

Jordanthorpe 33kV Fault Current Limiter

Progress Report November 2014

CONFIDENTIALITY (Confidential or not confidential) : NOT CONFIDENTIAL		
PROJECT OR PRODUCT : 33kV 800A normal current 1400A; 15 minutes overcurrent design		
UNIT APPROVAL	Name	Date
WRITTEN BY :	David Klaus	19/11/2014
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Issue 1	20/11/2014	Customer Issue
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1. INTRODUCTION

This report details the testing which has been carried out on the 33kV pre-saturated core Fault Current Limiter (FCL) in December 2013 and May 2014. The nature, sequence and severity of the tests, based broadly on IEC 60076 (transformers) part 6 (reactors), clause 8 (series reactors), was agreed with Paul Jarman of National Grid, who is responsible for the technical qualification of transformers and reactors for installation in the Grid. The plan was to follow National Grid's Type Registration process as closely as would be possible for an as yet unqualified product type for which there are no specific standards. This process is detailed in National Grid document TS2.03 (transformers and reactors), section 2 (testing). The intention was to carry out:

1.1 Thermal Tests

Thermal Test at Rated Normal Current (800A continuous) and Rated Overcurrent (1400A for 15 minutes). During the Rated Normal Current part of the test, measurements of Magnetic Field Density and Noise Intensity would be made and the current transformers mounted on the oil side of the FCL bushings would be tested both with and without the superconducting bias solenoids energised, to ensure that any potential saturation of the cores with the bias field on would not affect their accuracy. The pass criteria for the thermal tests are the temperatures of the oil and windings. The oil temperature was measured directly using a PT100 temperature probe and the winding temperatures were calculated from the resistance of the windings, measured a short time after removal of the current and again when the FCL had cooled to ambient temperature, with a correction applied based on exponential cooling of the system. Before and during the Thermal Test, loss measurements were made.

1.2 Short Circuit Tests

Short Circuit Test at the site fault level of 20.9kA peak; 7.7kA rms symmetrical at 33kV. 5 x 0.25 second duration tests, and 1 x 3second test.

1.3 High Voltage tests

- a Single-ended full-wave lightning impulse voltage withstand tests at 170kV, applied to one end of each winding in turn, with the other end and remaining windings and frame earthed.
- b Double-ended full-wave (170kV) and chopped (185kV) lightning impulse tests applied to both ends of each winding in turn, to cover the situation where the FCL is bypassed by closing the bypass circuit-breaker.
- c Power-frequency voltage withstand tests at 70kV rms, applied to each phase for 1 minute.
- d Partial discharge test in accordance with Grid 2.3.17

Of the above, only the thermal and associated tests have been satisfactorily completed along with one (out of 6 required) short-circuit test, during which a short-circuit occurred in one of the superconducting bias solenoids.

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2. TYPE TESTING

2.1 IPH December 2013

The FCL was transported to IPH in Berlin, Germany arriving December 2nd. IPH had been given a test programme covering the details of all of the testing described in the previous section. The superconducting solenoid assemblies (hereafter referred to as the magnets) were assembled to the FCL frame and energised, as the final stage of their commissioning. The ac tank was dropped in to the magnet warmbores and the magnets were energised again. The 800A ac current injection began 6th December.



Figure 1 FCL Assembly



Figure 2 FCL during thermal tests

2.1.1 Thermal Testing at 800A; 50Hz

Thermal testing at 800A continuous current was carried out until thermal equilibrium was achieved, during which measurements of magnetic field and noise intensity were made. Loss measurements were also made at the beginning and end of the thermal test, to determine the FCL main circuit losses both at ambient temperature and steady state with 800A flowing. At the end of the test the temperatures of the oil (at the top of the oil volume) and windings were measured and recorded. The thermal and associated tests were completed eventually on December 10th following some difficulties with the supply transformer overheating. The outcome was entirely successful and the results are summarised in Table 1.

Test parameter	Result	Limit
Top oil temperature rise	57.9°C ¹	60°C
Winding temperature rise (average)	56.1°C	65°C
Noise Level at 1m	75dB(A)	90dB(A)
Noise Level at 2m	74db(A)	-
Magnetic field density	40mT at 0.6m from magnet surface	Public Exposure Limit
Magnetic field density	0.5mT at 11m from magnet surface	Pacemaker Exposure Limit

Table 1 800A Thermal Test Results

The average winding temperature rise is determined by measuring the resistance of two of the FCL phase windings in series, at a known interval after switching off the 800A and again when the FCL has cooled to ambient temperature, then using these measurement points to place an exponential cooling profile, which allows back-extrapolation to the time of switch-off. By this means, the winding resistance at switch-off can be determined and by comparison with the cold winding resistance, the winding temperature rises are calculated.

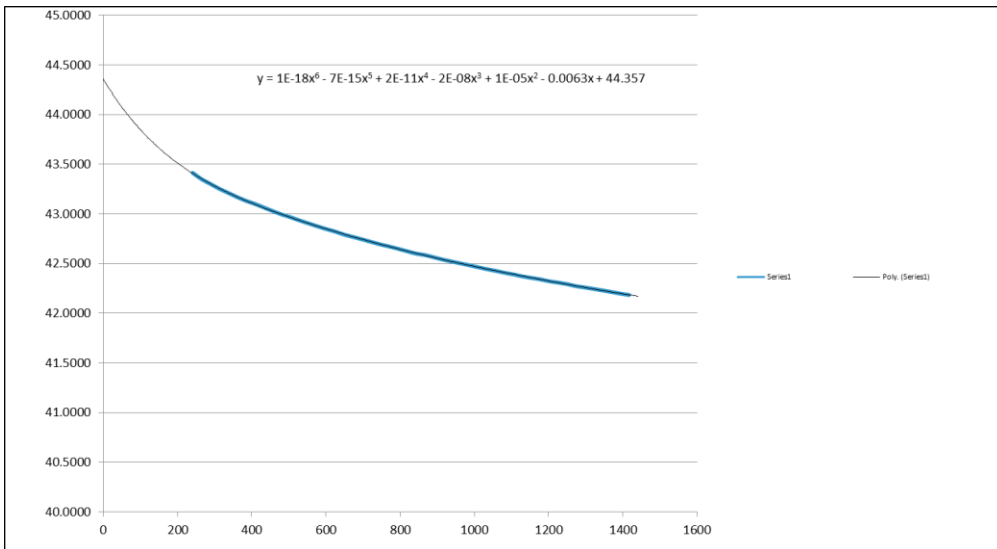


Figure 3 Winding temperature correction showing winding resistance (y) in milliohms measured (blue) and extrapolated (black) against time in seconds (x)

R_cold	35.985	mOhm
Ambient/Oil	20.7	°C
R_warm (extrapol)	44.357	mOhm
Ambient	24.1	°C
Top oil temp.	82	°C
Top oil temp. rise	57.9	K
Winding temp.	80.2	°C
Temperature rise	56.1	K

Table 2 Winding Average Temperature Calculation Results¹

The FCL main circuit losses were also measured, both at the beginning of the 800A thermal test, at ambient temperature and at the end of the test at thermal equilibrium. The results of this are shown in Tables 3 and 4.

	I (A)	U (V)	S (kVA)	P (kW)	Q (kvar)
L1	799	505	404	16	403
L2	789	501	396	20	395
L3	791	500	395	11	395

Table 3 FCL Losses at 20.7°C

	I (A)	U (V)	S (kVA)	P (kW)	Q (kvar)
L1	804	510	410	18	409
L2	796	505	402	22	401
L3	795	502	399	13	399

Table 4 FCL losses at steady state (ΔT oil < 1°C/hr)

2.1.2 Thermal Testing at 1400A; 50Hz

Thermal Testing at 1400A overload current for 15 minutes, during which the top oil temperature was monitored. This test is also reported in Appendix 2.

Test parameter	Result	Limit
Top oil temperature rise	63.7°C ¹	-

Table 5 1400A Thermal Test Results

NOTE 1 It was noted that the ambient temperature, used by IPH for calculating temperature rise from the measured temperatures, was measured some 10 metres distant from the FCL. The value used was 24.1°C. ASL had a PT100 sensor in the air on outside of the auxiliary enclosure, 1m distant from the FCL outer surface (the distance specified by IEC 60076), where the temperature was 29.1°C at the time the final measurements were taken. We therefore regard the oil temperatures in the tables above as being up to 5°C higher than would be encountered in service. This is supported by the observation that the top oil temperature rise in Tables 1 and 3, which is derived from the measured oil and ambient temperatures, is higher than the average winding temperature, which is derived from the two resistance measurements and has no dependency on the ambient temperature measured during the test. The unlikelihood of the top oil being hotter than the average winding temperature is reflected in the limits for top oil temperature rise (60°C) and average winding temperature rise (65°C).

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2.1.3 Current Transformer Performance Tests

Testing of FCL current transformer performance was undertaken on one measurement and one protection CT, both with and without the magnetic field from the two superconducting solenoids. The CTs performed within specifications under all conditions during both magnetisation curve and accuracy tests. Example results below show the ratio error of the measurement CTs with (Figure 4) and without (Figure 5) the magnets energised.

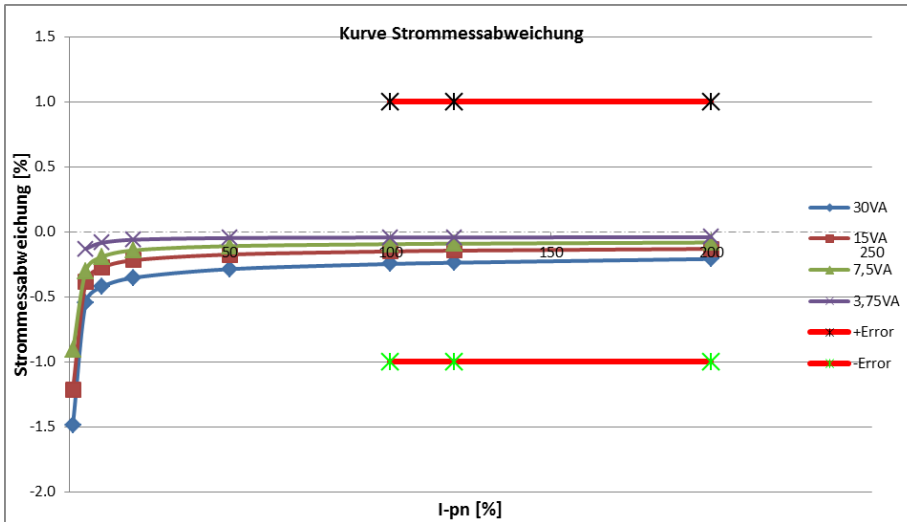


Figure 4 Measuring CT ratio error, Magnets Energised

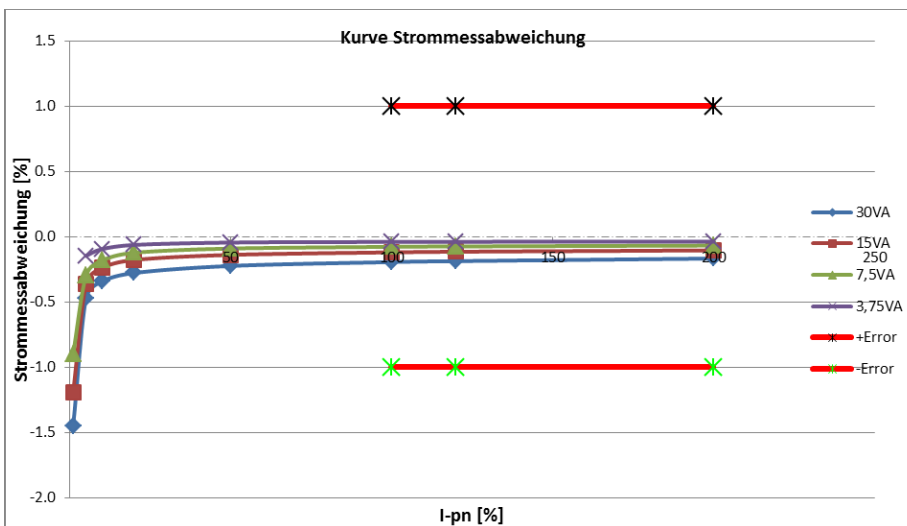


Figure 5 Measuring CT ratio error, Magnets De-energised

A full report of the Thermal and associated tests on the FCL has been received.



Figure 6 IPH Test Report

2.1.4 Short Circuit Tests

The FCL was moved to the short circuit test laboratory on December 11th and a test circuit was prepared to provide at 7.7kA symmetrical with 20.9kA peak at 33kV. Two tests with a positive and negative peak applied to each phase in turn (6 tests in all) are required, the first five having 250ms duration, followed by a single test with 3 second duration.



Figure 7 The FCL (left) and Auxiliary Enclosures (right) in the Short Circuit Test Cell

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During the first test, performed on December 12th, the limiter performed broadly as expected in terms of limiting performance (see Figure 2). The limited peak current was 13.7kA and the symmetrical limited current, measured at 100ms, was 4.9kA rms, the targets being 13.0kA peak and 4.8kArms respectively. However, during the test, the upper superconducting solenoid developed an internal short-circuit and could not subsequently be re-energised. This was later diagnosed as being due to an insulation failure at one of the current lead cooling clamps. Higher voltages than expected were also measured inside the magnet. Modelling of the electromagnetic behaviour of the system to understand why this occurred is ongoing and will indicate what alterations to the solenoid design are necessary.

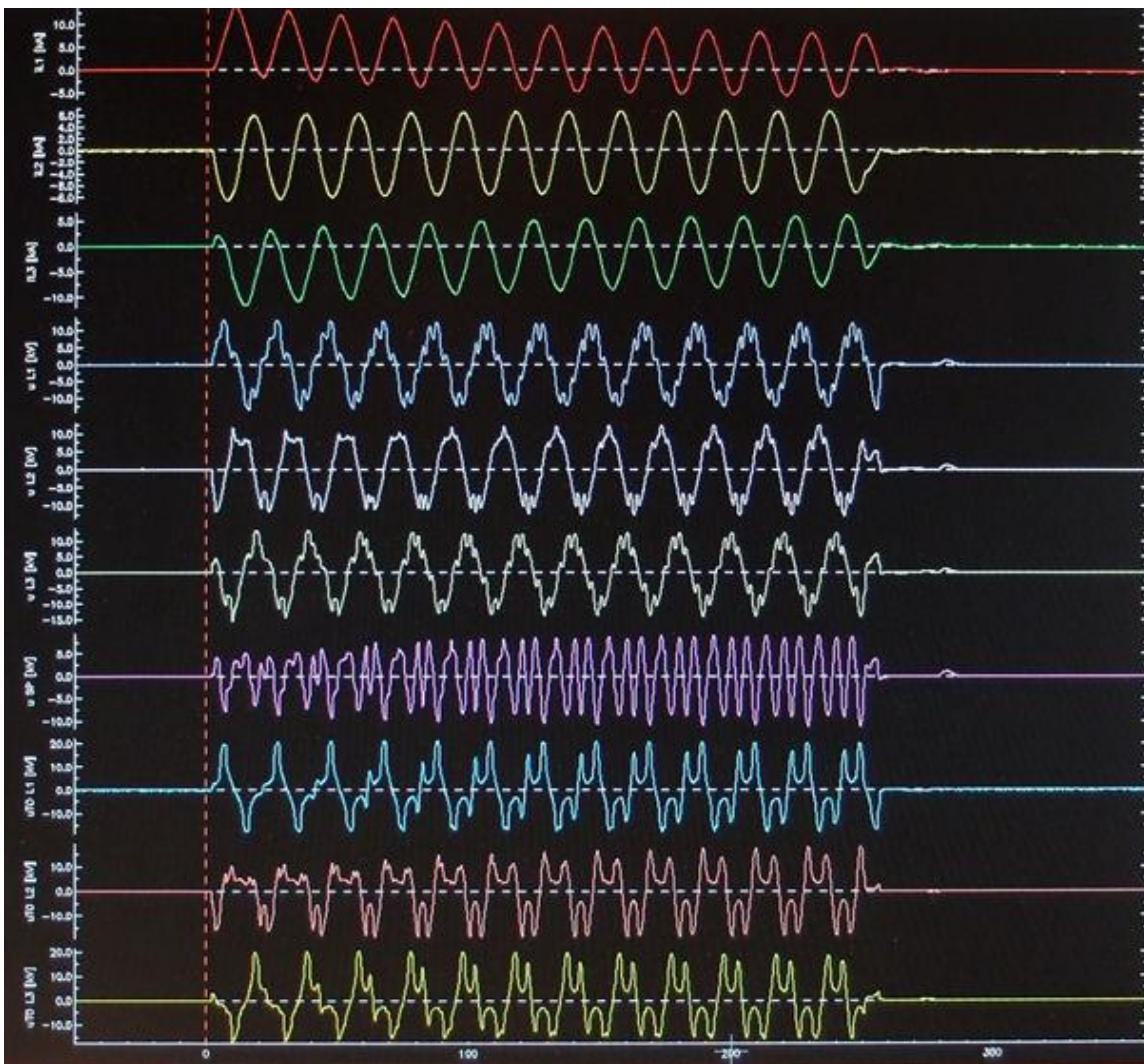


Figure 8 Photograph of IPH short circuit laboratory computer screen. The traces are 1-3 limited current, 4-6 phase voltages, 7 star-point voltage, 8-10 voltage across each phase of FCL.

2.1.5 High Voltage Testing

High Voltage testing comprising lightning impulse voltage withstand, power frequency voltage withstand and partial discharge tests has not yet been undertaken and will not be carried out unless successful short-circuit tests have first been performed.

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2.2 IPH May 2014

The FCL was transported to IPH in Berlin, Germany arriving May 5th. The test programme was as outlined in Sections 1.2 and 1.3 of this report, with an additional load-current test to be performed first. As the thermal test equipment, used in December 2013 was not available, it was agreed that a 3-phase 400V fixed voltage mains supply, capable of providing 640A, would be used and a diesel generator was brought in to provide this, with the FCL in the short circuit test cell. The purpose of this test was to demonstrate that the field generated by the two superconducting solenoids was sufficient to saturate the ac winding cores to the degree required and to allow some measurements to be made of the internal temperatures in the magnets' cryogenic systems.



Figure 9 FCL and Generator in Short Circuit Test Laboratory

Before the test was undertaken, attempts were made to raise the dc bias current in the two magnets to the 97A at which the magnets produce the field density required. An anomaly in the upper magnet, later shown to be caused by a number of turns being short circuited (as distinct from the entire solenoid, as had been the case during the December tests) was noted, so it was decided to continue testing with the upper magnet only partially energised.

The 400V supply, which was expected to cause about 640A to flow in each phase of the FCL, was connected. The FCL phase current only reached about 43A and it was clear that the fault in the upper magnet was having too severe an effect to allow any further testing to be carried out. No official report was requested and no further tests were undertaken.

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3. CONCLUSIONS

The solenoids and cooling equipment have been returned to ASG in Genoa and the solenoid assemblies have been dismantled. Modelling is being undertaken in conjunction with the University of Bologna, under the supervision of Professor Antonio Morandi who is an expert in the fields of coupled electromagnetic systems and superconductivity. ASG's intention is to provide magnets with the functionality and ac field immunity to ensure that the FCL operates as it was designed to do and to further develop understanding of the complex interactions in the electromagnetic system.

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