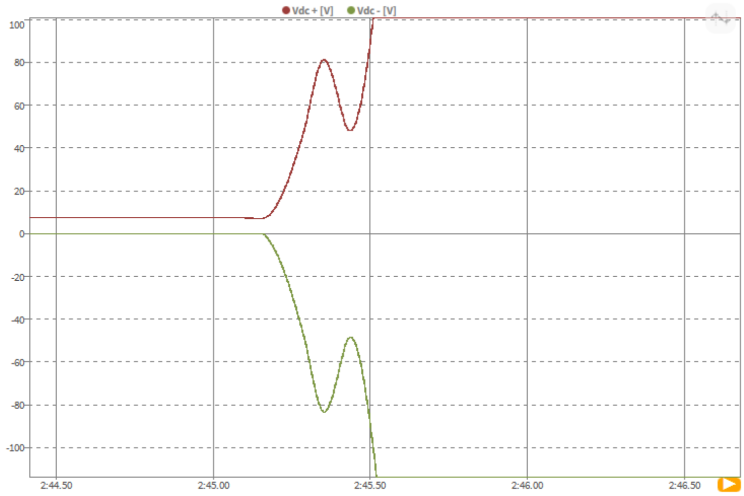


Figure 44 – Auto restore low voltage check

In contrast when the fault was applied at location 1 (LVDC switchboard incomer) the DC fault cannot be isolated and auto restore is attempted then aborted whilst the low DC voltage test is applied. The aborted auto restore for a positive pole to earth fault in location 1 is illustrated in Figure 45.

Figure 45 – Positive pole to earth fault in location 1 (LVDC switchboard incomer) and attempted auto restore and subsequent shunt trip

The plot shows that the low voltage DC test was applied to the negative pole but as the positive pole still had a short to earth so no potential could be applied on the positive pole. This condition resulted in auto restore being aborted and the UPFC sent a shunt trip signal to the ring main unit.

Outcome: The auto restore function of the S2 UPFC was demonstrated following the application of positive and negative pole to earth faults inside and outside the fault small zone of the UPFC. When the fault was inside the small zone (location 1) the auto restore was aborted when the low voltage of 48 V was applied to the two poles. When outside the small zone (location 2 and 3) auto restore was reliable and the user could configure the time delay for auto restore to be attempted following a DC fault.

5.3 AC and DC Load Testing

In phase 1 of testing, the S1 UPFC had a thermal limit on the DC output, thus DC loading was restricted in terms of the load duration (15 minutes). Internal revisions and a significant amount of testing was concluded prior to the S2 unit being shipped to PNDC for regression testing.

The AC and DC load testing considered the supply of resistive load banks on the PNDC test network and the Tritium PKM 150 EV charger. The charger was connected to three different electric vehicles, the general test setup is shown in Figure 46.

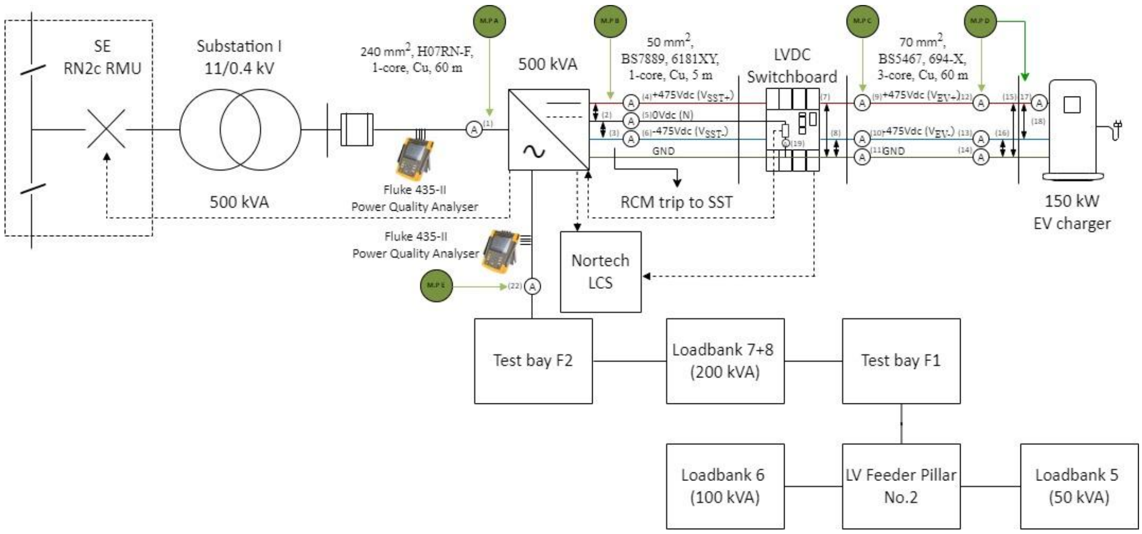


Figure 46 – UPFC supplying the Tritium PKM 150 kW EV charger and the PNDC loadbanks

During this test the PNDC loadbanks (5, 6, 7 and 8) were configured as an unbalanced load by removing selected fuses to alter the loading across the three phases. The setpoint on the loadbanks was 182 kVA with a power factor of 0.62. The AC output of the UPFC was being regulated at 240 V across all three phases. The applied phase voltage and phase current are shown in figures Figure 47 and Figure 48.

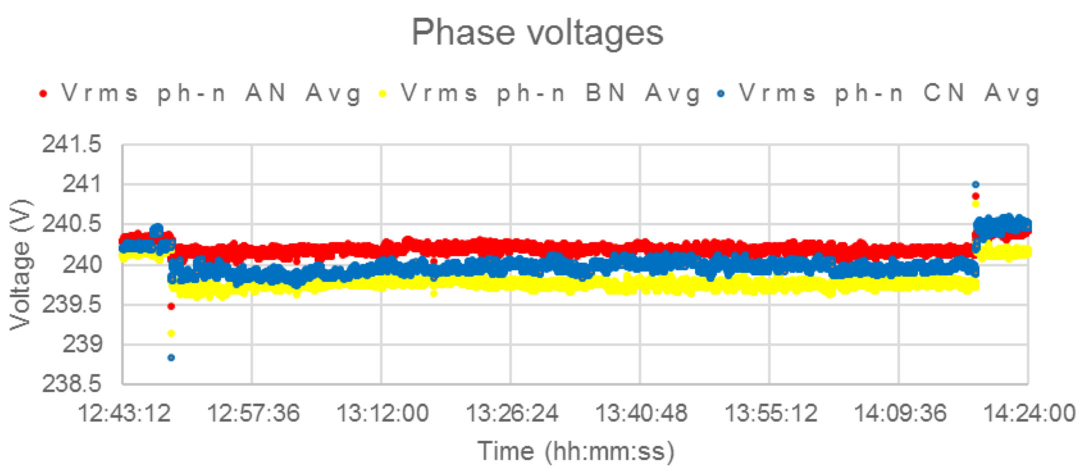


Figure 47 – Phase voltages with regulation at 240 V per phase

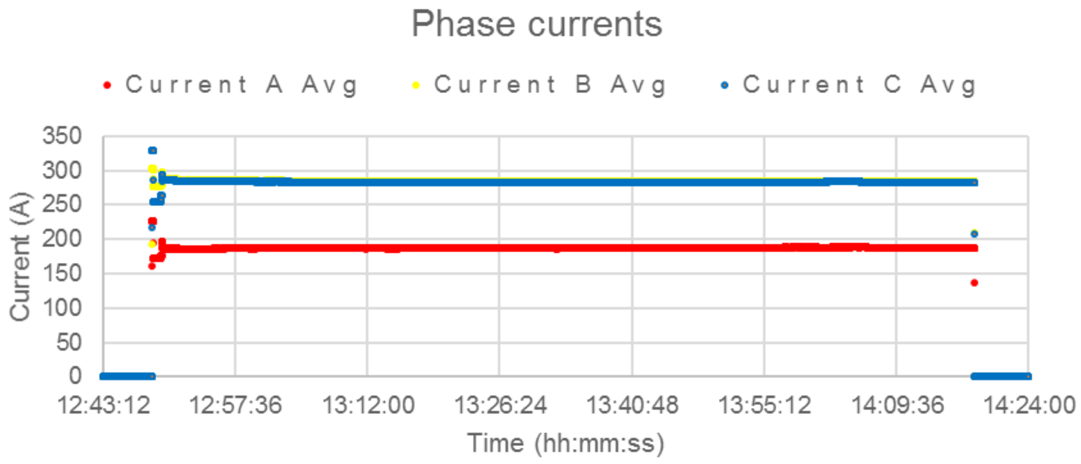


Figure 48 – Phase currents on the AC unbalanced load and PF=0.62

The total Harmonic Distortion (THD) at the output of the UPFC is illustrated in Figure 49.

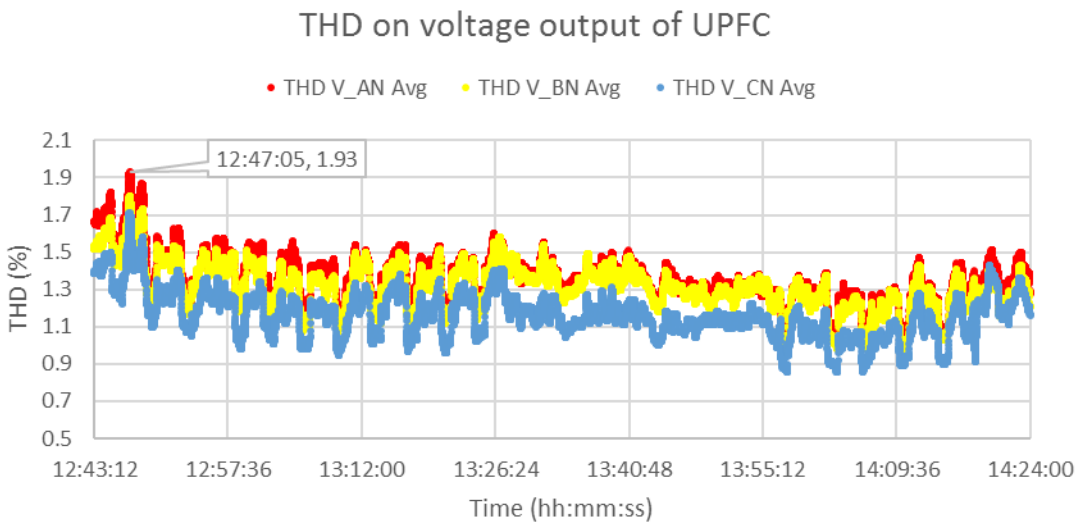


Figure 49 – THD of the output voltage from the UPFC for an AC unbalanced load and PF=0.62

The plots show that the THD remained below 2% throughout the period that the EVs were charging and whilst the UPFC was supplying an unbalanced AC load. The THD planning limits for LV are 5% according to G5/4-1 [7]. The testing with EV charging considered 1 hour 30 minutes of charging 3 EVs fully with AC loading simultaneously. Previously 20 minutes of EV charging was tested on the S1 UPFC. The PKM 150 was employed to charge three electric vehicles. The vehicle model, battery capacity, start percentage, end percentage and peak charging rate displayed on the charger are outlined in Table 20.

Table 20: Vehicles charged by the PKM 150 whilst supplied by the S2 UPFC

Electric Vehicle	Battery capacity (kWh)	Start percentage (%)	End percentage (%)	Peak charging rate (kW)
Nissan Leaf	30	16	98	46.2
Tesla Model 3	100	42	96	83.6
Hyundai Kona	64	16	90	75.8

The load current on the charger during the charging sessions is shown in Figure 50.

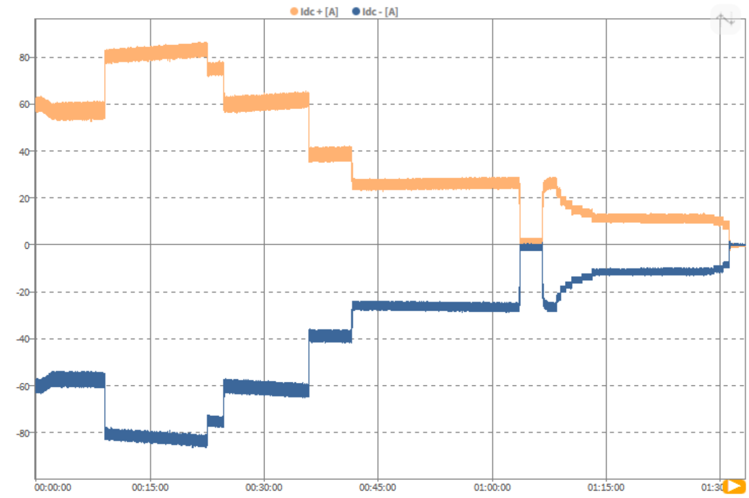


Figure 50 – Load current during charging session with Nissan leaf, Tesla Model 3 and Hyundai Kona

The pole to pole voltage during the EV charger session is shown in Figure 51.

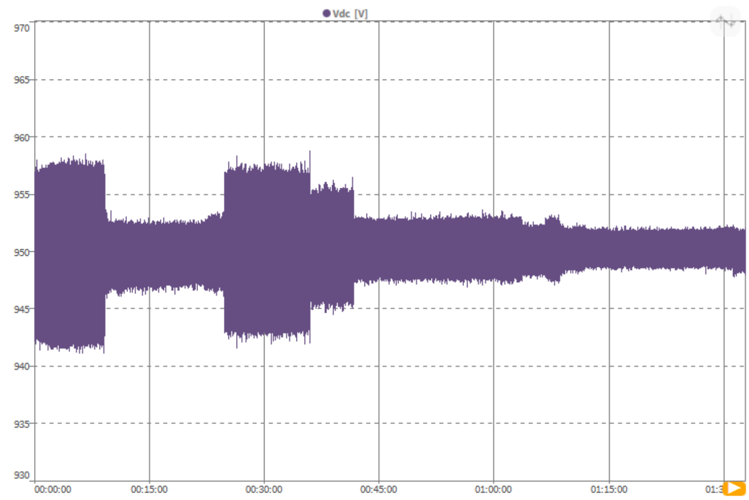


Figure 51 – Pole to pole voltage for the EV charging session

The model 3 and leaf were initially connected to the PKM150, the charging rate of the model 3 was limited to 75 kW over the first minute. With the leaf disconnected the charge rate of the model 3 increased to 83.6 kW this rate gradually tapered to 71.8 kW. After 9 minutes the leaf was reconnected to the PKM 150, and the leaf drew 46.2 kW from the charger. Both cars had a gradual taper in charge rate until 1 hour 3 minutes into the charging session, at this point the two vehicles were disconnected. After some downtime, the kona was connected 1 hour 6 minutes into the session and remained connected until the car automatically disconnected from the charger at 90% SOC, over this time the charge rate tapered.

Outcome: The S2 UPFC successfully performed 1 hour and 30 minutes of charging in one session with no thermal warnings apparent. Additionally, the UPFC was also supplying an AC imbalanced load throughout this charging session. The design revisions to the S2 UPFC have removed the previous thermal constraints that were apparent in the S1 UPFC. The maximum DC power draw was ~120 kW whilst the Tesla model 3 and Nissan Leaf were simultaneously charging. With the current configuration the S2 UPFC should be fit for site deployment where it will be supplying a single PKM150 EV charger and is likely to see regular charging sessions due to the increased capacity available on the 150 kW EV charger. It is believed that the existing fleet of EV chargers at Falkirk Football stadium have a capacity of 50 kW.

5.4 DC Faults with EV Charger

In phase 1 of integration testing on the S1 UPFC the main issues observed during DC fault testing were related to damage caused to the EV charger. The damaged components were the DC-DC converter (950-24 V) and the welding of the DC contactors. An external 24 V power supply was in place and easy to access cable tails were wired to the contact trigger (to bounce the contacts if welding was apparent) as the contactors were not easily accessible.

The DC faults were applied in locations 1 and 2 as illustrated by the red labels on Figure 52. The PKM 150 EV charger acted as the load whilst charging a 30 kWh Nissan Leaf. Location 1 is at the incomer to the LVDC switchboard. This represents a fault inside the small zone of protection where the fault is not isolated by the protection housed in the LVDC switchboard. When a fault is present at the incomer the protection is unable to isolate the fault, the UPFC should attempt auto restore, detect current present due to the permanent fault, shut down then shunt trip the RMU. Location 2 is on the outgoing terminals of the LVDC switchboard. The protection in the LVDC switchboard should act to isolate the fault, allow the auto restore function of the UPFC to operate and return the output of the UPFC to +/-475 Vdc. A Dewetron portable power analyser was also employed in this phase of testing to measure the pole to midpoint voltages, fault current contribution of the UPFC and EV charger. The main benefit of the Dewetron was an enhanced sampling rate of 100 kHz during the applied faults with the EV charger in circuit.

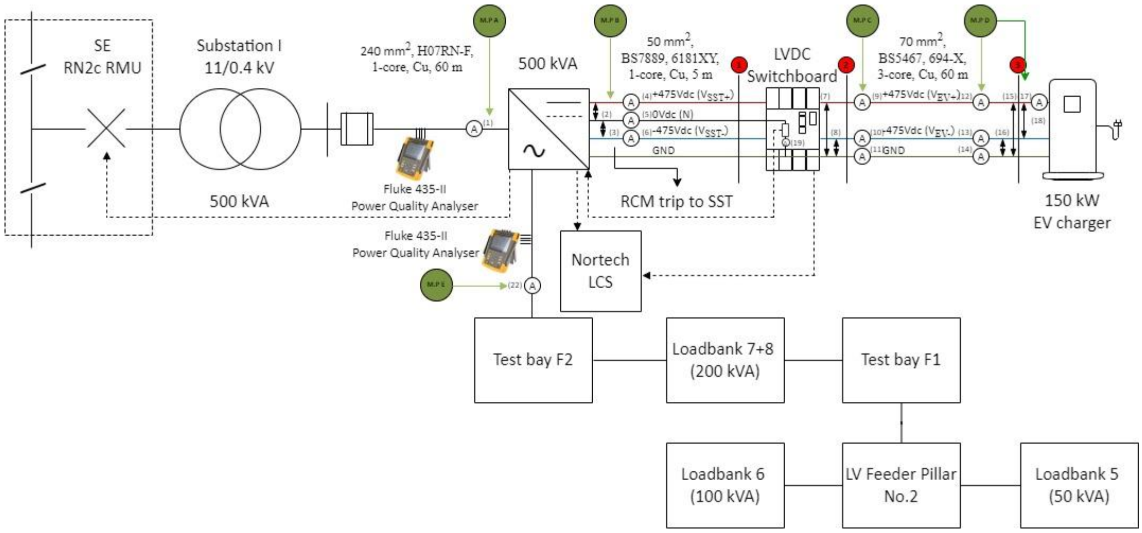


Figure 52 – Test circuit for pole to earth faults on the UPFC with the EV charger in circuit

5.4.1 Pole to Earth Location 1

Two pole to earth faults were applied at location 1 with the Tritium PKM 150 EV charger charging the Nissan Leaf. In both cases the fault was applied at the incomer to the LVDC switchboard. When the fault was applied the MCCB in the LVDC switchboard trips on under voltage and isolates the EV charger from the S2 UPFC. The auto restore function on the UPFC should operate post fault but if current is present during the low voltage test (48 Vdc) then the UPFC will shut down and shunt trip the RMU as a fault is present. In both faults, the auto restore function was not attempted. The voltage at the output of the UPFC during the second negative pole to earth fault at location 1 is shown in Figure 53.

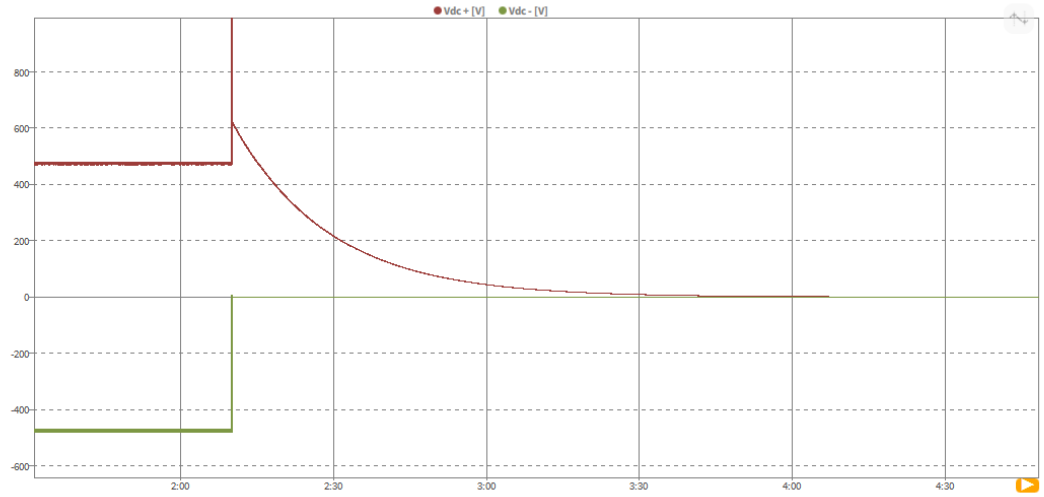
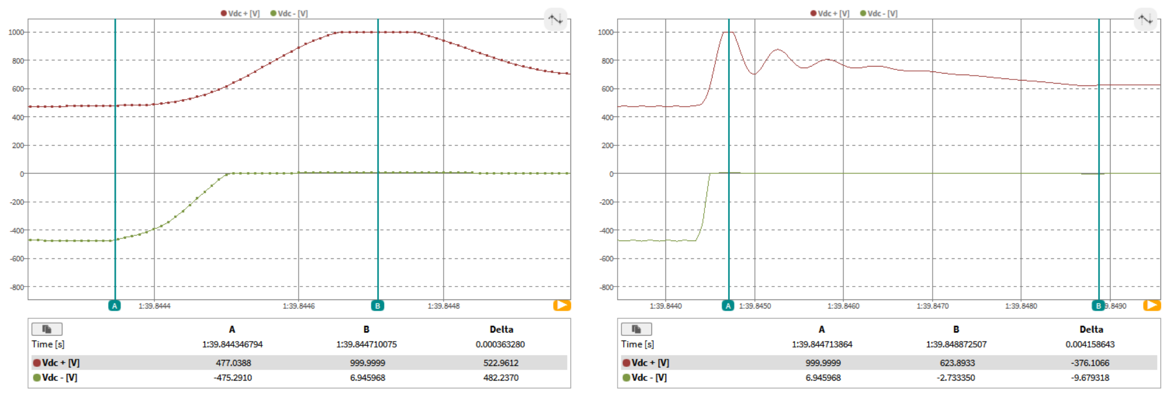


Figure 53 – Pole voltages at the output of the UPFC during a negative pole to earth fault with the EV charger in circuit [Attempt 2]

The voltage of the positive pole, which did not experience a fault, increased to more than1000 Vdc (reading clipped due to voltage threshold of measurement apparatus). There was no attempted auto restore and the RMU was shunt tripped by the UPFC control. The fault at location 1 was repeated and the same behaviour was observed. The overvoltage was clipped at 1000 V and a best fit polynomial (power of six) resulted in a turning point of 1027.2 Vdc. The rise time and setting time of the overvoltage event was analysed as shown in Figure 54.



	A	B	Delta
Time [s]	1:39.844346794	1:39.844710075	0.000363280
Vdc + [V]	477.0388	999.9999	522.9612
Vdc - [V]	-475.2910	6.945968	482.2370

	A	B	Delta
Time [s]	1:39.844713864	1:39.848872507	0.004158643
Vdc + [V]	999.9999	623.8933	-376.1066
Vdc - [V]	6.945968	-2.733350	-9.679318

Figure 54 – Voltage at the output of the UPFC, Rise time for the over shoot on the positive pole (left) and setting time for the voltage overshoot in the positive pole (right) [Attempt 2]

The positive pole voltage settled at 625 Vdc, the bleed resistor allowed the voltage on the positive pole to decay as illustrated in Figure 55.

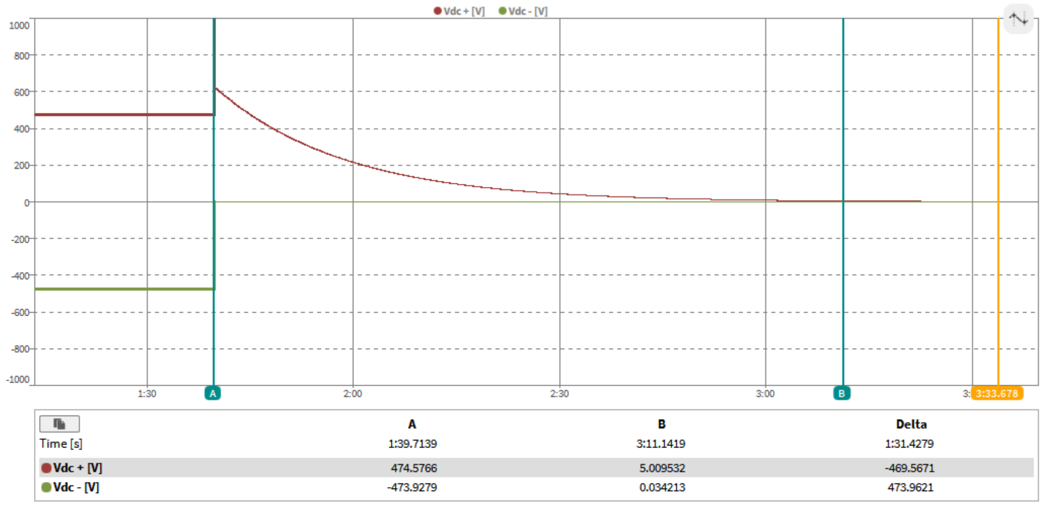


Figure 55 – Positive pole voltage decay via the UPFC bleed resistors [Attempt 2]

The rise time for the voltage overshoot event was found to be 0.000363 seconds and the setting time (to 625 Vdc) for this event was 0.00415 seconds (Figure 54). The time for the bleed resistor to drop the voltage in the positive pole from 625 Vdc to 5 V was 1 minute 31 seconds.

In both of the negative pole to earth faults at location 1 the UPFC did not attempt to perform an auto restore and an immediate shunt trip was completed. Following consultation with ERMCO-GridBridge the UPFC log files revealed that an overvoltage condition had been detected (DC_GRIM_OC_DC_1|DC Grim). An overvoltage fault is triggered when a pole voltage exceeds 500 Vdc and in this case a voltage of 588.165 Vdc was apparent to the UPFC control. In the firmware version tested on the S2 UPFC at location 1 an overvoltage condition leads to an immediate shunt trip on the RMU.

Discussions followed between SPEN and ERMCO-GridBridge with the outcome being the addition of a 3 minute timeout and the overvoltage condition was added to an exception list. These revisions were applied to ensure that when an overvoltage fault was detected there was not an immediate shunt trip. To implement this change a firmware update was devised by ERMCO-GridBridge. It was decided that the best test was to perform a fault at location 2. In location 2 a shunt trip was not expected and auto restore should function as the fault was isolated by the under voltage trip on the LVDC switchboard MCCB. The operation of this firmware update will be discussed in section 5.4.2.

It was also identified that the positive pole voltage was slower to discharge through the bleed resistors (83 kΩ) when the incomer to the LVDC switchboard was closed. When the breaker was closed the under voltage relay was in circuit. The under voltage relay has a 20 kΩ resistance in series with the bleed resistor this resulted in a slower discharge on the positive pole. The circuit diagram of the Schneider panel and the interaction between the positive pole and UVR is outlined in Figure 56.

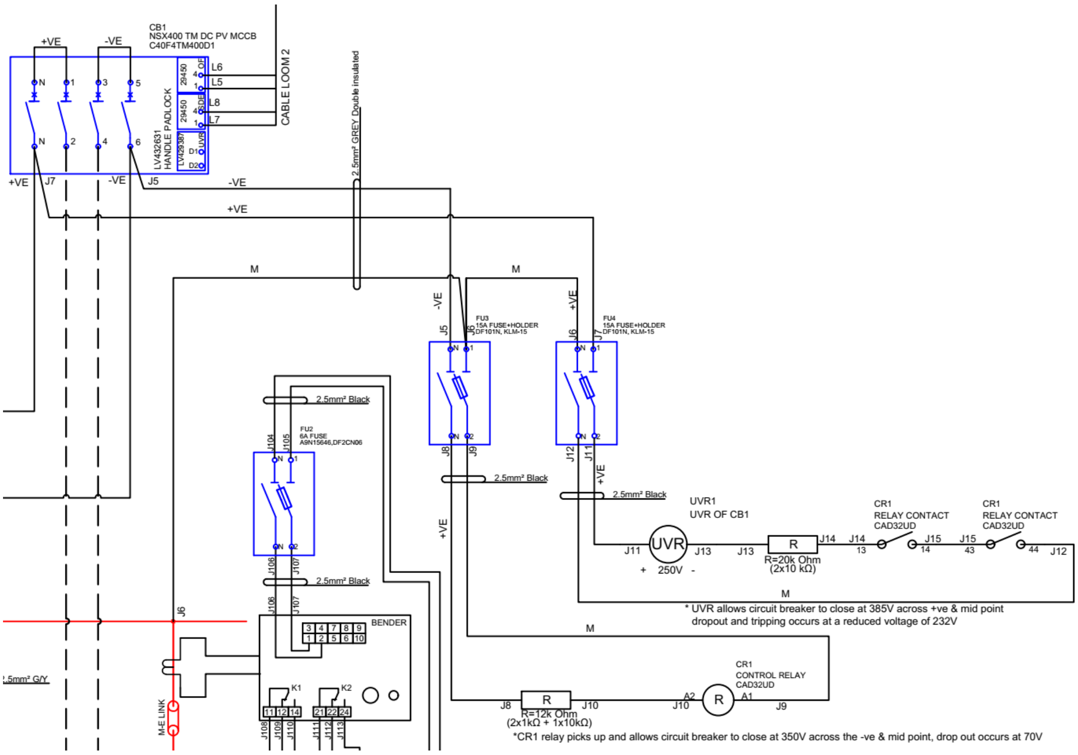


Figure 56 – UVR and series resistance connected between the positive pole and midpoint

The fault current apparent during the two negative pole to earth faults in location 1 was also considered. The largest fault current was apparent on the negative pole. The fault current recorded for the first negative pole to earth fault at location 1 is shown in Figure 57.

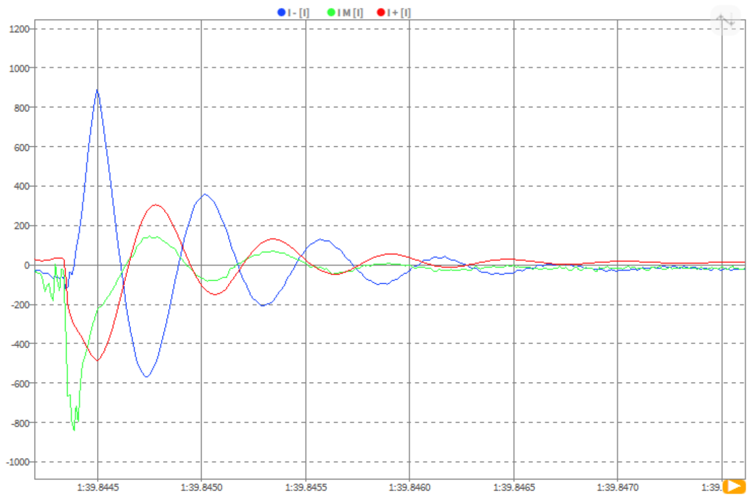


Figure 57 – Fault current recorded at the UPFC output for the negative pole to earth fault at location 1 [Attempt 1]

The fault current contribution from the EV charger is shown in in Figure 58.

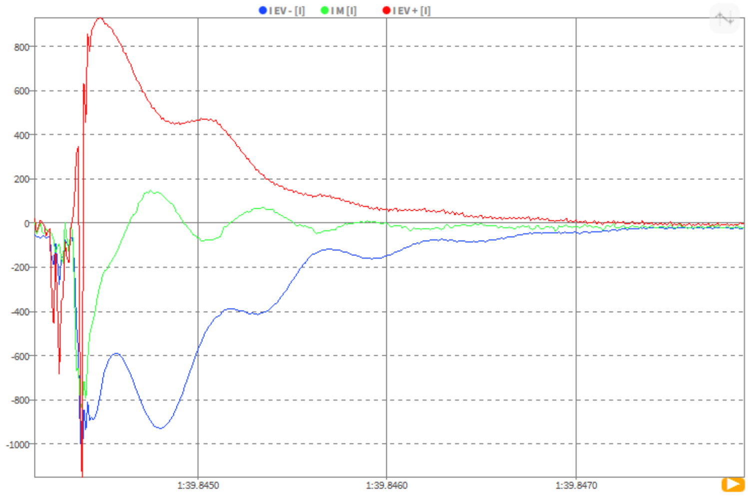


Figure 58 – EV charger fault current contribution [Attempt 1]

The EV charger fault current has a short duration pulse with an elevated magnitude and the peak aligns across the two poles and midpoint. There are slower duration oscillations in fault current until the current settles (0.00282 seconds). The fault current contribution of the EV charger was higher than that of the UPFC in location 1. The rise time was significantly shorter for the EV charger fault current and the settling time was very similar for both the EV charger and UPFC. The fault current recorded in the second negative pole to earth fault at location 2 is shown in Figure 59.

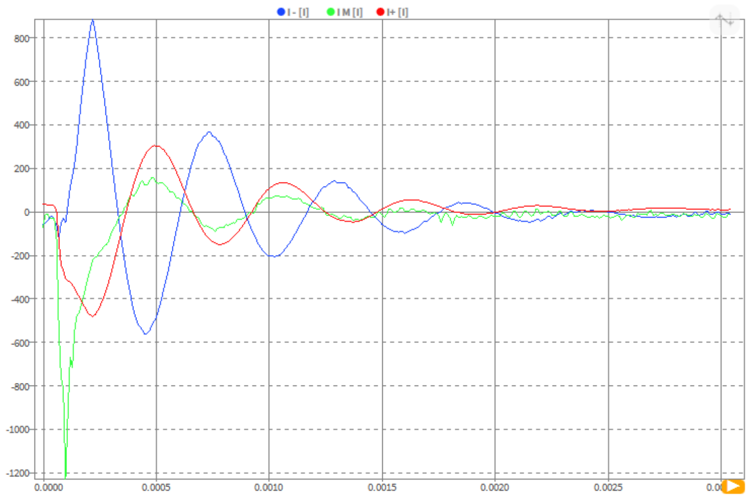


Figure 59 – Fault current for the second negative pole to earth fault at location 1 [Attempt 2]

The fault contribution of the EV charger is shown in Figure 60.

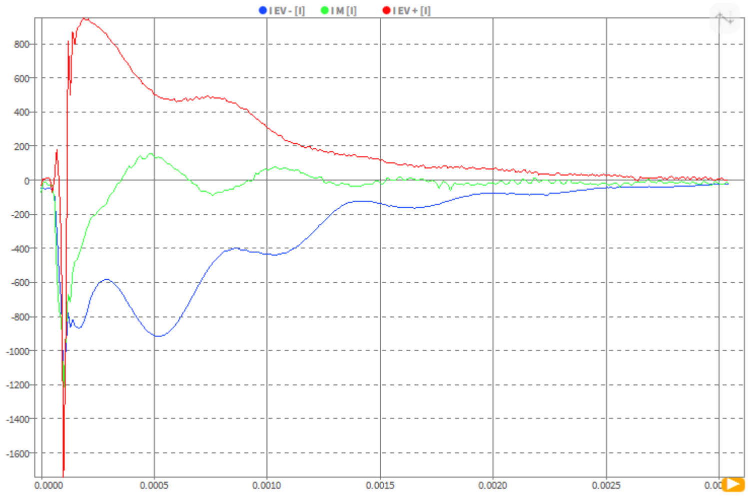


Figure 60 – Fault current contribution from the PKM 150 [Attempt 2]

The fault current contribution of the UPFC was 890 A on the negative pole. The fault current on the positive pole was 485 A. The EV charger fault current had an impulse disturbance with peaks of 1150 A on the negative pole, up to 1740 A on the positive pole and a maximum of 1230 A on the midpoint. The fault current behaviour for the two pole to earth faults at location 1 are summarised in Table 22. Following the application of the two negative pole to earth faults the function of the UPFC was confirmed by applying an AC and DC load. The UPFC control was also verified by operating in bypass and voltage regulation mode.

5.4.2 Pole to Earth Location 2

One negative pole to earth fault was applied at location 2 (LVDC switchboard out going terminals). The S2 UPFC had a firmware update prior to applying the fault at location 2 to ensure that auto restore could be demonstrated with the EV charger in circuit. The firmware update included the addition of a 3 minute wait period for the pole voltage to drop to an acceptable level (15 Vdc previously observed) and the overvoltage condition was added to the exception list. If the pole voltage did not drop below the threshold within the wait period then the UPFC would shunt trip. The expectation from the firmware update was that the wait period would provide a suitable window for the pole voltage to drop (via the UPFC bleed resistors) following the overvoltage condition on the pole which did not experience a fault. A fault at location 2 triggers the under voltage protection on the MCCB at the incomer of the LVDC switchboard which enables the permanent fault to be isolated and the UPFC auto restore to be successful. The objective of this revision was to confirm that the UPFC could auto restore after a negative pole to earth fault at location 2. The pole voltages during the negative pole to earth fault at location 2 is shown in Figure 61.

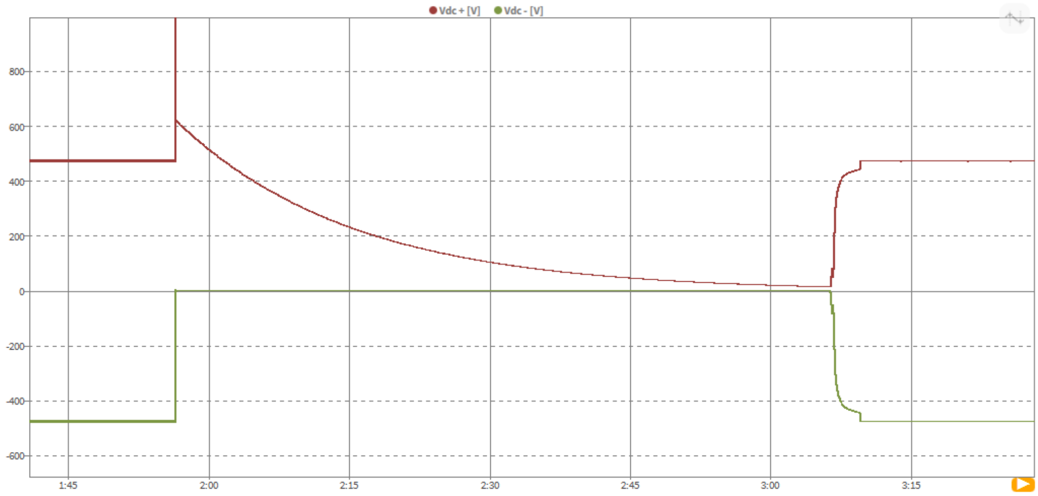


Figure 61 – Negative pole to earth fault at location 2

The fault was applied and the UPFC successfully auto restored after a 1 minute 9 seconds. This proved that the firmware revision was successful and that no adverse behaviour was observed. Analysis of the rise and fall times on key segments of the UPFC terminal voltages are shown in Figure 62.

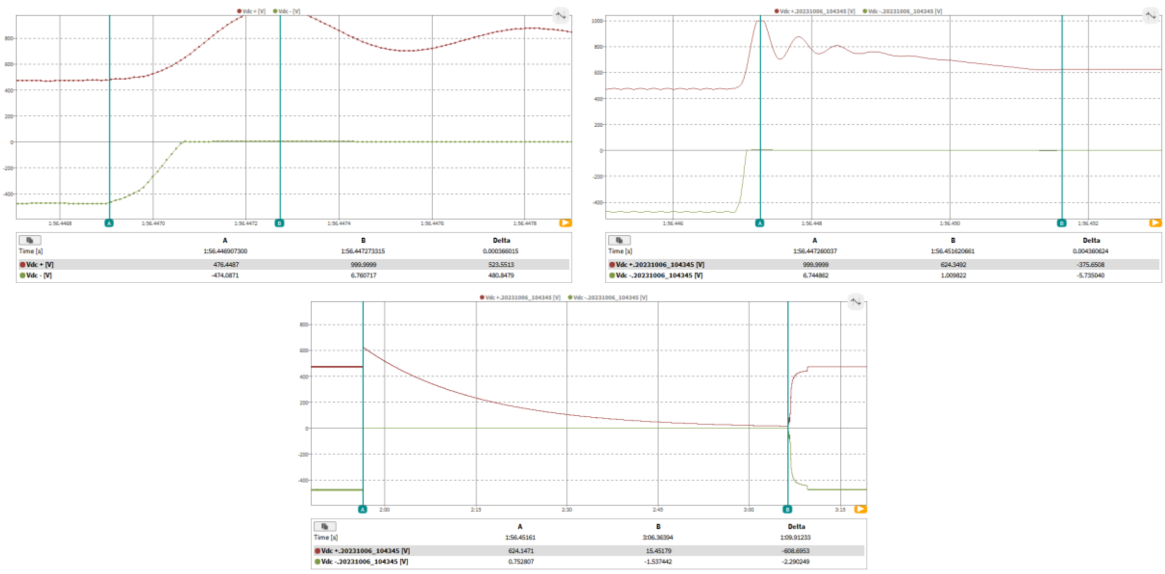


Figure 62 – Voltage rise time on the positive pole (upper left) decay time to 625 V on the positive pole post fault (upper right) and decay time from 625 V to 15.45 volts prior to auto restore operating (lower)

All observed behaviour matches the expectation and the firmware update was effective in ensuring that auto restore could be attempted and completed for a negative pole to earth fault at location 2. The fault current observed at the UPFC output is shown in Figure 63.

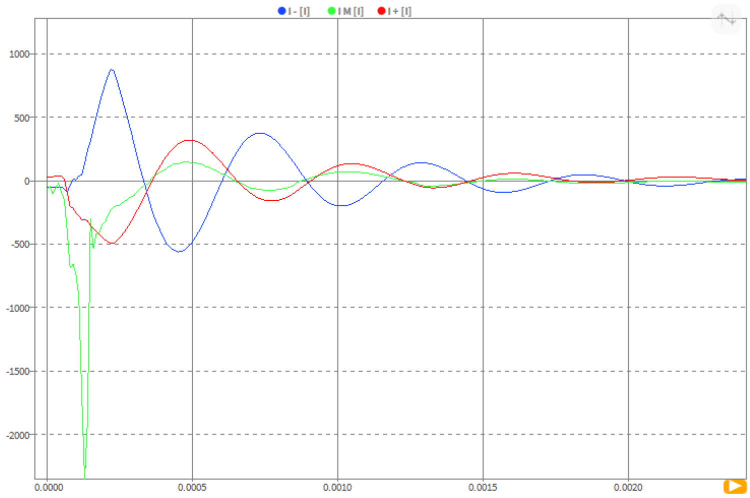


Figure 63 – Fault current contribution of UPFC for a location 2 –P to earth fault

The peak current on the negative pole was 874.5 A, positive pole current was lower at 491.7 A and the current on the midpoint had a peak of 2.3 kA. The midpoint current is higher as it contains the contribution of the UPFC and charger. The contribution from the EV charger is illustrated in Figure 64.

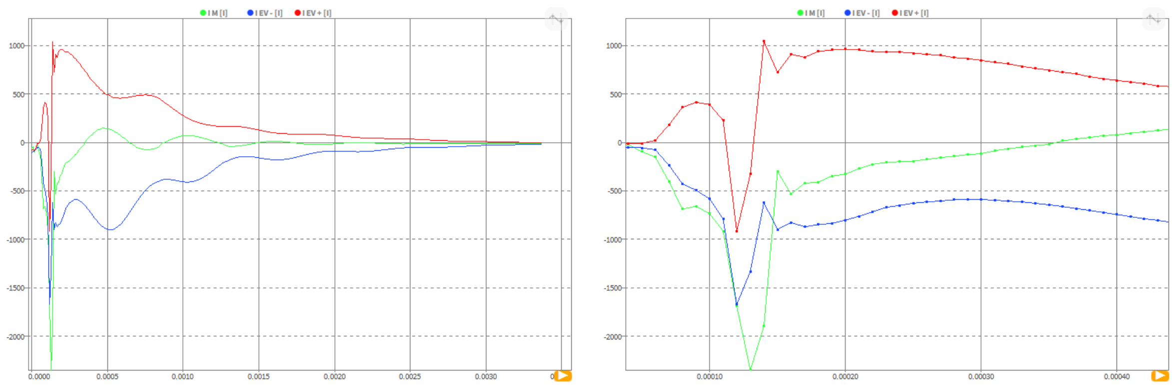


Figure 64 – Fault contribution of EV charger for a fault at location 2; overall behaviour (left) and detailed view of impulse (right)

The fault current from the EV charger had an impulse disturbance and a slower oscillation. When considering the impulse, the current on the positive pole from the EV charger had a peak value of 915.4 A and on the negative pole a peak fault current of 1671.7 A was detected. The peak midpoint current was 2348.5 A, this peak value was at 9 µS after the impulse event on the positive and negative poles.

Functional tests of the UPFC and the EV charger was completed after the applied fault. The 30 kWh Nissan Leaf was charged from 9% to 98% in a 30 minute charging session. A 215 kVA balanced AC load was applied on the AC output of the UPFC. No issues were observed during these functional checks.

Outcome (all DC faults on S2 UPFC): The DC faults applied during the regression testing of the S2 UPFC considered negative pole to ground faults with the EV charger in circuit. The DC faults were applied at location 1 and 2 whilst charging a 30 kWh Nissan Leaf and AC load via resistive loadbanks. Following the application of each fault the functionality of the UPFC and EV charger was proven.

The pole to earth faults at location 1 were explored first. The voltage on the pole which did not experience a fault rose above the nominal 475 V. The final voltage achieved was above the 1000 V detection threshold of measurement apparatus but a best fit value of 1027.2 Vdc was calculated. After each pole to earth fault at location 1 the UPFC did not attempt an auto restart. The overvoltage on either pole triggered an overvoltage alarm (>500 Vdc) and immediate shunt trip of the ring main unit. Based on the observed behaviour a firmware update was devised to include a maximum wait period in the UPFC control for the voltage of the positive pole to drop to an acceptable level (15 V) in order for auto restore to be attempted. The expected result for location 1 faults was; apply the fault, trip the MCCB on under voltage, UPFC to attempt auto restart, UPFC detects that the fault is still present and shunt trip the ring main unit. The inactive auto restart function post fault was caused by the voltage rise on the positive pole of the UPFC (pole with no fault). The voltage rise was anticipated from University of Strathclyde (UoS) modelling [2] but was not on the UPFC exception list in the firmware version on S2 UPFC. The main issue with this behaviour would have been evident at all other fault locations (outside the small zone). The design decision to uprate the voltage of the output capacitors of the UPFC based on UoS simulations was also vindicated.

Prior to applying the negative pole to earth fault at location 2, a firmware update was completed. The firmware update included the addition of the overvoltage condition to the exemption list and a 3 minute maximum wait period in order to allow the S2 UPFC auto restore to function. These revisions were successful. The UPFC was shown to auto restore once the fault was isolated and when the positive pole voltage dropped to 15 V (via the UPFC bleed resistors). The time duration for this decay of voltage in the positive pole was 1 minute 10 seconds. The voltage and current behaviour for the three faults at the two locations are summarised in Table 21 and Table 22.

Table 21: Voltage behaviour during faults with EV charger in circuit

Fault	V_+ (V)	V_- (V)	V+ PK Rise time (s)	V+ PK Fall time to 625 V (s)	V+ discharge period 625 V to 5 V (min:ss.ss)
-P to E location 1 [Attempt 1]	>1000	0	0.000363	0.00415	1:31.43
-P to E location 1 [Attempt 2]	>1000	0	0.000365	0.00449	1:30.54
-P to E location 2	>1000	0	0.000366	0.00436	1:09.91

Table 22: Fault current summary with the EV charger in circuit

Fault type and location	Source of fault current	I_- (A)	I_+ (A)	I_M (A)	Rise time (s)	Fall time (s)
-P to E location 1 [Attempt 1]	UPFC	887.512	-484.79	-233.284	0.00016	0.00270
	EV charger	-1099.667	-1150.58	-840.801	0.000075	0.00282
-P to E location 1 [Attempt 2]	UPFC	885.393	-481.109	-222.158	0.000162	0.00281
	EV charger	-1179.186	-1742.245	-1229.12	0.000065	0.00294
-P to E location 2	UPFC	874.506	-491.684	-226.469	0.000176	0.00278
	EV charger	-1329.006	-327.98	-2348.526	0.000111	0.00315

5.5 Enspec MK2 Testing

The MK2 version of the standalone Enspec fault detection system was deployed on the incomer to the LVDC switchboard. The unit itself was repackaged and a touch screen was added for the user to change threshold settings and reset the unit. The front touch screen of the Enspec MK2 is shown in Figure 65.

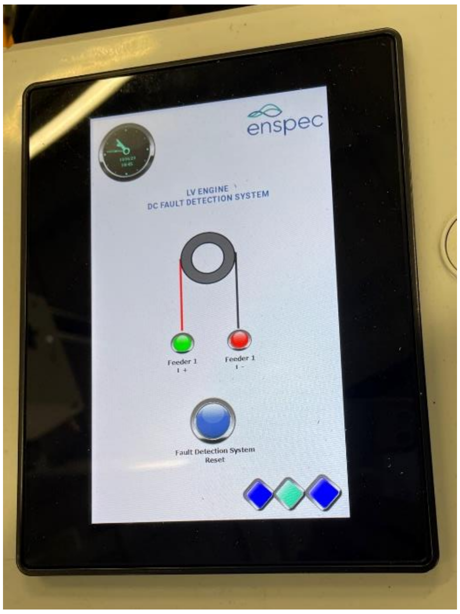


Figure 65 – Enspec MK2 front touch screen

Further revisions to the unit included a reduction in the system overall size with the objective of fitting it inside the LVDC switchboard. The space confines of the LVDC switchboard (with all plastic guards in place) was such that even with the reduced size of the MK2 Enspec unit, it was thought to be challenging to install the Enspec unit inside the LVDC switchboard.

In the MK1 Enspec unit, the threshold values were manually changed by a potentiometer inside the Enspec enclosure. The threshold value on the MK2 unit was set via the touch screen by accessing firstly the SPEN login then separately setting the value for the user account. The full QWERTY keyboard on the touch screen meant that each key was relatively small and finger presses could hit the wrong key. Potentially a stylus or keypad (0-9) passcode could make user interactions easier. An additional observation was that when the Enspec unit was powered down the current threshold values had to be reset. For the PNDC test programme the threshold value of 85 A was set.

The CTs were installed based on the installation guide which stipulates that the positive pole CT must face the load and the negative pole CT should face the source. The observations from the applied changes are outlined in

Table 23.

Table 23: Enspec MK2 observations from setup changes

Positive pole CT orientation	Negative pole CT orientation	Current threshold setting on Enspec GUI (A)	Observation
Facing load	Facing source	85	Faults detected on the positive pole no fault indication for negative pole faults
Facing load	Facing source	50	Unit detecting fault during the power up of the UPFC. Reset prior to applying faults. The faults were detected on the positive pole no fault indication for negative pole faults.
Facing load	Facing load	85	Consistently detecting the faults and no false detections during normal load conditions

Pole to earth faults were applied and the CT on the positive pole detected positive pole to earth faults fine. The negative pole to earth faults were not being detected by the CT on the negative pole. Following consultation with Enspec the threshold value was reduced. When the direction of the negative pole CT was reversed so it faced the load, this revision enabled the pole to earth faults to be detected. Alternatively swapping the S1/S2 cabling from the CT would also correct this detection issue. It was not clear if this was a wiring fault or an error in the installation guide.

Once the Enspec unit was successfully detecting faults, attention changed to the trip confirmation output from the Enspec unit. The ABB KC6-22Z 24 V relay which was driven by the PLC in the Enspec unit was not providing a status change on the normally closed terminals when the trip condition was met. Upon investigation it was found that the installed contactor was a 24 V unit and the PLC output was 12 V. We were unable to get the contactor to respond to 24 V bench tests so we believe the relay was burnt out whilst being driven by 12 V (excessive current in the coil). The 24 V relay was replaced by a 12 V automotive relay from Halfords [8] as it was readily available. In a series of tests the PLC was proven to trigger the contactor and close the normally open contact on the relay for the trip status indication. This alternative relay presents a logic change with a normally open relay replacing the original normally closed. If the normally closed logic is preferred then a revised 12 V relay will be required. The original and revised relay arrangement inside the Enspec unit is shown in Figure 66.

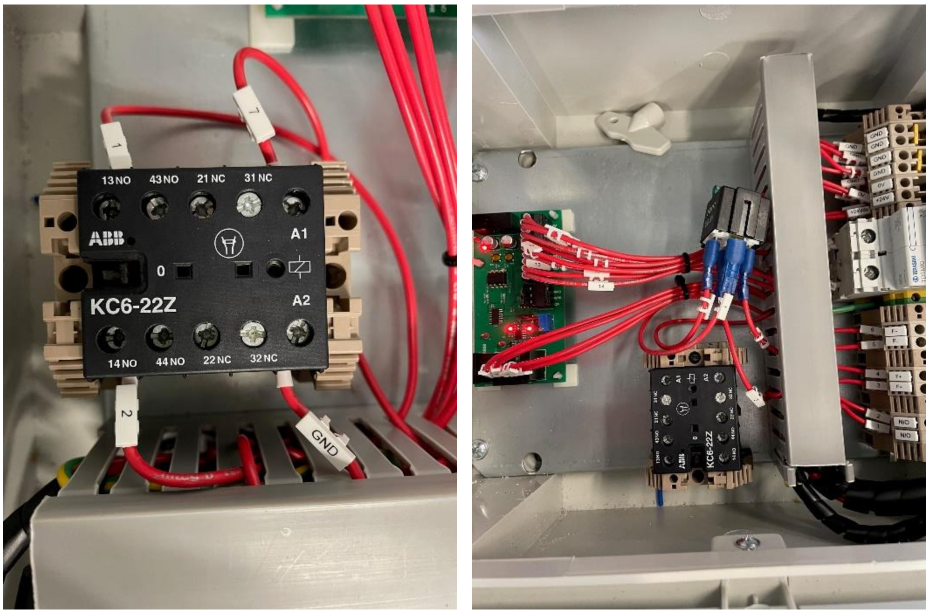


Figure 66 – Enspec internal view ABB KC6-22Z relay (left) Halfords 12 V relay (right)

Outcome: The Enspec MK2 unit was shown to detect pole to earth and pole to pole faults following revisions to the installation guide. When the negative pole CT was installed based on the guide (negative pole CT facing the source) no negative pole faults could be detected. The orientation of the CT was reversed whereby the CT was facing the load rather than the source. This enabled the faults to be detected on the negative pole. One hypothesis was that the algorithm in the PLC requires this orientation for zero crossings etc. The threshold value was set via 2 logins (SPEN and user) and had to be reset on all re-powering of the Enspec unit (no memory of past setting). The 24 V relay inside the Enspec unit was replaced with a 12 V unit which matches the output of the PLC, this was previously a 24 V unit being driven by 12 V from the PLC. The normally closed contact on the 24 V relay was originally employed but the automotive relay is a normally open contact so there was a logic change due to this revision but the end to end signalling was proven to operate. It is envisaged that there will be a more permanent 12 V relay revision by Enspec. Following these revisions the Enspec fault detection system could detect pole to earth faults, pole to pole faults and the status indication from the unit was available via the relay output.

5.6 Schneider Panel Revisions

A number of revisions were applied to the Schneider LVDC switchboard whilst it was at PNDC by a Schneider fitter. All revisions were actioned based on observations from testing at PNDC. The revisions were as follows:

- Rewired Bender relay connections – this employed Schneider approved wire and ferules that fitted properly into the receptacle on the Bender relay.
- The trip from the outgoing MCCB was switched from the overcurrent relay to the under voltage relay. The trip status on the Nortech now indicates the under voltage trip rather than the over current trip. There is an option to use the overcurrent relay trip status indication on one of the spare Nortech indicators.
- A revised plastic guard panel was brought to PNDC for installation. The panel was inserted but damaged trunking and the plastic guard panel was also damaged when removing the guard panel.

The Schneider fitter believed that the original guard panel was in better shape than the replacement and there was an action outstanding to revisit the guard panel design (date to be confirmed).

Outcome: The revisions by Schneider improved the setup of the LVDC switchboard and should prevent any connections from being dislodged during transit to the Falkirk trial site. The rewiring of the trip status to the undervoltage relay should now match the intended LV Engine logic to be displayed on the Nortech LCS. The plastic guard was not installed during PNDC testing as it would have prevented the instrumentation from being installed on the incomer and outgoing terminals of the LVDC switchboard. Whilst the LVDC switch board was energised appropriate risk control measures were employed by the PNDC/SPEN project team (insulated gloves, face shield and an arc flash suit) when interacting with the LVDC switchboard. The plastic guard issue was not resolved by Schneider and an action still exists for the guard to be replaced or modified to allow easier removal from the LVDC switchboard panel.

5.7 Power Sharing

The test programme used the S1 UPFC to share power between two neighbouring substations on the PNDC test network. The S1 UPFC did not have the final power sharing control function enabled. The power sharing process was verified by manually adjusting the AC voltage set point at the UPFC output. This test case will demonstrate the adjustment of LV voltage setpoint at the UPFC so that the overall LV load can be shared between the two neighbouring transformers.

Throughout the testing substation I (500 kVA) was used to supply the S1 UPFC. The second substation used during power sharing tests was substation A (315 kVA). Four loadbanks (hardwired in to the PNDC test network) were employed as a load for the power sharing tests. The test network arrangement for power sharing tests is shown in Figure 67.

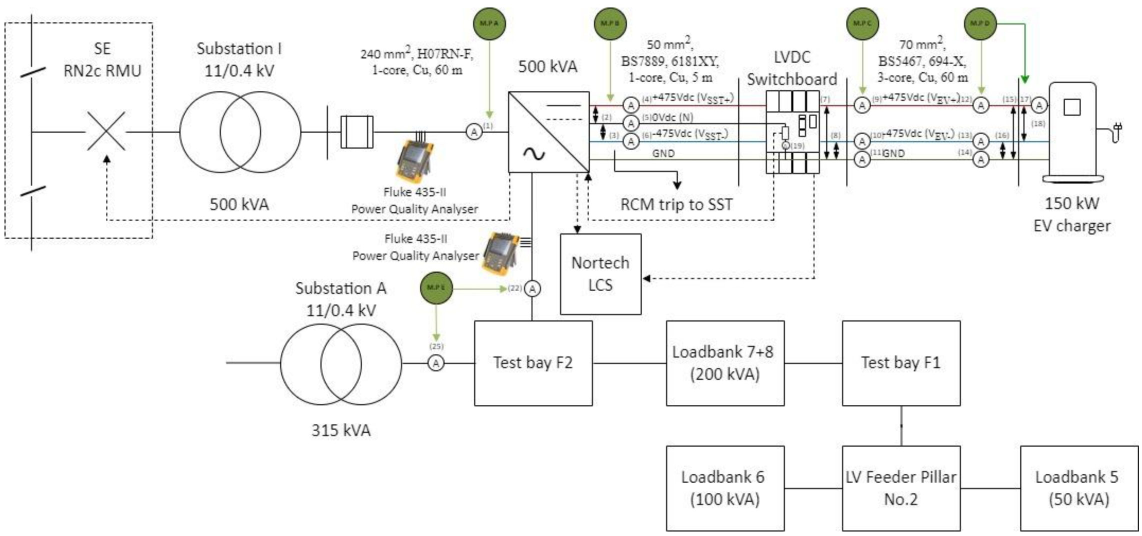
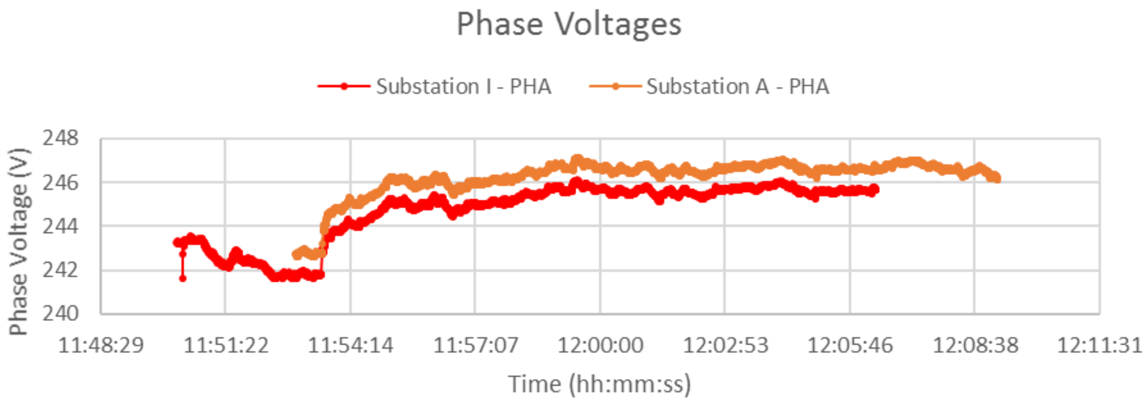


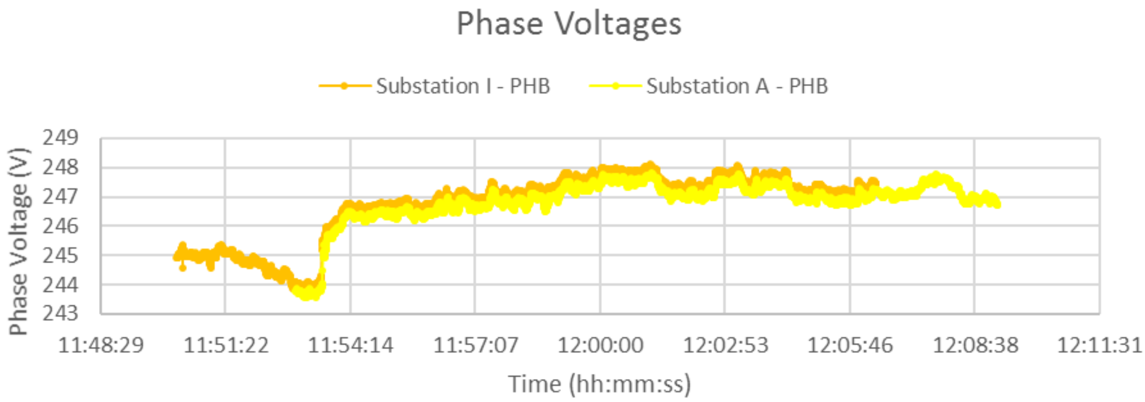
Figure 67 – PNDC test network arrangement for power sharing tests

Prior to connecting the two neighbouring substations, a voltage and a phase rotation check was completed by the PNDC technical team. These checks were performed at the output of the UPFC whilst supplied by substation I and at Test bay F2 when supplied by Substation A with the UPFC disconnected from test bay F2. A voltage difference of 0.5 V was apparent across all three phases. The phase rotation check also confirmed the correct orientation of the three phases.

The S1 UPFC was employed based on the limited number of lab based tests considering the UPFC in a power sharing scenario. During initial trials the fuses were down rated (Sub I=63 A fuses, Sub A= 32 A fuses) to ensure that if a fault occurred then there was limited exposure time for the UPFC and PNDC test network.

Baseline measurements were performed on the two substations prior to interconnection and with no load present. A comparison of the phase voltages for substation I and A is shown in Figure 68.





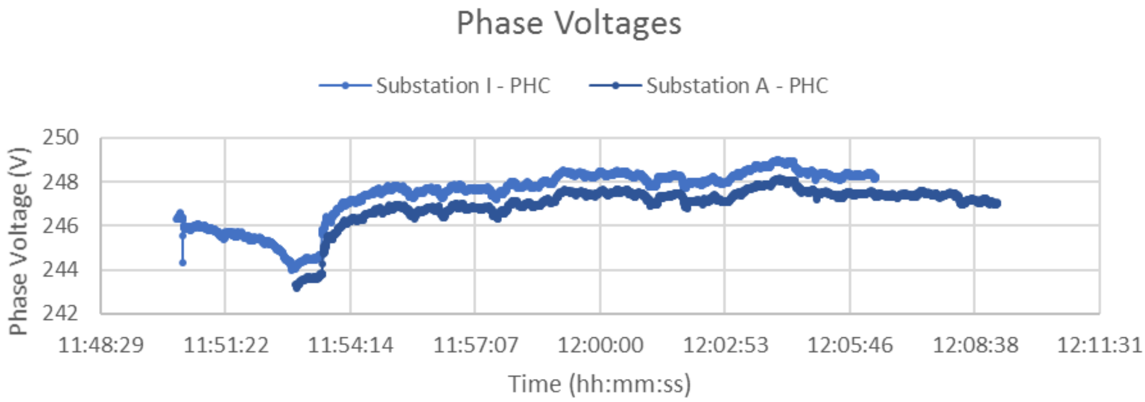


Figure 68 – Baseline phase voltage measurements at substation I and A prior to interconnection

Over this time window the average phase voltage at the two substations was calculated and the breakdown of phase voltages is shown in Table 24.

Table 24: Average phase voltage at each substation prior to interconnection

Phase Voltage	Average Phase Voltage (V)		
	Phase A	Phase B	Phase C
Substation I	244.7	246.7	247.4
Substation A	246.2	246.9	247

Following this initial profiling and with the same fuse arrangement as above, substation A was closed onto the output of the UPFC whilst the UPFC was in bypass mode. Gradually the loading was increased from 4 kW to 22 kW to confirm there was no abnormal behaviour at any equipment under test. Following this initial trial the fuses at the two substations were upgraded (Sub I=163 A, Sub A=100 A) to enable increased loading on the AC and DC outputs of the UPFC.

The load sharing test commenced with the DC service turned on but no load was present initially. The EV charger load was added at 12:29 and was charging the 30 kWh Nissan leaf. On the AC side the UPFC was initially in bypass mode then voltage regulation was applied (11:25) and bypass mode was reactivated at 11:29. Whilst in bypass mode the loading on the two substations was increased (50, 102, 150 and 200 kVA). With the load at 200 kVA the UPFC was switched over to voltage regulation. Table 25 summarises the set points and observations during the second round of the power sharing.

Table 25: Summary of set points during the second power sharing test

Time	DC service	DC load	AC service	Voltage regulation setpoint (V)	Load bank Power factor	Sub I contrib. (kVA)	Sub A contrib. (kVA)	Total load (kVA)
11:22	ON	0	Bypass	-	-	7.23	0.09	7.32
11:25	OFF	0	Regulation	245 (all PH)	-	5.73	1.62	7.35
11:26	ON	0	Regulation	245 (all PH)	-	39.5	33.3	72.8
11:29	ON	0	Bypass	-	1	39.57	23.1	62.67
11:30	ON	0	Bypass	-	1	59.37	45.75	105.12
11:31	ON	0	Bypass	-	1	89.01	67.68	156.69
11:32	ON	0	Bypass	-	1	117.72	89.58	207.3
11:34	ON	0	Regulation	241 (all PH)	1	138.15	72.96	211.11
11:34	ON	0	Regulation	242 (all PH)	1	144.66	63.42	208.08
11:36	ON	0	Regulation	244 (all PH)	1	162.39	46.95	209.34
11:46	ON	0	Regulation	244 (all PH)	1	199.2	65.19	264.39
11:47	ON	0	Regulation	245 (all PH)	1	204.45	67.38	271.83
11:52	ON	0	Regulation	244 (all PH)	0.95	211.41	50.43	261.84
11:54	ON	0	Regulation	245 (all PH)	0.95	183.15	28.56	211.71
11:55	ON	0	Regulation	243 (all PH)	0.95	161.25	42.78	204.03
11:57	ON	0	Regulation	240 (all PH)	0.95	128.94	76.47	205.41
11:58	ON	0	Regulation	237 (all PH)	0.95	100.32	125.07	225.39
12:01	ON	0	Regulation	235 (all PH)	0.95	94.77	147.81	242.58
12:04	ON	0	Regulation	232 (all PH)	0.95	98.16	179.61	277.77
12:10	ON	0	Regulation	232 (all PH)	0.91	97.92	178.86	276.78
12:12	ON	0	Regulation	235 (all PH)	0.91	94.5	143.16	237.66
12:13	ON	0	Regulation	237 (all PH)	0.91	113.22	111.48	224.7
12:15	ON	0	Regulation	240 (all PH)	0.91	141.57	76.47	218.04
12:16	ON	0	Regulation	243 (all PH)	0.91	176.1	42.27	218.37
12:17	ON	0	Regulation	245 (all PH)	0.91	194.1	26.91	221.01
12:18	ON	0	Regulation	248 (all PH)	0.91	216.99	43.83	260.82
12:19	ON	0	Regulation	240 (all PH)	0.91	140.79	79.65	220.44
12:20	ON	0	Regulation	248, 240, 230	0.91	140.94	77.5	218.44
12:21	ON	0	Regulation	240, 240, 230	0.91	151.41	124.4	275.81
12:22	ON	0	Regulation	240, 235, 230	0.91	119.43	133.56	252.99
12:29	ON	44.3	Regulation	240, 240, 240	0.91	171	90.3	261.3
12:33	ON	Leaf	Regulation	243, 243, 243	0.91	201.57	51.63	253.2
12:35	ON	Leaf	Regulation	245, 245, 245	0.91	214.05	40.86	254.91
12:36	ON	Leaf	Regulation	248, 248, 248	0.91	228	56.61	284.61
12:37	ON	Leaf	Regulation	240, 240, 240	0.91	174.45	79.71	254.16
12:38	ON	Leaf	Regulation	237, 237, 237	0.91	144.18	118.23	262.41
12:39	ON	Leaf	Regulation	235, 235, 235	0.91	133.41	143.58	276.99
12:39	ON	39.7	Regulation	232, 232, 232	0.91	108.96	180.63	289.59
12:42	ON	Leaf	Regulation	240, 240, 240	0.91	172.74	81.42	254.16

The total apparent power contribution of substation I and A during this power sharing test is shown in Figure 69 along with the voltage setpoint on phase A of the UPFC.

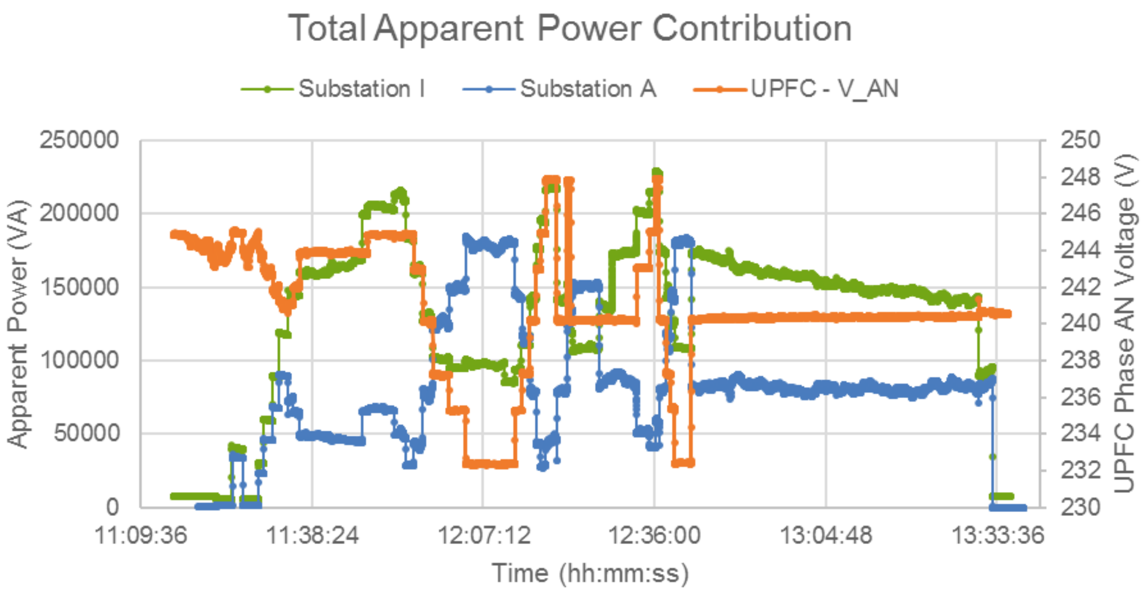
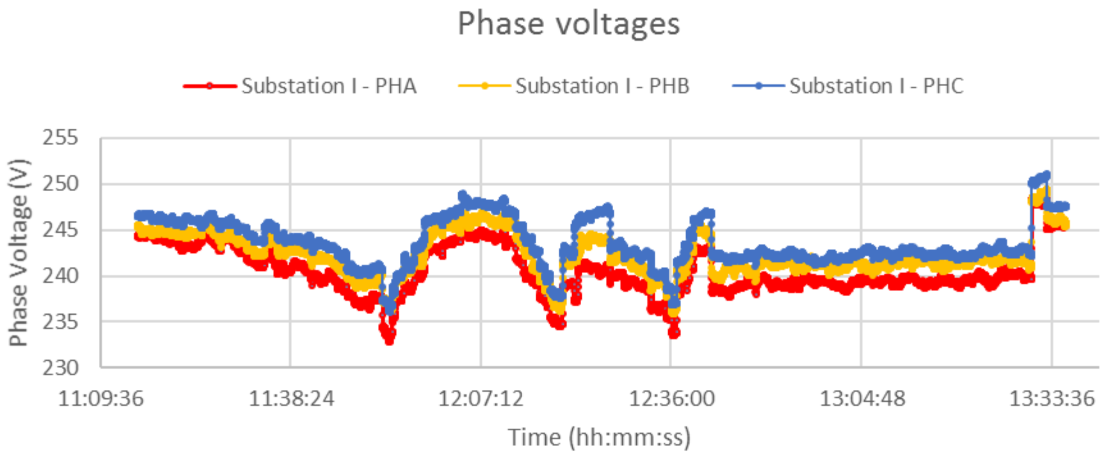


Figure 69 – Total apparent power contribution of substation I and A during power sharing alongside the phase A to neutral voltage at the UPFC output

The contribution of each substation was controlled by altering the output voltage of the UPFC. The test results show that at a UPFC setpoint of 237 V the power sharing between substation I and A was shared equally. When the voltage was above 237 V the apparent power contribution of substation I was larger. With the UPFC setpoint below 237 V Substation A supplied the larger proportion of apparent power. The phase voltages a substation I and A are outlined in Figure 70.



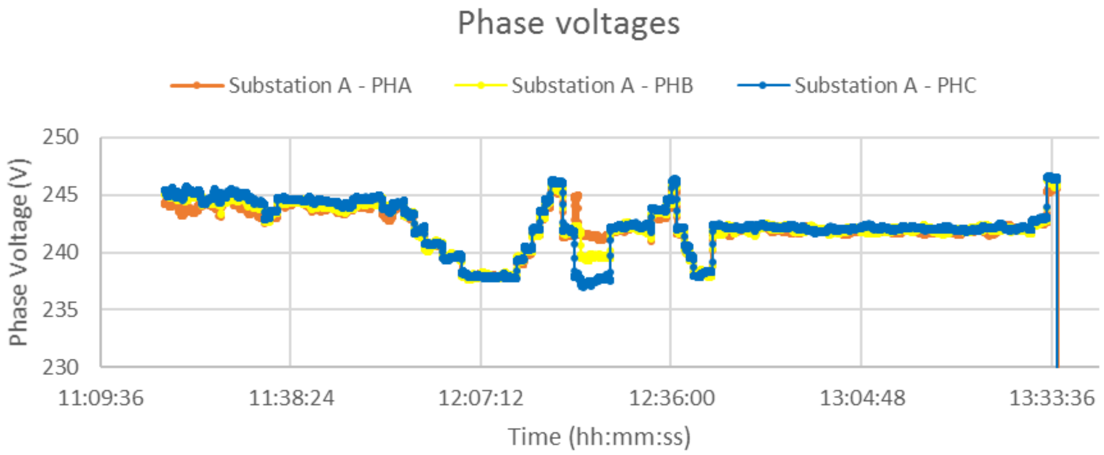


Figure 70 – Phase voltages at substation I (upper) Phase voltages at substation A (lower)

Outcome: The interconnection of two substations via the S1 UPFC was successfully demonstrated on the PNDC test network. Baseline measurements were performed to confirm the correct phase orientation and to determine the voltage difference between each phase on the neighbouring substations. Initially, the UPFC was in bypass and no load was present on the network. The AC loading was gradually increased up to 250 KVA with the power factor of the load also varied. The DC load of the PKM150 charging a 30 kWh leaf was also applied to the UPFC whilst power sharing was taking place. The option of using the voltage regulation of the UPFC output to alter the apparent power contribution of the two substations was fully demonstrated. The successful outcome of this power sharing test should provide confidence and also data for refining future power sharing controls on further iterations of the UPFC.

Take care of the environment.
Printed in black and white and only if necessary.

6 Conclusions

The integration testing at PNDC enabled the complete setup for LV Engine schemes to be tested in different fault and normal operating conditions. The integration testing has been a crucial part of LV Engine development de-risking interruption to the customer or any safety issue. As all components of the system were from different suppliers some debugging and de-risking was completed in the controlled test environment at PNDC before field trials.

Initially, integration testing was performed on the S1 UPFC then, after a break for revision activities, and upgrading hardware/software by manufacturers, regression testing was performed on the S2 UPFC. The integration test programme was successfully completed and in general LV Engine schemes tested were passed with some small issues resolved on specific equipment.

The LV Engine schemes tested at PNDC were as follows:

- LV Engine DC only supply scheme – The PNDC test setup replicating the Falkirk LV Engine trial for full demonetarisation. All the equipment were those which will be deployed in the first LV Engine installation at Falkirk.
- LV Engine AC/DC supply in radial – This was a test demonstrating functionalities of simultaneous AC and DC supply while AC independent phase voltage regulation and power correction services were active.
- LV Engine AC/DC supply in an interconnected network - This was a test demonstrating functionalities of simultaneous AC and DC supply while AC voltage regulation service is active in an interconnected network demonstrating power sharing capability between to neighbouring substations.

In addition to demonstrating normal operation of the schemes above, the integration testing also included the following operating conditions:

- LVDC faults in different locations and conditions demonstrating the effectiveness of DC protection strategy and UPFC ability to auto restore.
- LVAC faults while UPFC was in regulation demonstrating the bypass capability of UPFC with no safety issue identified.

At the conclusion of PNDC testing the project team have an integrated system ready for deployment at the Falkirk trial site.

7 Key Outcomes

The key outcomes of the test programme are outlined below:

- The complete LV Engine Falkirk trial setup was successfully trialled at PNDC.
- Key debugging/de-risking activities were completed and revisions noted for key suppliers.
- The UPFC was demonstrated to charge multiple EVs simultaneously using a Tritium PKM 150 EV charger.
- The DC protection operated as required for the specified DC faults.
- The voltage regulation of the UPFC AC output was demonstrated and presents a useful tool for AC voltage control.
- AC faults were applied to the output of the UPFC with appropriate fuses in place and the UPFC withstood the applied faults.
- The system start up and shut down of the UPFC was demonstrated throughout testing by both the ERMCO-GridBridge and SP Energy network representatives.
- The function of the MCCB in the LVDC switch board was tested for manual operation and for tripping (under voltage).
- The inter-trip function of the Schneider RN2C RMU was verified through applying a 24 V trip command and whilst a fault was apparent in the small zone.
- A wide range of functional tests were completed on the DC output of the UPFC, the loads employed included the Tritium PKM 150 EV charger and a 14.5 Ω resistive load.
- The ability to independently control the three phase voltages (imbalanced loads etc.) on the AC output of the UPFC was highlighted throughout the test programme.
- The reactive power compensation function of the UPFC was demonstrated by an ERMCO-GridBridge representative.
- Tuning of both the Bender relay and the Enspec protection device were explored with recommended baseline settings outlined for the Falkirk trial site.
- The auto restore function on the UPFC was shown to reliably operate for faults outside the small zone.
- Prolonged supply to an AC and DC load was demonstrated with no thermal constraints on the UPFC.
- DC faults with the Tritium PKM 150 charger were demonstrated.
- Revisions were made to a number of subsystems through the testing at PNDC enabling de-risking prior to site deployment thus avoiding customer downtime.
- Key stakeholders visited PNDC during the integration testing and viewed/witnessed the complete test setup (SP Energy Networks Future Networks Team, Falkirk City Council, OFGEM, 3rd party installation team, SP Energy Networks Engineering Design and Standards representatives, SP Energy Networks protection engineers and field operatives).

8 Key technical learnings

The integration test programme also explored a number of additional tests such as the application of AC faults, the 215 V AC output of the UPFC, reactive power compensation mode of the UPFC, independent phase voltage control on the UPFC AC output, tuning the Bender relay and Enspec DC fault monitor. The regression testing confirmed that selected revisions to the S2 UPFC and supporting equipment still conformed to the original integration test procedure. Specific areas of interest during regression testing were; bypass mode behaviour, auto restore operation, AC/DC load testing, DC faults with the Tritium PKM 150 EV charger in circuit, Enspec MK2 testing, Schneider LVDC switchboard revisions and power sharing between neighbouring substations.

An area of specific focus for testing was to confirm that the proposed LVDC protection scheme was fit for purpose and behaved as expected compared to simulation studies. One specific challenge was the EV charger itself which had issues following the application of DC faults at the input terminals of the charger. As such, the fault contribution of the EV charger was not captured at all fault locations but fault behaviour inside and outside the small zone were considered. At no point during the testing was the charger left in an unsafe state following the application of DC faults, the unit simply failed to power up and presented an error screen.

Initially, the S1 UPFC was tripping when being connected to the Tritium PKM 150 EV charger. This issue was resolved via a firmware update by the ERMCO-GridBridge team. This mainly involved increasing the damping in the UPFC control. After this firmware update there were no further issues when connecting the load to the UPFC. Following a DC fault there was some start up issues with the auto restore function of the S1 UPFC. This was not resolved during the integration test programme but the UPFC was able to demonstrate auto restore on a number of occasions. When start-up of auto restore was not initiated a manual reset of the UPFC was required (accessing the front panel on the device). Prior to the execution of the regression tests on the S2 UPFC the ERMCO-GridBridge team investigated the auto restore behaviour in the lab. The regression testing at PNDC on the S2 UPFC demonstrated reliable auto restore operation when the fault was out with the small zone. When the fault was within the small zone auto restore was attempted then the RMU was shunt tripped by the UPFC.

The lockout/warning if the operator tried to exceed the statutory voltage limits in the UK, upper voltage limit (+10%=253 V) and the lower limit (-6%=216.2 V) was successfully implemented via a firmware update by the ERMCO-GridBridge team. The ERMCO-GridBridge team were planning to investigate this issue when time permitted. Additionally, there was a thermal limit on the DC output of the S1 UPFC, this was resolved in the S2 version of the UPFC through a hardware update and extensive lab tests in an environmental chamber. There was no thermal limit observed on the AC output, with a load of ≥200 kVA supplied for over an hour. Similarly, on the DC output of the S2 UPFC no thermal alarms or constraints were observed whilst charging three electric vehicles (max rate 120 kW) in succession. Throughout the test programme the internal logging system of the UPFC was operational and regular downloads were completed and compared between subsequent tests.

DC faults were applied at the incoming and outgoing terminals of the S2 UPFC whilst charging a Nissan Leaf during the regression testing (S2 UPFC). The execution of DC faults with the EV charger in circuit highlighted the voltage rise which occurred on the pole which did not experience a fault. The pole voltage rose above 1000 Vdc, higher than UoS simulations suggested [2]. After each pole to earth fault at location 1 the UPFC did not attempt an auto restart. The overvoltage on the pole which did not experience a fault triggered an overvoltage alarm (>500 Vdc) and immediate shunt trip of the ring main unit. Based on the observed behaviour, a firmware update was devised to include the overvoltage alarm on an exemption list and a maximum wait period in the UPFC control for the voltage of the pole to drop to an acceptable level

(15 V) in order for auto restore to be attempted. The design decision to uprate the voltage of the output capacitors of the UPFC based on UoS simulations was also vindicated. Prior to applying the negative pole to earth fault at location 2 a firmware update was completed by the ERMCO-GridBridge team. The firmware update included the addition of the overvoltage condition to the exemption list and a 3 minute maximum wait period. The UPFC was shown to auto restore once the fault was isolated and when the positive pole voltage dropped to 15 V (1 minute 10 seconds) within the 3 minute wait period.

Some revisions were recommended on the overall setup for the Falkirk trial site. The SPEN team may review the use of the Bender earth leakage relay to trip the RMU. There were concerns raised around tripping the RMU for earth leakage faults mainly caused by the start-up of the UPFC. The tuning work completed on the Bender relay should allay these concerns. At the conclusion of integration testing, solely using the UPFC to trip the RMU was thought to be the best way forward. In this alteration the UPFC would send a trip command to the RMU if a failed restart procedure was evident. The Nortech control panel required some revisions to the internal circuitry after the integration testing and a revised unit was issued for the regression testing. In the MK1 panel the trip signal from the Bender earth leakage relay went via the digital input of the Nortech control panel and this appeared as a high impedance and acts to block the trip signal. Therefore the control cables were rearranged to bypass the digital input of the Nortech panel. The permanent solution required a 24 V interposing relay to separate the digital input (status) and the RMU shunt trip. The MK2 version of the Nortech panel was demonstrated to provide all necessary indications and the customer emergency stop was also trialled.

The protection in the Schneider LVDC switchboard was proven to reliably operate through the range of tests included in the integration and regression tests. Some panel wiring issues were apparent from the factory and revisions were made by PNDC personnel to prove operation. A Schneider fitter visited PNDC during the regression testing to apply a number of permanent changes to the LVDC switchboard. The trip status signal from the MCCB which passes on to the Nortech control panel initially employed the overcurrent relay. The trip status signal was rewired to use the undervoltage relay to ensure that the intended LV Engine logic could be displayed on the Nortech control panel. The plastic guard was not installed during PNDC testing as it would have prevented the instrumentation from being installed on the incomer and outgoing terminals of the LVDC switchboard. The plastic guard issue was not resolved by Schneider and an action still exists for the guard to be replaced or modified to allow easier removal from the LVDC switchboard panel.

The interconnection of two substations via the S1 UPFC was successfully demonstrated on the PNDC test network within the regression testing. The contribution of each substation was altered by varying the output voltage of the UPFC. Baseline measurements were performed to confirm the correct phase orientation and to determine the voltage difference between each phase on the neighbouring substations. Initially, the two substations were closed together with the UPFC in bypass mode and the AC load was gradually increased (250 kVA). The DC load of the Tritium PKM150 charging a 30 kWh leaf was also applied to the UPFC whilst power sharing was taking place. The option of using the voltage regulation of the UPFC output to alter the apparent power contribution of the two substations was successfully demonstrated. It is envisaged that the power sharing function will be critical in meshed networks like the Wrexham LV Engine trial site. This initial demonstration should provide a level of confidence prior to further development work by the SP Energy Networks/ERMCO-GridBridge team.

9 References

[1] A. Kazerooni, "Falkirk LVDC Trial Site – LVDC Protection Strategy Document," SP Energy Networks, 2021.

[2] V. Psras, "Protection of LVDC networks integrating SSTs: Falkirk trial site LVDC protection study," University of Strathclyde, 2021.

[3] SP Energy Networks, "LV Engine LVDC Protection Strategy Testing - Test Plan," 2023.

[4] Energy Networks Association, "A Transistion to LVDC - Phase 2," 2022. [Online]. Available: https://smarter.energynetworks.org/projects/nia_spen_0047/. [Accessed June 2022].

[5] Bender GmbH & Co. KG, "RCMB300-series, AC/DC sensitive residual current monitoring module for MRCD applications," 2023.

[6] Cleveland Cable Company, "H07RN-F FLEXIBLE MAINS AND CONTROL CABLE BS EN 50525-2-21," [Online]. Available: https://www.clevelandcable.com/media/pdfs/H07RN-F-flexible-mains-and-control-cable.pdf. [Accessed April 2023].

[7] Energy Networks Association (ENA), "Engineering Recommendation G5/4-1," 2005.

[8] Halfords, "Halfords Relay 12V 30A 4 PIN (ELEC256)," [Online]. Available: https://www.halfords.com/motoring/tools/fuses-electricals-and-fixings/electricals/halfords-relay-12v-30a-4-pin-elec256-725510.html. [Accessed October 2023].

[9] SourceForge, "QModMaster," August 2022. [Online]. Available: https://sourceforge.net/projects/qmodmaster/ . [Accessed July 2023].

10 Appendix A: RCMB-301 Modbus Interface

The DI-2USB manufactured by Bender (USB to RS-485 converter) was used to connect the PC hosting QmodMaster and the Bender RCMB301. The USB interface has connections A and B which are in turn connected to terminals A and B on the RCMB301.

Figure 71 – USB interface with Bender RCMB301

QmodMaster can be downloaded from source forge [9]. Follow the installation process for QModMaster. The sections below detail key setting to be applied on QModMaster and examples of reading and writing to specific Modbus addresses. A list of Modbus addresses are outlined in the Bender manual [5] section 7.

Apply the settings outlined in Figure 72 for the Modbus RTU settings accessed via Options>Modbus RTU settings.

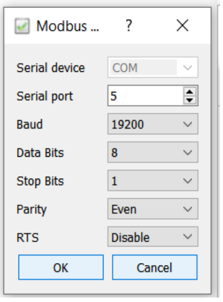


Figure 72 – QModMaster Modbus RTU settings

Check the settings on QModMaster (Options>Settings) and apply the settings outlined in Figure 73.

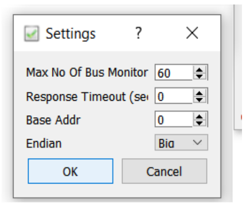


Figure 73 – QmodMaster settings

The default Modbus slave address is 1XX with XX being the last 2 digits of the serial number on the Bender RCMB301 as illustrated in Figure 74.

Figure 74 – Bender RCMB301 serial number location

In the example below the Bender serial number ends in 94 and Modbus address 16012 (limit value alarm/trip value) was read on QModMaster as illustrated in Figure 75.

Take care of the environment.
Printed in black and white and only if necessary.

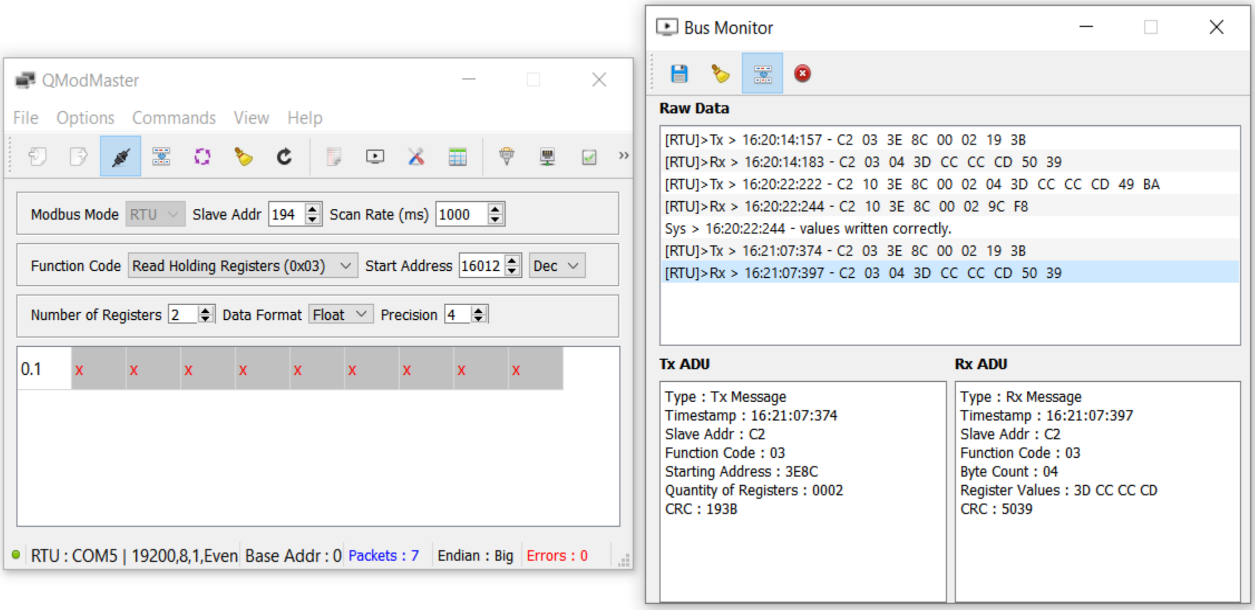


Figure 75 – Reading Modbus address 16012 (limit value alarm)

An example of writing a value to a Modbus address is shown in Figure 76.

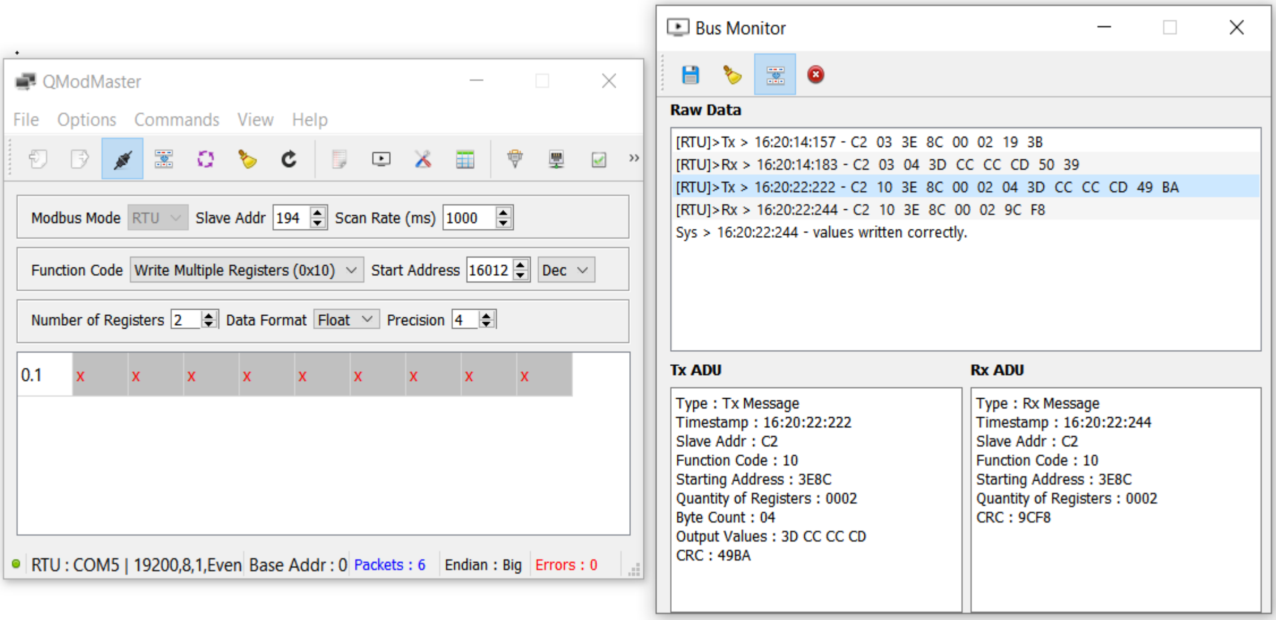


Figure 76 – Writing Modbus address 16012 to set the limit value alarm

The calibration procedure for the RCMB301 is as follows:

1. Connect the CT while the relay is supplied by at least 14V
2. Disconnect the power supply
3. Hold T button
4. Supply the module with at least 14V
5. While holding T button, LED goes from red (device not ready) to flashing red slowly (ready for calibration) and finally to LED flashing red very quickly (calibration mode)
6. Release T button
7. Calibration continues for about 15-20 seconds
8. If successful LED lights green permanently.