Superconducting Fault Current Limiter

33kV Network Impact Report

Milestone 3

CONFIDENTIALITY (Confidential or not confidential) :NOT **CONFIDENTIAL**
PROJECT OR PRODUCT : 33kV 800A normal current 2000A continuous over current design

UNIT APPROVAL	**Name**	**Date**
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REVISION HISTORY RECORDS

Revision	**Date**	**Creation / Update summary**
Issue 1	28.2.2011	Customer Issue
Issue 2	14.3.2011	Updated after AC comments

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1. INTRODUCTION

This report details the modelling of the performance of the 33kV Fault Current Limiter in location at Jordanthorpe and shows the proposed design to be fit for purpose.

2. MODELLING DATA

2.1 Network Data

The network data required for the fault current limiter modelling has been extracted by ASL from the CE YEDL LTDS. This data includes the Network X/R Ratio (~35), the network fault ratings, and the normal load current (800A [>50% of the forecast winter peaks, i.e. the load seen by the FCL which is half the substation load]). The unit will pass 800A with a voltage drop not exceeding 600V. At 2000A the voltage drop is higher, but the unit can carry 2000A continuously.

2.2 Transformer Data

The transformer data required for the fault current limiter has been extracted by ASL from the National Grid Seven Year Statement (SYS). The highest of the impedance transformer figures have been used from the SYS individual transformer data to model the transformer with the FCL installed, leaving the lower impedance transformer (and therefore worst overall case fault current) unlimited.

3. SIMULATION RESULTS

3.1 Results

Zenergy, in their report have shown that the Fault Current Limiter can perform the required limiting function for the Jordanthorpe Network installation. A fault current limiter normal current of 800A (with an associated voltage drop of ~600V), with a continuous overcurrent rating of 2000A can be designed to limit the Jordanthorpe Fault Level by over 40%. The associated figures are shown in Figure 1 below and can be checked by CE using DINIS:

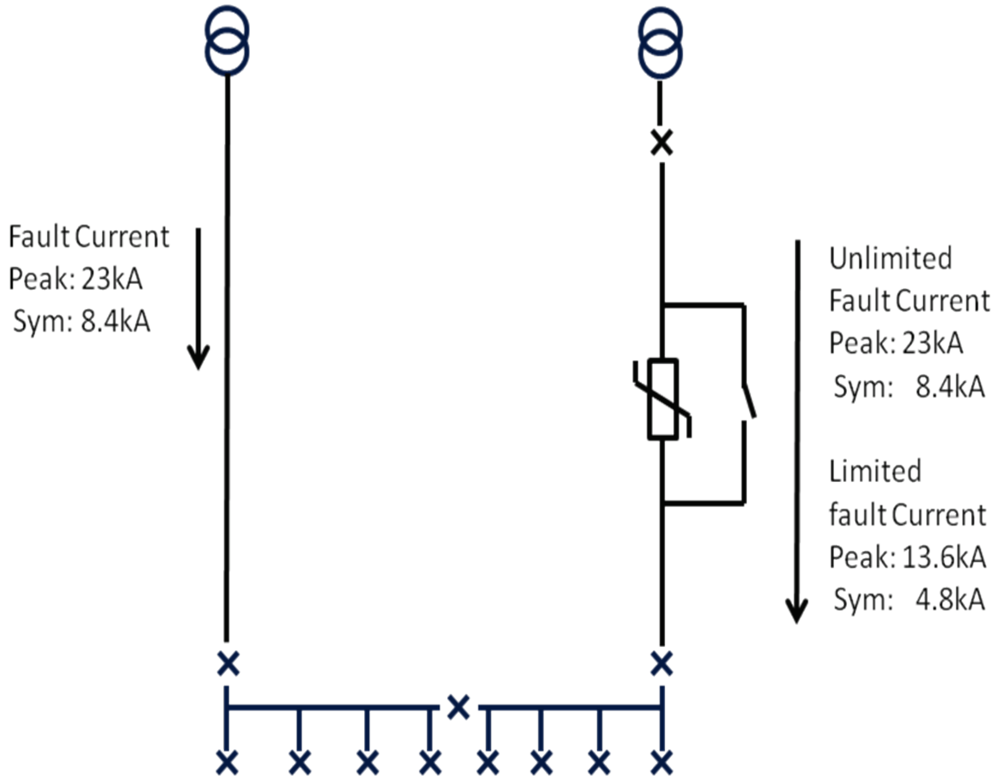

Figure 1: Fault current limiter impact at Jordanthorpe. Data from Zenergy report.

3.2 Model outputs

Zenergy, in their report have provided code and values for a dynamic, real time model. This can be used for transient analysis. For a fixed analysis the following values of impedance for the Fault Current Limiter should be used:

Time	R	X
T<0 (pre fault)	0.009 Ω	0.6500Ω
T=10ms (after fault onset, 1st peak)	0.009 Ω	1.51325Ω
T=100ms (breaker opens)	0.009 Ω	1.51325Ω

4. DELIVERABLES

There are five deliverables that form this milestone.

4.1 Network Configuration

This deliverable has been documented in the Phase 1 milestone report. The connection will be a transformer tail connection suitable of carrying normal load current [50% of winter peak] with a continuous overcurrent capable of carrying the full transformer output including a 1.3x overload factor [2000A]. The FCL will be installed with a 5 panel board such that the FCL can be isolated or bypassed as necessary.

4.2 Zenergy report

A report by Zenergy, modelling their device in the Jordanthorpe network is included as Appendix 1.

4.3 Data Suitable for network modelling software

Zenergy, in their report have provided code and values for a dynamic, real time model. This can be used for transient analysis. For network modelling, section 3.2 provides fixed values of impedance.

4.4 Protection Scheme

The 33kV Protection scheme is based upon the 11kV scheme developed for the Scunthorpe installation with some minor changes. The 33kV units have a different bus zone protection scheme which does not rely on a CT in the National Grid transformer neutral, so the 11kV scheme will need to be simplified to remove this. Further a new metering point is required for grid on the breaker it is proposed that they adopt. The other provisions for the 33kV protection, based on the 11kV scheme are as follows:

- Move NG board incomer metering [CT&VT] to new NG breaker
- Move NG board OC&EF to new NG breaker
- Fit fast acting differential protection around FCL
- Fit OC&EF relay on FCL Transformer side, paralleled on bypass breaker and paralleled with the transformer neutral to protect cable to new board and back up protection to FCL
- Fit unit protection between FCL (board side), bypass breaker and board incomer to protect cable to existing board from new board
- Fit VTs and CTs for disturbance recorder

The overlapping zones are shown in figure 2.

These changes will need to be discussed further with National Grid.

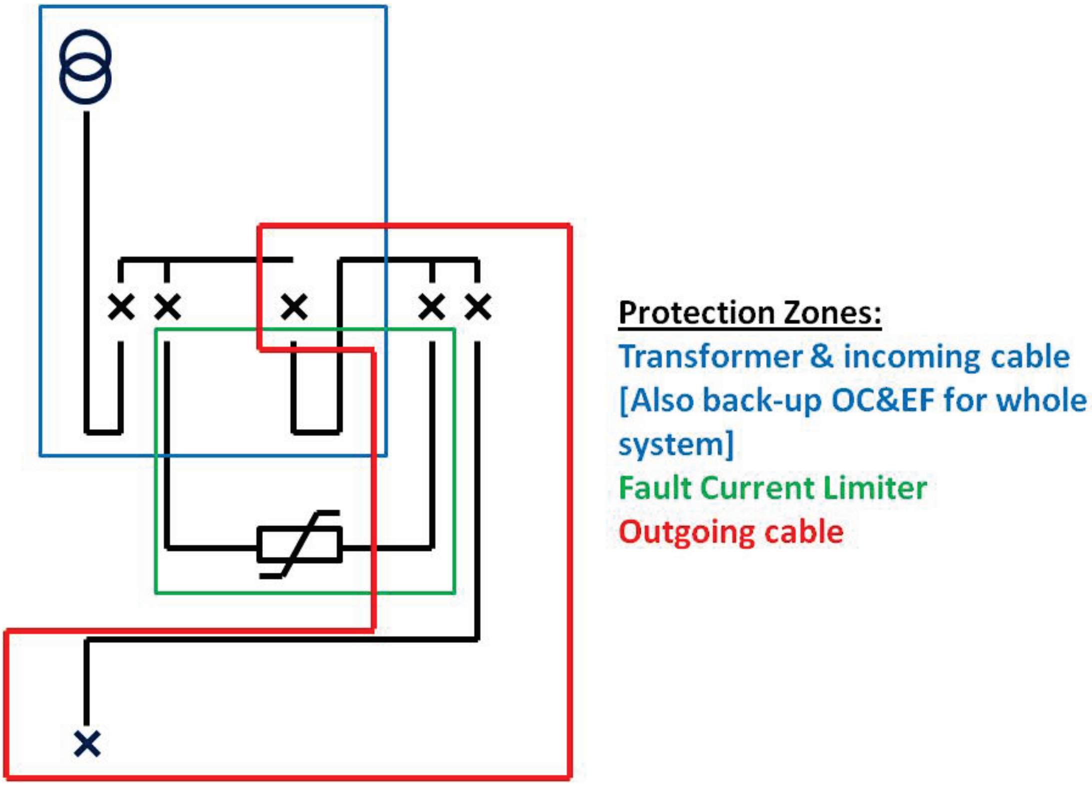

Figure 2: protection zones

4.5 X/R Ratio, Test lab and actual network impact.

The difference between Jordanthorpe and a Test Laboratory is the X/R ratio it is capable of achieving. The lab will typically have an X/R ratio of ~60 whereas Jordanthorpe has an X/R of 35. This implies that the prospective peak and rms values cannot be simultaneously delivered, so a simple conversion is necessary.

LTDS peak/rms fault level ratios are higher than you would expect for a circuit with the given X/R. This is because the network contribution to fault level as you calculate it raises the peak value without affecting the symmetrical too much. But the test lab X/R is big enough to create a similar peak/rms ratio, so we can confirm the performance without making a special test-circuit.

In this case, The Transformer impedances (in Ohms) are

	R	X_L
T1	0.064796	2.27601
T2	0.065231	2.27057

These give X/R = 35 which gives a peak/rms factor of 2.708

The limiter impedances to fault current are

R	X_L
0.009	1.51325

If we add them (T2 + FCL) we get

R	X_L
0.074231	3.78382

These give X/R=51, which gives a peak/rms factor of 2.744 [1.3% higher], but on an rms fault level which is reduced by 40% due to the insertion of the FCL's impedance.

4.6 Network Losses.

The voltage drop (reactive) is, based on an impedance of 0.65 Ω, about 520V at 800A. A fixed reactor having the same fault-limiting capability as the FCL, would have a constant impedance of 1.5Ω and would thus drop 1200V. These impedances are largely inductive.

5. CONCLUSION

This report details the evidence that the 33kV Fault Current Limiter has been modelled in location at Jordanthorpe and is shown at this stage to be fit for purpose. The Zenergy report is included as an Appendix.

End of Report

Engineering Report

ASL Sheffield
ASL Fault Current Limiter Model

February 2011

ZENERGY POWER

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Engineering Report

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Executive Summary

A description of the ASL Sheffield Fault Current Limiter model is presented. The elements of the electric power grid in the Jordanthorpe Grid Supply are described and the fault current limiter non linear model is illustrated including the non-linear behavior of the inductive performance of the FCL. With the elements provided, ASL together with CE Electric shall implement the non-linear behavior of the FCL in their IPSA software or other modeling platform to simulate fault current limitation as per the issued requirements.

List of Revisions ZP-ER2011-002

Revision	Date	Action	Modified Page
A	02/24/11	Released	

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1 Applicability

ASL Sheffield Network Fault Current Limiter at the Jordanthorpe Grid Supply Point

2 Acronyms and Definitions

2.1 Acronyms

ASL	Applied Superconductor Limited
FCL	Fault Current Limited
HTS	High Temperature Superconductor
ZEN	Zenergy Power, Inc.
PSCAD	Power System Computer Aided Design

2.2 Definitions

Continuous Normal Current: The root-mean-square (rms) power frequency current in amperes that can be carried for the duty specified at rated frequency without causing further measurable increase in temperature rise under the prescribed test conditions and within established standards limitations.

Prospective Unlimited Peak Fault Current: Maximum first peak asymmetric fault current without any reduction by fault current limiting action.

Peak Limited Current: Maximum first peak asymmetric fault current reduced by fault current limiting action.

Symmetrical Unlimited Current: RMS value of the fault current where its waveform is symmetrical about its zero axis, under no fault current limiting action

Symmetrical Limited Current: RMS value of the fault current where its waveform is symmetrical about its zero axis, under fault current limiting action

Nominal Voltage: A line-to-line voltage assigned to a system or circuit of a given voltage class for the purpose of convenient designation.

Impedance: The phasor sum of the reactance and resistance expressed in Ohms.

Impedance Voltage Drop: The product of the rated Ohms impedance and the rated current.

Rated Inductance: The total installed inductance at a specified frequency. It may consist of mutual aswell as self inductance components.

Maximum Allowable Steady State Voltage Drop: The maximum acceptable voltage drop on the FCL under normal operation and continuous normal current.

Asymmetry Factor: The ratio between the Prospective Unlimited Peak Fault Current and the Symmetrical Unlimited Fault Current.

3 Description of the ASL Fault Current Limiting Requirements

The list of ASL requirements for the 33kV Sheffield Network Fault Current Limiter was presented in [1] ASL Circuit Analysis and Specification, and is listed in table 1 below

Parameter	Requirement
Rated voltage	36kV
Line frequency	50Hz
Line voltage at fault level below	33kV
Maximum allowable steady state voltage drop at rated continuous normal current (800A)	600V rms
Lightning impulse voltage withstand level	170kV; 1.2/50µs
Power frequency voltage withstand level	70 kV for 1 minute
Continuous normal current	$800A_{rms}$
Maximum normal current (magnitude and duration)	$2000A_{rms}$ continuous
Prospective unlimited peak fault current	$23\ kA_{peak}$
Peak limited current	$<13.6\ kA_{peak}$
Prospective unlimited symmetrical fault current	$8.4\ kA_{rms}$
Symmetrical limited current	$<5kA_{rms}$
Fault duration	Up to 3 seconds
Reclosure sequence (if applicable)	N/A
Transformer Impedance (ohms)	R 0.0645231 X_L 2.27057
Feeder X/R; Asymmetry Factor	35.19 2.708
Typical test laboratory X/R	60
Load power factor	0.98
Size or weight constraints (if applicable)	N/A (yet)

Table 1: Sheffield Network Data at the Jordanthorpe Grid Supply Point

3.1 Fault Current Limiter at the Jordanthorpe Location

3.1.1 General representation

The Fault Current Limiter will be connected into a 275 kV/33 kV transformer tail at Jordanthorpe Grid Supply point, as depicted in figure 1, on the load side of one of the two 275/33 kV transformers. Figure 2 is a basic PSCAD representation of the circuit in figure 1 which yields the peak fault current value, X/R fault ratio and load parameters needed to draw the required continuous normal operating current requested in the customer requirement sheet of table 1.

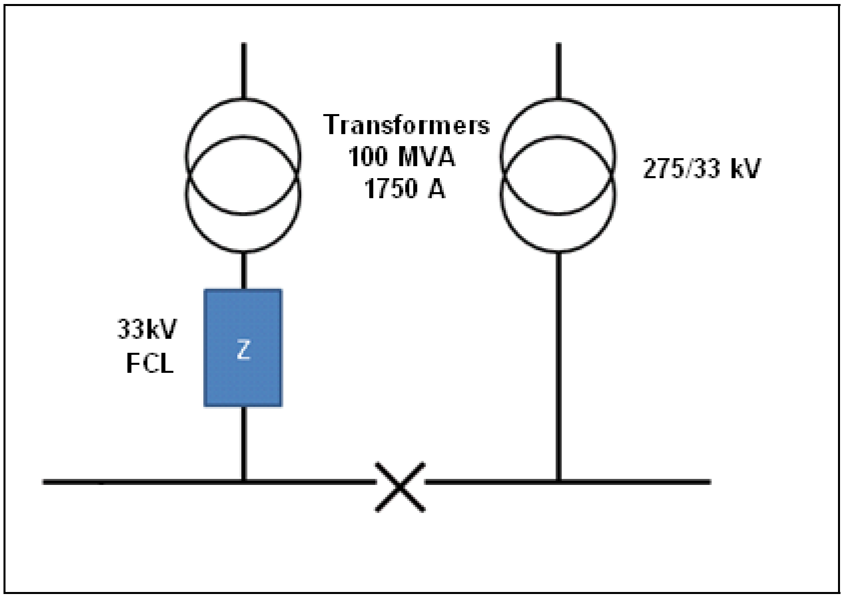

Figure 1: Single Line Representation of the ASL FCL Model at Jordanthorpe Site for Calculation of Prospective Fault Currents

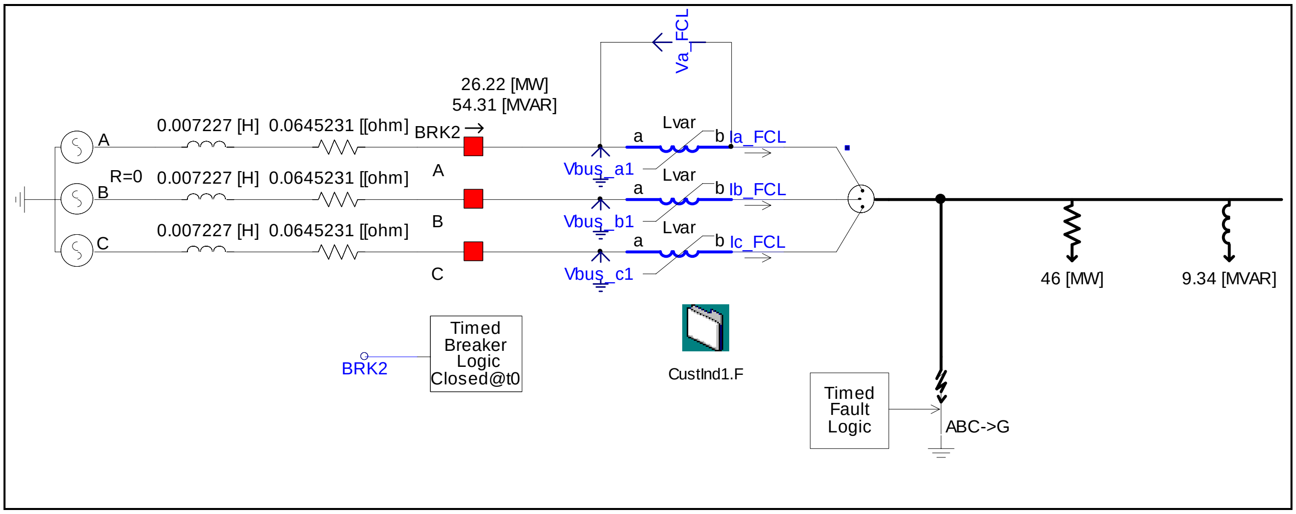

Figure 2: Three Phase Representation of the ASL FCL Model on a Transformer Tail at Jordanthorpe

3.1.2 Grid parameters

Circuit parameters in [1] were used in the design and simulation of the FCL. We summarize below the circuit parameters and the FCL model. AC source

The source parameters in the ASL Sheffield network at the Jordanthorpe site are as follows:
AC source voltage: 33 kV
Rs=0.0645231 [ohms]
Xs = 2πfL$_s$ = 2.27057 [ohms]
Xs/Rs= 35.19

3.1.2.1 Load Parameters

Z_{load} = 46MW + 9.34 MVAR three phase resistive and inductive loads,, which render a load power factor of 0.98 [1].

3.1.2.2 Non-linear behavior of the FCL

The back EMF across the FCL is a function of the instantaneous AC current i, and its time derivative. It is calculated as follows:

$$V_{FCL}(t) = f(i)\,\frac{di}{dt}$$

$$= \frac{2\,d\,c\,e}{\left\{1 + \tan^{-1}\left[\pi\left(K - \frac{1}{2}\right)\right]\right\}} \frac{1}{\left\{1 + \left[K\frac{\pi}{a}(a - |i|) - \frac{\pi}{2}\right]^2\right\}} \left(K\frac{\pi}{a}\right)\frac{di(t)}{dt} \qquad (1)$$

$$-a \leq i \leq a$$

Where:

$$K = \frac{a}{b} \; for \; K > 1$$

If the instantaneous function f(i) is smaller than the air core inductance (L_{air}) then f(i) takes the value of L_{air}. The total inductance of the two coils in series is the instantaneous sum of the two inductances. At any given value of current one of the two coils has the L_{air} inductance value and the total equivalent inductance is given by:

$$L_{total} = f(i) + L_{air}$$

If the computed value of f(i) is less than or equal to L_{air} then the total equivalent inductance is equal to 2*L_{air}

For this particular design the model has to adopt the following values:

$a = 7500$
$b = 4000$
$c = 100$
$d = 2.2$
$e = 0.11$
$L_{air} = 691\ \mu H$

Changing any of these parameters in the model will alter the expected behavior of the fault current limiter.

3.1.2.3 Implementation of the FCL model formula

A variable impedance/source branch model as it was implemented in EMTDC/PSCAD can be used to represent a non-linear inductor. This is illustrated in figure 3.

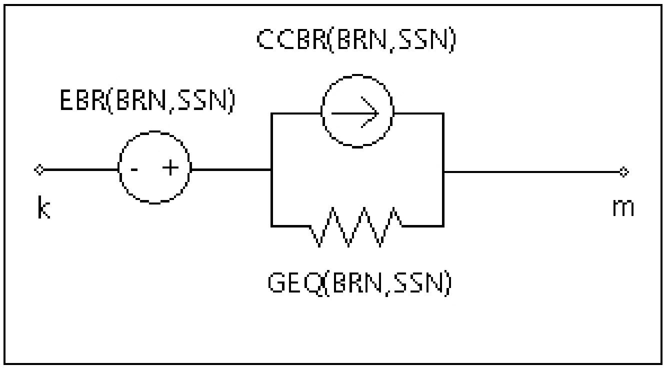

Figure 3: Branch-based Electric Interface

These three quantities are represented by the following EMTDC Internal Variables:

EBR (BRN,SS) sets the value of the optional branch voltage source
CCBR (BRN,SS) sets the value for the equivalent history current source
GEQ (BRN,SS) sets the value of the branch equivalent conductance

The model uses the following variables:
CURR - Output Branch Current (from last time step)
Z - Input Branch Impedance L (Henries)
E - Input Branch Series Voltage Source (kV)

For every calculated f(i) value in equation (1) the Fortran Subroutine Custom_VARL(NBR , M , RLC , CURR , Z , E) in PSCAD is called. Here the inductance is controlled by the signal “Z” while “E” controls the internal voltage source EBR. BRN is the branch number assigned in the component definition in the circuit.

The process in PSCAD is iteratively carried out by setting the source voltage and measuring the total current that arrives at the current source and conductance branches in parallel in figure 3 since that would be the current through the FCL.

3.1.2.4 PSCAD Fortran Subroutine

The Fortran 90 subroutines developed in PSCAD and that are used for the calculation of the back EMF developed across the FCL terminals are included here as a reference and presented in the Appendix.

3.1.2.5 Simulation example

Figure 4 shows results from a simulation run with a staged three phase to ground fault using the PSCAD model depicted in figure 2. The prospective and limited fault currents along with the load current prior and after the fault are included.

	Prospective Fault Current	Limited Fault Current	Load Current
First peak asymmetric current	22.72 (kA)	13.57 kA (40.2% reduction)	X
Symmetric fault current	8.39 (kA)	4.76kA (43.3% reduction)	800A

Table 2: ASL Sheffield FCL PSCAD Simulation Results

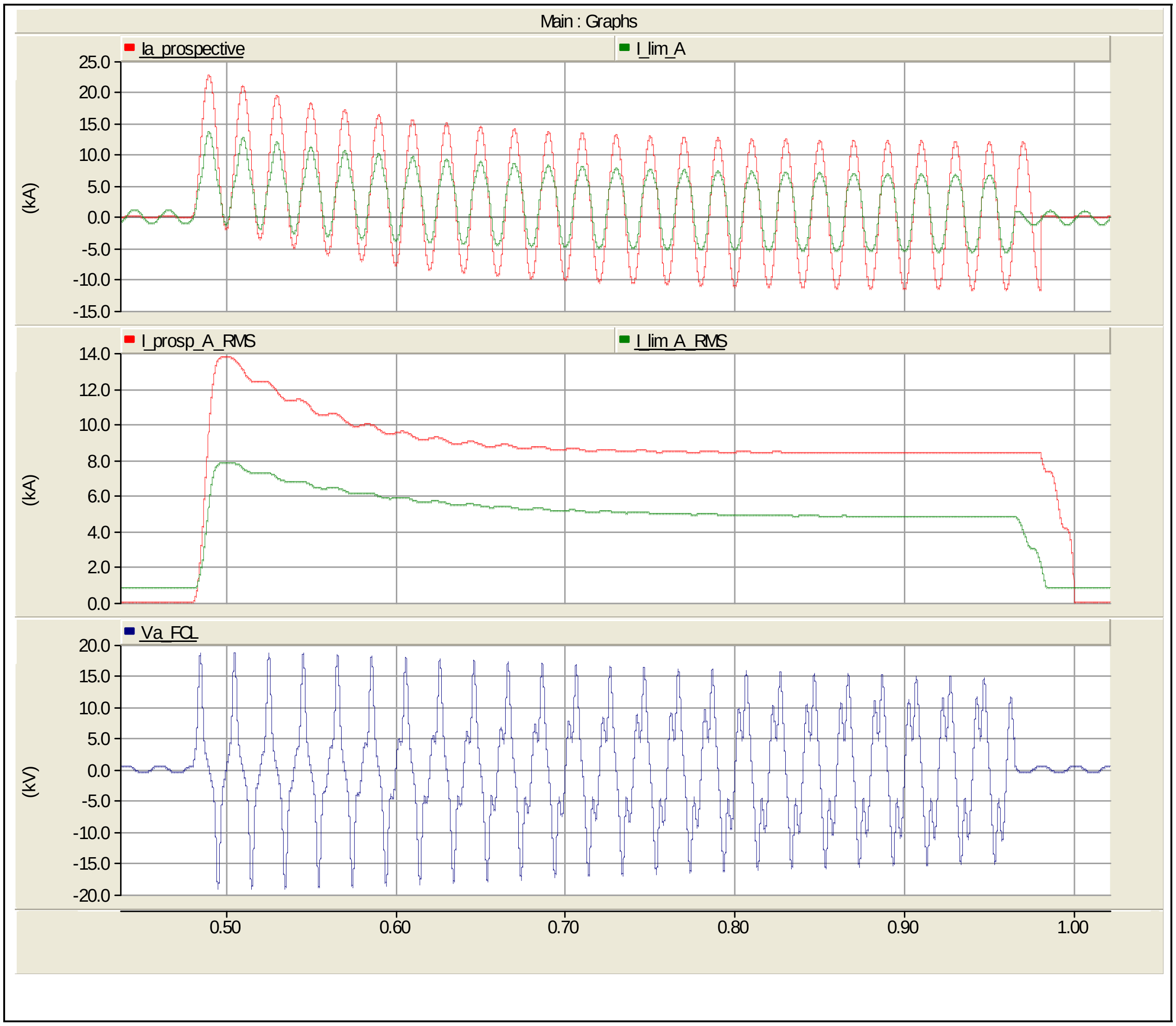

Figure 4: Simulation of a Tree Phase to Ground Fault at the Jordanthorpe Grid Supply Point

4 Conclusions

The electrical components of the ASL 33 kV Sheffield FCL model are described and the non-linear representation of the FCL is illustrated through a Fortran 90 subroutine that Zenergy used when developing the PSCAD model of the FCL. This model shall be implemented in the CE modeling platform.

5 References

[1] “33 kV Project Specs“, ASLInternal Document, 2010.

6 Appendix A FCL PSCAD Subroutine

```
      SUBROUTINE SIMPLE_L(SS, BR1, BR2,c,a,b,d,e,Lair, &
     &Ltot,Iac)
! --------------------
      INCLUDE "emtconst.h"   ! Commonly used constants
      INCLUDE "nd.h"         ! dimensions
      INCLUDE "emtstor.h"    ! storage arrays and indexes
      INCLUDE "s0.h"         ! VDC,CCIN,GGIN,
      INCLUDE "s1.h"         ! TIME,DELT,PRINT,FINTIM,
      INCLUDE "branches.h"   ! CBR,CCBR,EBR,GEQ,IEF,IET,
!------------------------------------
!  Subroutine parameter declarations
!------------------------------------
      INTEGER SS,BR1,BR2
      REAL c,a,b,d,e,Lair
! --------------------
! Variable Declarations
! --------------------
      REAL Ind
      REAL K
      REAL Iac
      REAL Ltot
      REAL VARR_I
! --------------------
      K = a/b
      If (K.LT.1.0) K = 1.0
      Iac = CBR(BR2,SS)

      Ind = 2.0*d*c*e*K*pi_/a
      Ind = Ind/(1.0 + atan(pi_*(K-0.5)))
      Ind = Ind/(1.0 + (K*(pi_/a)*(a-abs(Iac)*1000)-pi_*0.5)**2)

      If (Ind.LT.Lair) Ind = Lair

      Ltot = Ind + Lair

      CALL Custom_VARL(BR1,SS,1,VARR_I,Ltot,0.0)

      RETURN
      END


      SUBROUTINE Custom_VARL( NBR , M , RLC , CURR , Z , E )
! -----------------------------------------------------------------
! ====================================================================
!   Include and Common Block Declarations
! ====================================================================
```

```
      INCLUDE 'nd.h'
      INCLUDE 'harmimp.h'
      INCLUDE 's0.h'
      INCLUDE 's1.h'
      INCLUDE 's2.h'
      INCLUDE 's8.h'
      INCLUDE 'branches.h'
      INCLUDE 'ideal.h'
      REAL    CURR,Z,E,VARGEQ
      INTEGER IFR,ITO,NBR,M,RLC
!
! ======================================================================
!   Model Begins
! ======================================================================
!
! Check If Impedance Value Has Changed:
      IF ((TIMEZERO).OR.(ABS(STOR(NEXC+1)-Z).GT.1.0E-20)) THEN
        SOURCE(NBR,M) = .TRUE.
        IF ( ABS(Z) .GT. 1.0E-20 ) THEN
! Inductor
          IF ( RLC .EQ. 1 ) THEN
            VARGEQ  = 0.5 * DELT / Z
            RESISTOR(NBR,M) = .FALSE.
            INDUCTOR(NBR,M) = .TRUE.
            CAPACITR(NBR,M) = .FALSE.
            G2L(NBR,M)  =  VARGEQ
            RLG(NBR,M)  =  1.0
            RCG(NBR,M)  =  0.0
            BRANCH_L(NBR,M)  =  Z
          ENDIF
        ELSE
          VARGEQ  = 1.0E20
          RESISTOR(NBR,M) = .TRUE.
          INDUCTOR(NBR,M) = .FALSE.
          CAPACITR(NBR,M) = .FALSE.
          RCG(NBR,M)  =  0.0
          RLG(NBR,M)  =  0.0
          BRANCH_R(NBR,M)  =  1.0E-20
        ENDIF
          IDEALBR(NBR,M) = .FALSE.
! ----------------------------------------------------------------------
! VARIABLE IMPEDANCE BRANCH
! ----------------------------------------------------------------------
        GEQ(NBR,M)  =  VARGEQ
        IFR = IEF(NBR,M)
        ITO = IET(NBR,M)
        CALL SETMXINV(M,IFR,ITO)
        STOR(NEXC+ 1) = Z
      ENDIF
! ----------------------------------------------------------------------
!  SET SOURCE VOLTAGE AND MEASURE CURRENT
```

```
! ------------------------------------------------------------------------
     EBR(NBR,M)      =   E
     CURR           = CBR(NBR,M)
! ========================================================================
! INCREMENT STORAGE POINTER
! ========================================================================
     NEXC = NEXC + 10
     RETURN
     END
```

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