Angle-DC

Verification and Validation Report

Future Networks

SP ENERGY NETWORKS

Index

1 Introduction

ANGLE-DC is an innovative project demonstrating a smart and flexible method for reinforcing distribution networks by converting AC assets for DC operation. ANGLE-DC has adapted existing power electronic technologies to build a Medium Voltage Direct Current (MVDC) link which could be an effective solution to facilitate the integration of renewable resources and accommodate future demand growth.

SP Energy Networks (SPEN) believe that changing the Electromagnetic Fields (EMF), causing Electromagnetic Interference (EMI), is the primary mechanism by which the project could affect the railway, as part of the MVDC circuit is installed on the Britannia Bridge rail deck (Figure 1-1). By converting existing AC cables to DC, it is assumed that many of the hazards to the Britannia Bridge and railway operations remain unchanged (e.g. fire and contribution to the consequences of a derailment). A new AC cable (3 x 500 mm^2 XLPE sheathed single cores in trefoil arrangement) has been laid alongside the original, converted, DC cables. The new AC cable is currently operational; again, it is assumed that this will have little impact on the existing risk profile.

Figure 1-1 Britannia Bridge lower deck showing the proximity of the Bangor to Llanfair AC circuit cables to the railway.

2 Scope and Objective

SP Energy Networks has converted an existing double 33kV AC circuit to Medium Voltage Direct Current (MVDC) operation using two MVDC converter stations at either end. A section of the converted circuit is located on the rail deck of the Britannia Bridge, which crosses the Menai Strait between the island of Anglesey and the mainland of Wales. The MVDC project will enable a fully controllable bi-directional DC link between two existing substations located at Llanfair PG and Bangor.

As part of managing the risk arising from hazards associated from Electromagnetic Interference (EMI) that may be encountered, SPEN appointed Ricardo Certification to act as the Assessment Body (AsBo), to provide an independent assessment of a Common Safety Method for Risk Evaluation and Assessment (CSM-RA) activity for the AC to DC conversion. The risk management process, as defined in the CSM-RA, has been performed by SPEN's appointed sub-contractor, Frazer-Nash Consultancy Ltd.

The CSM-RA process was split into two phases:

- Phase I: Risk evaluation and assessment activities (completed)
- Phase II: Verification and validation of the Phase I CSM-RA

The scope of this Verification and Validation report (Phase 2) is to: provide an evidence base that demonstrates the link has been commissioned in accordance with the test schedule, the DC harmonic performance is compliant with the converter modelling results and the EMC/EMF measurements support the EMC limits specified in the standards.

The objective of this Verification and Validation report is to demonstrate the measurements taken, before energisation and during commissioning tests, support the conclusion that the risk from operating the MVDC link, on NR infrastructure, is controlled to an acceptable level in accordance with CSM-RA.

Following completion of the MVDC Link commissioning activities and recording of the EMC & EMF measurements, the Project has updated the Hazard Record. The Safety Justification Report and Safety Assessment Report will then be updated following acceptance of this report by Network Rail. The Safety Case will then be submitted to SRP for consideration of endorsement.

3 Test Schedule

Real power commissioning testing took place between 00:30 and 04:55, between 00:30 and 00:42, the start-up sequence, voltage change, and very low real power pulse tests were carried out. These results have been omitted from the presentation of results, as current levels were too low to register on the monitoring equipment. Four sets of monitoring system were in place during the testing:

- The SP Energy Networks GPS AC network monitoring system linked to PI data historian;
- Two PM7000 Ranger Power Quality Monitors, one at each station AC bus;
- The GE control system linked to the Pertu data historian;
- A Unilyzer DC cable power quality monitor and logger capable on monitoring up the 100th harmonic; and
- The Network Rail monitoring system.

The schedule was split into three main parts: 1) low power steady state tests 2) high power transmission tests and 3) step response tests. The complete schedule can be visualised in Figure 1-1, which shows the real and reactive power, PM7000, monitoring data at the AC bus of each MVDC station. Small differences in power were observed due to losses in each converter station. During the tests, several shutdown commands were issued, to observe the impact on DC cable harmonics and induced voltages. The first set of shutdown tests took place during the low power steady state tests.

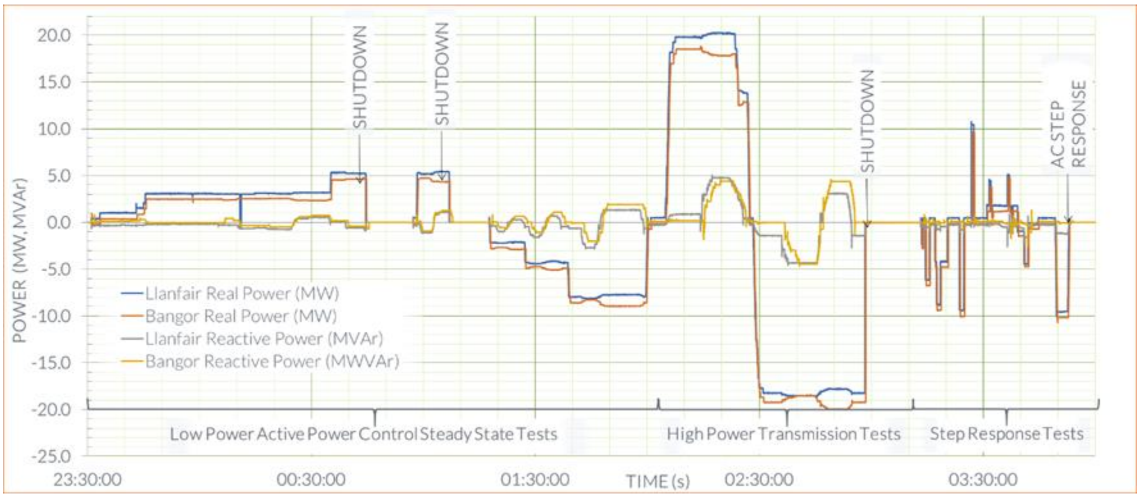

Figure 3-1. AC Power at Station Bus (MVA) - Pi Data. Plot shows the apparent power over the whole test schedule. Positive values represent power flow from Bangor Grid to Llanfair PG MVDC converter stations.

3.1 LOW POWER ACTIVE POWER CONTROL STEADY STATE TESTS

The low power tests took place between 00:42 and 02:50. The low power tests tested permutations of set point transitions to assess the performance of the MVDC Link's power transfer capability and control system response. These tests were used to satisfy SP Energy Networks and GE Power Conversion that the control system was ready for high power transmission testing. During the testing, some intermate setpoint permutations were skipped as confidence in the control system performance was gained. Table 3-1 shows the completed test schedule tables, with setpoints witnessed by SP Energy Networks and GE Power Conversion commissioning engineers. Detailed plots, of the low power tests, have not been included in this report, due to the high-power transmission test being of most interest from an Electro Magnetic Compatibility perspective.

Table 3-1. Actual test schedule for Low Power Active Power Control and Steady State tests.

Set-Point (MW)	pf	Time	SPEN Witnessed	GE Witnessed	Notes, Recommendations or Actions to be Taken
0	1	NA			Skipped
3.1	1	00:42:00	X	X	Setpoint achieved
3.1	0.9	01:11:10	X	X	Setpoint achieved
3.1	0.85	01:18:50	X	X	Setpoint achieved
3.1	-0.90	01:27:23	X	X	Setpoint achieved
3.1	-0.85	01:30:20	X	X	Setpoint achieved
4.63	1	01:36:10	X	X	Setpoint achieved
5.35	0.95	01:40 35	X	X	Setpoint achieved
5.35	0.9	01:45:31	X	X	Setpoint achieved *SHUTDOWN at 01:46:00*
5.35	0.85	02:00:46	X	X	Setpoint achieved
5.49	-0.95	NA			Skipped
5.49	-0.9	02:04:20	X	X	Setpoint achieved
5.49	-0.85	02:05:25	X	X	Setpoint achieved
6.4	1	NA			Skipped
6.4	0.95	NA			Skipped
6.4	0.9	NA			Skipped
6.4	0.85	NA			Skipped
6.4	-0.95	NA			Skipped
6.4	-0.9	NA			Skipped
6.4	-0.85	NA			Skipped
0	1	NA			Skipped
5.49	1	02:07:30	X	X	Setpoint achieved *SHUTDOWN at 02:08:20*
-2	0.9	NA			Skipped
-2.77	0.85	02:21:18	X	X	Setpoint achieved
-2	-0.9	NA			Skipped
-2.77	-0.85	02:24:45	X	X	Setpoint achieved
-4.85	1	02:28:25	X	X	Setpoint achieved
-3.6	0.95	NA			Skipped

Set-Point (MW)	pf	Time	SPEN Witnessed	GE Witnessed	Notes, Recommendations or Actions to be Taken
-3.6	0.9	NA			Skipped
-4.85	0.85	02:30:45	X	X	Setpoint achieved
-3.6	-0.95	NA			Skipped
-3.6	-0.9	NA			Skipped
-3.6	-0.85	02:35:10	X	X	Setpoint achieved
-8.44	1	02:40:42	X	X	Setpoint achieved
-6.2	0.95	NA			Skipped
-6.2	0.9	NA			Skipped
-8.44	0.85	02:44:38	X	X	Setpoint achieved
-6.2	-0.95	NA			Skipped
-6.2	-0.9	NA			Skipped
-8.44	-0.85	02:49:25	X	X	Setpoint achieved

3.2 HIGH POWER TRANSMISSION TESTS

The high-power transmission tests took place between 02:50 and 04:00. All testing was successful, with no issues encountered with the MVDC link real power performance. The test was designed to push the operating setpoint envelope to its extremes. To achieve this, intermediate setpoint transitions were omitted from the testing. The MVDC link real power limit is 20MW and the power factor extremes are +/- 0.85. All the setpoint extremes were reached, except for 20 MW import from Bangor to Llanfair PG at 0.85 pf. This was due to network voltage limits being reached with the maximum real power transfer.

Table 3-2. Actual test schedule for High Power Transmission tests.

Set-Point (MW)	pf	Time	Witnessed		Notes, Recommendations or Actions to be Taken
			SPEN	GE	
-6.2	-0.85	02:49:25	X	X	Setpoint Achieved
STOP/START Mid ramp			X	X	Stop 03:27:32– RAMP to stop within 2 seconds
19.26	1	03:08:05	X	X	Setpoint achieved
19.26	-0.88	03:19:55	X	X	Setpoint achieved
20	0.85	NA			Skipped low volts at Llanfair PG
19.26	1	03:28:44	X	X	Setpoint achieved
-19.09	1	03:32:51	X	X	Setpoint achieved
-19.74	-0.85	03:41:45	X	X	Setpoint achieved

Set-Point (MW)	pf	Time	Witnessed		Notes, Recommendations or Actions to be Taken
			SPEN	GE	
-19.74	0.85	03:50:05	X	X	Setpoint achieved
-19.17	1	03:56:00	X	X	Setpoint achieved
STOP/START Mid ramp			X	X	Stop 03:59:31 – RAMP to stop within 2 seconds
0	0	03:59:33	X	X	Setpoint achieved

The GE Pertu data logger recorded the high-power transmission test response, of the MVDC converters, which can be seen in Figure 3-2 and Figure 3-3 for a 20MW power transfer at 1 and 0.88 power factor respectively. The plots show the converter control system is stable at the extremes of operation.

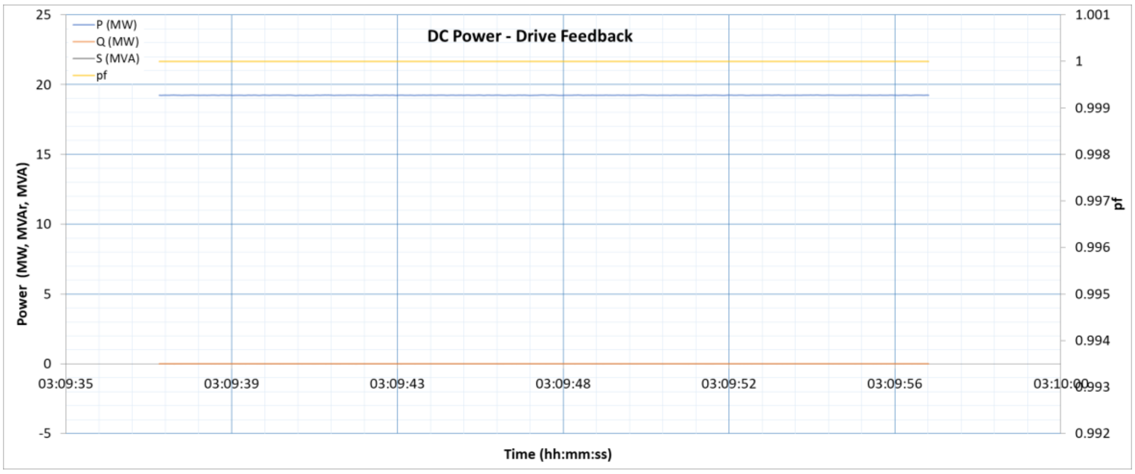

Figure 3-2. GE Pertu data for the 19.26 1 pf high power transmission test showing setpoint being held for 30 seconds.

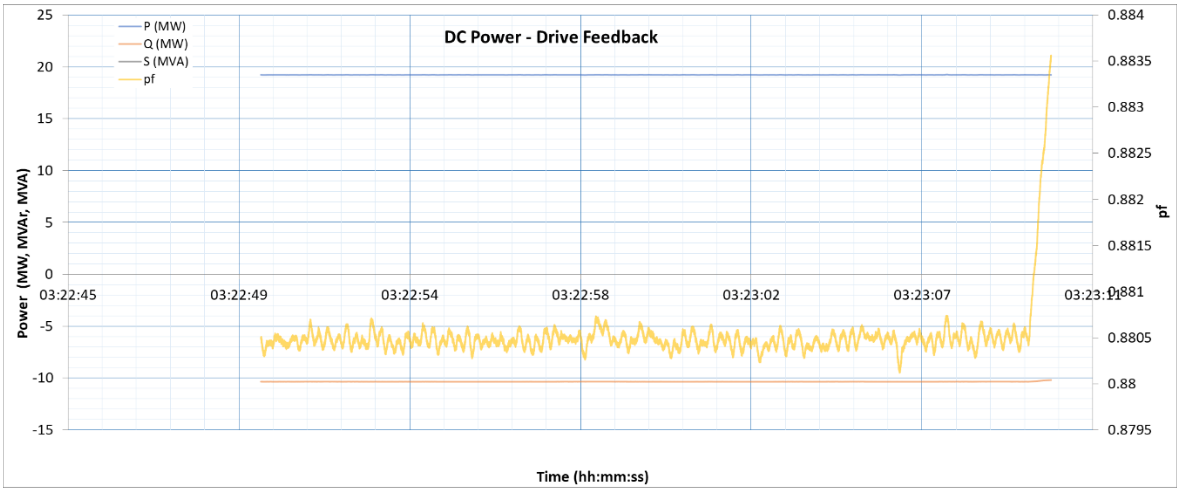

Figure 3-3. GE Pertu data for the 19.26 -0.88 pf high power transmission test showing setpoint being held for 20 seconds.

3.3 STEP RESPONSE

The step response tests were carried out between 04:19 and 04:52. All testing was successful, with no issues encountered with the MVDC link real power performance. The purpose of these tests was to assess the converter dynamic performance and stability during large setpoint step changes and AC network voltage step changes. The first tests were carried out in small intermediate step with 1 pf. Once confidence was gained, large step changes were completed with 1 pf and +/-0.85 pf. The real power step size was reduced from 10 MW to 5.4 MW, in one direction, to avoid large swings in voltage on the Llanfair PG bus.

Table 3-3 Actual test schedule for Step Response tests.

Step Test		Time	Witnessed		Notes, Recommendations or Actions to be Taken
			SPEN	GE	
Pf =1	-0 – -10 MW in ~-5 MW steps	04:19:14	X	X	-2.77 MW Setpoint at 04:14:48 0 MW Setpoint at 04:15:21 -6.60 MW Setpoint at 04:16:02 0 MW Setpoint at 04:17:06 -9.25 MW Setpoint at 04:16:02 0MW Setpoint at 04:21:41
Pf =1	-10 – 0 MW	04:25:00	X	X	-10.02 MW Setpoint at 04:25:00 0 MW Setpoint at 04:26:40
Pf =1	0 – -- 10.MW	04:28:00	X	X	-9.25 MW Setpoint at 04: 28:00
Pf =1	10 – 1 MW	04:30:00	X	X	0 MW Setpoint at 04:30:00
Pf=0.85	0 MW - 5.4MW	04:37:39	X	X	5.4 MW Setpoint at 04:37:39
Pf=0.85	5.41 MW – 0 MW	04:38:32	X	X	0 MW Setpoint at 04:38:32
Pf=-0.85	-1 MW – -5 MW	04:42:00	X	X	- 5.1 MW Setpoint at 04:42:00
Pf=-0.85	-5 MW – -0MW	04:43:00	X	X	0 MW Setpoint at 04:43:00
At -- 10.14 MW	AC voltage	04:52:30	X	X	Backup AC circuit closed – 04:52:30

The GE Pertu data logger recorded the step-up and step-down response, of the MVDC converter control system, which can be seen in Figure 3-4 and Figure 3-5 respectively. The plots show the converter control system is critically damped when responding to a step change of 4.6MW, 1-second in duration.

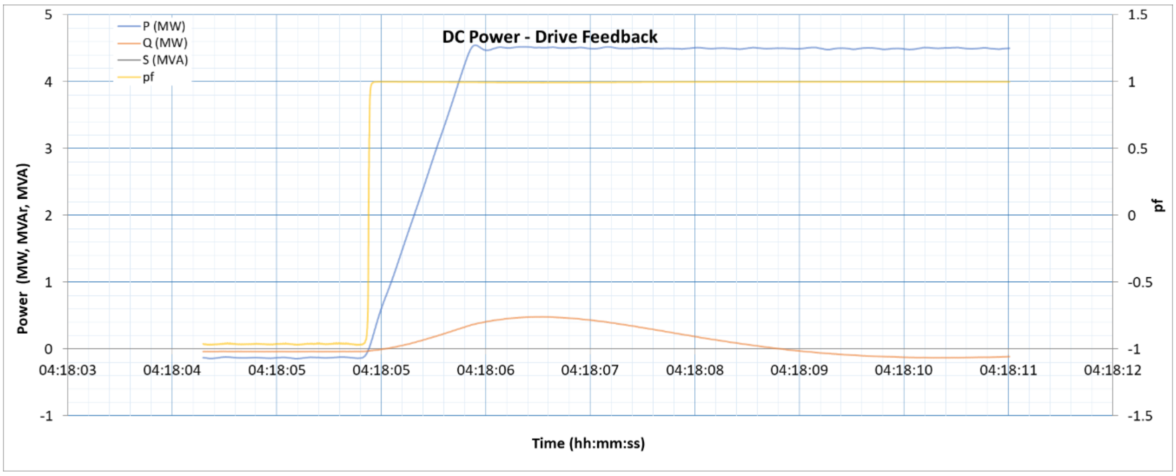

Figure 3-4. GE Pertu data for a 0 - 4.18 MW step response test at 1 pf showing setpoint being held for 6 seconds.

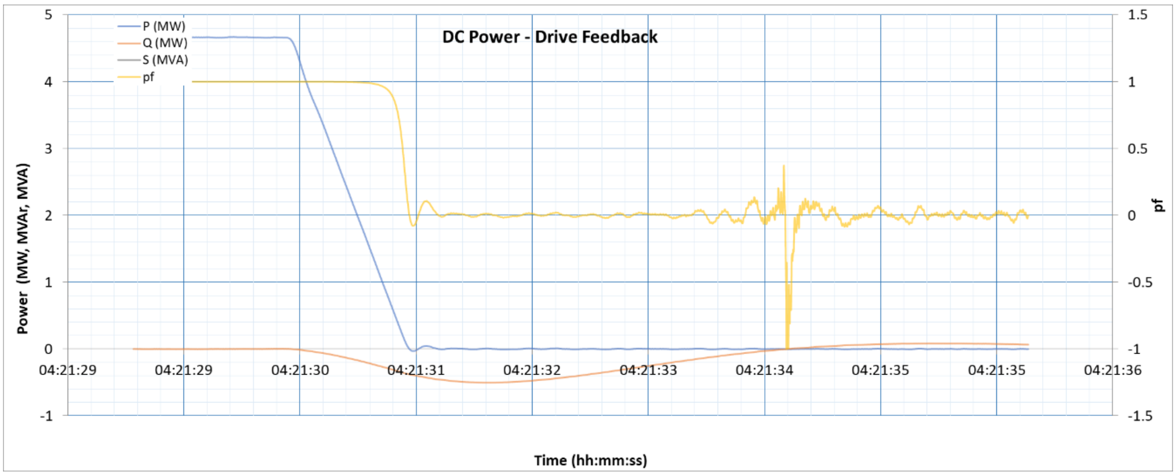

Figure 3-5. GE Pertu data for a -4.67-0 MW step response test at 1 pf showing setpoint being held for 6 seconds

3.4 AC VOLTAGE STEP CHANGE

Throughout the step change tests, the changes in AC bus voltages were driven by the MVDC link setpoint changes. At 04:52, the parallel AC circuit was closed, while the MVDC link was importing 10.14 MW from Bangor Grid to Llanfair PG. A step change in AC voltage of 1.03% can be seen in Figure 3-6. This is the only step change in AC volts caused a change to the network, rather than changes to the MVDC link setpoint. When the link power is reduced to 0MW, at 04:54, the voltage change is an order of magnitude smaller, due to the connection of Llanfair PG to the Bangor Grid 132kV transformer. The converter power transfer was stable throughout the AC voltage step change test.

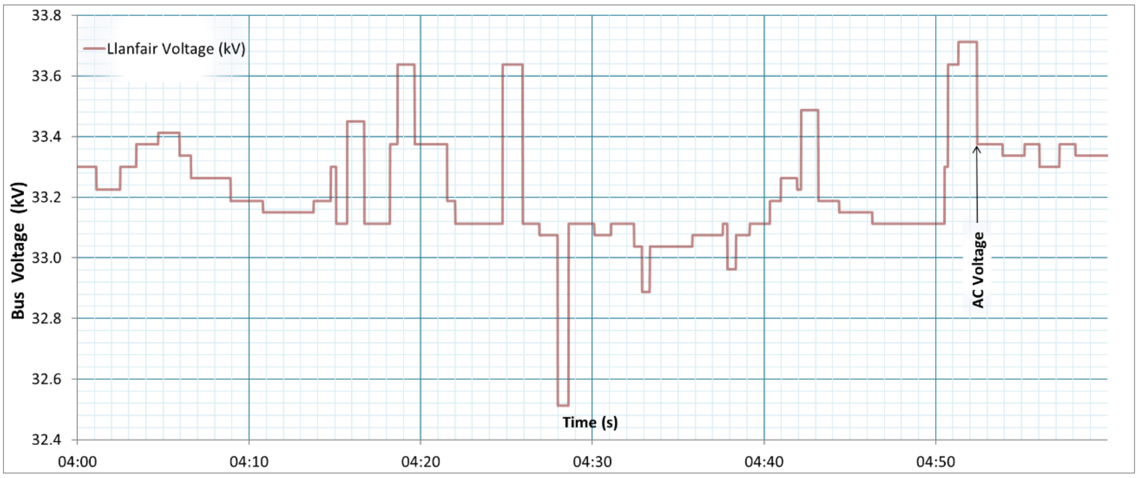

Figure 3-6. PI Historian data showing the LLanfair PG bus voltages during the step change tests. The AC voltage step change was driven by closing the parallel AC circuit, connecting the LLanfair PG bus to Bangor Grid.

4 DC Cable Power Quality Monitoring

Power quality measurements have been made on the Angle DC 33kV positive and negative pole cable circuits during a sequence of energisation steps carried out between 2300 and 0700 in the morning.

There are three cables used on each pole, Six Rogowski coil current sensors were installed, on one cable of each pole. Results are thus presented with respect to one cable for each pole. A reference voltage was derived from the mains to synchronise the 50 Hz frequency, voltage results are omitted from this report, since current is of interest for the CSM-RA.

4.1 INDIVIDUAL CURRENT HARMONICS

The current harmonics were used as a key input parameter for the CSM-RA EMC modelling. The monitoring system used, recorded harmonics up the 100th or 5 kHz. The frequency distribution plots for the positive and negative pole, are shown in Table 4-2, Figure 4-1 and Figure 4-2. The data shows negligible maximum harmonic currents above the 6th harmonic or 300 Hz. This monitored data covers 3 rapid shutdown events, an AC step change and multiple DC step changes, The results suggest the actual MVDC link harmonic levels are well below the modelled MVDC link harmonic values, used in the EMC modelling. This provides a high level of confidence that the risk from operating the MVDC link are controlled to an acceptable level.

Table 4-1. EMC model input data for system currents at different frequencies for normal MVDC operation. Yellow highlights are the largest current amplitudes closest to Network Rail train detection equipment operating frequency.

Frequency	+ve Pole	-ve Pole	Ground Resistor (A)	TI21 Frequency (Closest)
0 Hz (DC)	565	565	-	-
1.5 kHz	0.03(-15.1°)	0.01(133.5°)	0.03(-8.8°)	E (1532/1566)
3 kHz	0.01(21.9°)	0.01(213.2°)	0.01(13.3°)	H (2428/2462)
4.5 kHz	0.01(4.6°)	<0.01(185.2°)	<0.01(4.1°)	H (2428/2462)
9kHz	0.01(33.8°)	<0.01(215.9°)	<0.01(32.1°)	H (2428/2462)
18kHz				H (2428/2462)

Figure 4-1Maximum current harmonics, in Amps, for the positive pole between 2300 and 0700.

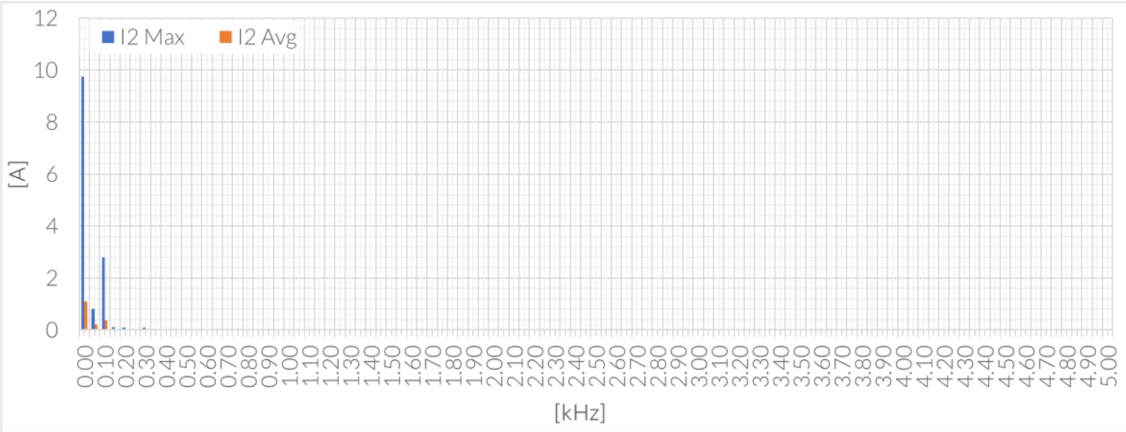

Figure 4-2 1Maximum current harmonics, in Amps, for the negative pole between 2300 and 0700.

Table 4-2. Harmonic currents in amps.

#	Max I1 [A]	99% I1 [A]	95% I1 [A]	Max I2 [A]	99% I2 [A]	95% I2 [A]	Max I3 [A]	99% I3 [A]	95% I3 [A]
2	2,839	2,765	1,556	2,804	2,732	1,541	2,801	2,731	1,508
3	0,117	0,000	0,000	0,115	0,000	0,000	0,114	0,000	0,000
4	0,086	0,000	0,000	0,083	0,000	0,000	0,084	0,000	0,000
5	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
6	0,098	0,097	0,094	0,096	0,095	0,093	0,099	0,098	0,097
7	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
8	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
9	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
10	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
11	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
12	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
13	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
14	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
15	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
16	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
17	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
18	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
19	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
20	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
21	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
22	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
23	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
24	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
25	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
26	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
27	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
28	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
29	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
30	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
31	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
32	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
33	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
34	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
35	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
36	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
37	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
38	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000

#	Max I1 [A]	99% I1 [A]	95% I1 [A]	Max I2 [A]	99% I2 [A]	95% I2 [A]	Max I3 [A]	99% I3 [A]	95% I3 [A]
39	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
40	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
41	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
42	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
43	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
44	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
45	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
46	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
47	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
48	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
49	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
50	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000

4.2 INSTRUMENT DESCRIPTION

The Unilyzer 900 is a norm-compliant, portable PQ analyser accredited for field measurements with gapless integration intervals according to the highest accuracy class, IEC 61000-4-30 Class A. The U900 is designed for high precision field measurement campaign.

4.3 TECHNICAL SPECIFICATION UNILYZER U900

4.3.1 Voltage Channels:

Inputs 3 or 4 I Voltage level 0-1000V RMS I Resolution 24 bits I Basic Sampling rate 5000 samples/cycle I Bandwidth 40 kHz I Accuracy U900: IEC 61000-4-30 Class A (< 0,1%)

High speed voltage channels:

Range +/- 1,4 kV peak level I Fast transient detection (FT) 31 000 samples/cycle I Bandwidth 3,1 MHz Filters Analogue anti-aliasing filters

4.3.2 Current Channels:

Inputs 3 or 4 I Current level 0-10 A with current clamps I 0-5000 A with flexible current clamps Resolution 24 bits I Basic Sampling rate 5000 samples/cycle I Input impedance Galvanically isolated Bandwidth 40 kHz Accuracy U900: IEC 61000-4-30 Class A (< 0,1%).

4.3.3 Sampling synchronisation

To obtain maximal accuracy the instrument is synchronized with the power frequency using a phase-locked loop (PLL).

Anti-alias filters in accordance with IEC 61000-4-30 and IEC 61000-4-7

The voltage and current inputs have analogue low pass anti-alias filters in accordance with IEC 61000-4-7 ensuring that signals outside the bandwidth are attenuated. This is mandatory for any digital sampling instrument in order not to produce false results.

4.4 STANDARDS UNILYZER U900

Complies with IEC 61000-4-30 ed.3 Class A

Complies with IEC 61000-4-7 Class I

Complies with IEC 61000-4-15 F3

Fulfils requirements for measurements in accordance with EN 50160

IEC 61000-2-2, IEC 61000-2-12, EIFS and others.

EN 61010-1 Personal safety

EN 50081-1,2 and IEC 61000-6-4 EMC Emission

EN 50082-1,2 and IEC 61000-6-2 EMC Immunity

4.5 METER INFO

Site name: Angle-DC
Meter serial no: 27100209
Period start: 23:00:00
Period end: 06:59:00
Voltage level: 240,00V
Version: 22.0
Maximum short-circuit current (ISC): 10000,0A
Maximum demand load current (IL): 1000,0A

5 Network Rail Load Monitoring

See ETS TR 22 17 - Anglesey Britannia Bridge report.

6 Conclusions of Results

The SP Energy Networks and GE Power Conversation data, detailed in Section 3, shows the MVDC link achieved the setpoint extremes for high power transmission and completed the step response tests during the monitoring period. The monitoring data and interpretation in Section 4.1 supports the conclusion that the risk from operating the MVDC link, on NR infrastructure, is controlled to an acceptable level in accordance with CSM-RA phase 1 findings. This is evidenced by the DC maximum currents, through the entire testing period, being of lower value than the those used to derive the EMC modelling results. The conclusion is further supported by the report results referenced in Section 5, which show all longitudinal voltages and psophometrically weighted transverse voltage values are compliant with Network rail limits.

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