2008

Investigation on the suitability of PSCAD/EMTDC models to study energisation transients of 132kV underground cables

Muhamad Daud
University of Wollongong

Philip Ciufo
University of Wollongong, ciufo@uow.edu.au

Sarath Perera
University of Wollongong, sarath@uow.edu.au

Publication Details

M. Daud, P. Ciufo & S. Perera, "Investigation on the suitability of PSCAD/EMTDC models to study energisation transients of 132kV underground cables," in AUPEC 2008: Australasian Universities Power Engineering Conference, 2008, pp. 1-6.

Investigation on the Suitability of PSCAD/EMTDC Models to Study Energisation Transients of 132 kV Underground Cables

M. Z. Daud, P. Ciufo, S. Perera
Integral Energy Power Quality and Reliability Centre
School of Electrical, Computer and Telecommunications Engineering,
University of Wollongong,
NSW 2522 Australia

***Abstract*-Behaviour of energisation transients of high voltage (HV) underground cable system can be established through carefully crafted simulation studies. This information is useful for design engineers to ensure that protection and insulation co-ordination are able to meet design criteria. This paper presents an assessment of the validity and applicability of existing cable models in PSCAD/EMTDC to study energisation transients of HV cable systems. The models considered are the Distributed Parameter Travelling Wave models (FD-Phase and FD-Mode models). Their performance is analysed through comparison of simulated results with measured current transient behaviour during the energisation of a 132kV, 5.6 km underground cable system. The results obtained from FD-Phase model demonstrate acceptable agreement with experimental data, whereas the simulation results of FD-Mode model predicted slightly lower transient peak magnitudes. Both models give reasonable settling time of the corresponding transient envelope.**

I. INTRODUCTION

As part of the design process, electricity utilities require suitable cable models that can be used to predict energisation transients of underground high voltage cables. Accurate modelling and simulation of such behaviour provides guidance in the determination of the adequacy of protection schemes as well as insulation coordination. Underground cable modelling, for example, has become a topic of ongoing interest and research over many years. Some of the difficult factors of modelling the underground cables include their distributed nature, frequency dependent parameters and the asymmetrical arrangement of coupled conductors with ground return [1].

From decades of development of electromagnetic transient simulators, reasonable accuracy can be mostly achieved for the case of overhead lines. Many distributed parameter travelling wave transmission line models can be reliably used [2-4]. However, reliable underground cable models are not widely available as is the case of overhead lines. As a consequence, the applicability and validity of underground cable models currently incorporated in electromagnetic transient simulation platforms remains questionable and requires further development.

A number of ATP/EMTP cable models such as the PI (cascaded), KC Lee and Semlyen models have been previously modelled and investigated, resulting in inconsistent behaviour of the simulated current transient [5]. More accurate models such as the Universal Line Model (ULM) [6] and the L Marti [7] underground cable model are required instead. The ULM forms the FD-Phase model, whereas [7] is currently not available in PSCAD/EMTDC. However, the FD-Mode model based on [2] is generally valid for certain cases of transient studies. The main difference between [7] and [2] is the way their transformation matrices performed.

This paper provides an assessment of the suitability of existing cable models in PSCAD/EMTDC to study energisation transients of underground HV cable systems. Model performances are analysed through the comparison of simulated data with experimental results of a HV cable energisation current transient. A brief review of the related cable models considered is presented in Section II. The cable arrangement and testing procedure will be presented in Section III. The comparative performance of experimental and simulated data will be analysed in Section IV followed by the conclusions in Section V.

II. CABLE MODELS

A. *Simulated Models*

The network in which the underground cable system under investigation is located, is modelled in PSCAD/EMTDC. The modelling includes representation of underground cable system as the main component and the surrounding components particularly the source, transmission lines and other distribution equipment. The following cable models are selected to represent the entire underground system:

- Frequency Dependent (Mode) model or FD-Mode
- Frequency Dependent (Phase) model or FD-Phase

B. *Frequency Dependent (FD) Models*

The Frequency Dependent models, based on travelling wave methods in PSCAD/EMTDC, are derived from a set of Telegrapher's equations given by:

$$-\frac{dV}{dx} = Z \cdot I \tag{1}$$

$$-\frac{dI}{dx} = Y \cdot V \tag{2}$$

where V and I are vectors representing the voltages and currents at a distance x along the cable system. Z and Y are the corresponding impedance and admittance matrices respectively. The formulation of impedance and admittance parameters, taking into account the frequency dependence of the cable system, is generally performed by Cable Constant (CC) routines in EMTDC-type simulators. In multi-conductor systems, where conductors are mutually coupled, a set of coupled equations obtained as following:

$$-\frac{d^2V}{dx^2} = ZY \cdot I \tag{3}$$

$$-\frac{d^2I}{dx^2} = YZ \cdot V \tag{4}$$

Equations (3) and (4) are then broken-up into modes so that the variables can be solved respectively in the modal domain. Modal transformation matrices may be required and can be obtained from eigenvalue analysis performed by CC routines [8]. Curve fitting calculations are also performed using CC for the frequency dependent distributed parameter travelling wave cable models in PSCAD/EMTDC.

C. *FD-Mode Models*

The FD-Mode model incorporated in PSCAD/EMTDC is based on the formulation in [2]. It assumes a real and constant transformation matrix to decouple the phase variables of Equations (3) and (4) into mode variables to be solved. The transformation of voltage and current variables into modes (matrix diagonalisation) can be simply described by the following:

$$V = T_v\, V' \tag{5}$$

$$I = T_i\, I' \tag{6}$$

$$T_v^{\,T} = T_i^{-1} \tag{7}$$

where *V'* and *I'* are the modal voltages and currents. T_v and T_i are the corresponding voltage and current transformation matrices respectively. This model is considered to be reliable for most cases of overhead lines but not for underground cables where parameters exhibit strong frequency dependence. Nevertheless, a reasonably good accuracy can be still achieved for certain cases of underground cable with using the assumption of [2].

D. *FD-Phase Models*

The difficulties associated with handling the frequency dependence transformation matrix, as outlined in [2], are transcended through direct formulation in the phase domain introduced by the FD-Phase model [6]. The matrix elements of the propagation function and the characteristic admittance which characterises the behaviour of waves over the conductors are fitted directly in the phase domain. This model is theoretically the most accurate since it represents the frequency dependence of internal transformation matrices [8]. The details regarding implementation of this model in EMTDC-type program as a standard model described in [9].

III. CABLE CONFIGURATION AND TEST PROCEDURE

A. *Cable Actual Configuration*

A 132 kV, three phase, 630 mm² single core (copper) coaxial XLPE cable systems with cross-bonded sheath is modelled. The transition points of the sheaths are terminated with sheath voltage limiters (SVL) that are earthed. This should minimise the steady state and transient voltages. The total length is approximately 5.6 km and it is laid underground in open trefoil arrangement as depicted in Figure 1. Further details on the cable dimensions and the cross-section are provided in Appendix 1.

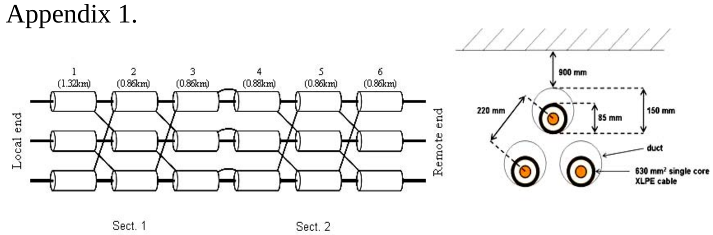

Figure 1.Underground cable cross-bonding and arrangement

B. *Test Procedure*

Two Rogowski coils and a digital oscilloscope were used. The probes are capable of measuring the current transient up to 50 kHz which is considered sufficient for this test. They were connected to the blue and white phases, close to circuit breakers at local end of 132 kV underground cables. To accurately predict the switching time to be used in simulation, the red-to-white and white-to-blue voltages are also measured at the secondary of Voltage Transformer (VT) at the local end.

Remote ends of the cable was first isolated. Then, the loads at nearby busbars were also disconnected to reduce their impact on the transient waveforms to be observed. A period of time was used to allow the capacitive elements to fully discharge. Finally, the local end (circuit breaker) was connected to the supply to energise the cable and the resulting high frequency current transient data were recorded. The data of the second out of four tests were used as benchmark for comparison purpose. These data were considered since their transient peak magnitudes and the transient envelope times were at the average values.

Closer analysis of circuit breaker poles showed that the white phase closed first followed by the red and blue phases. At the instant of switching, the red phase voltage was at the highest magnitude (positive) whilst the blue phase instantaneous voltage was more negative than the white phase.

IV. Measured and Simulated Results

Measurement of the phase current energisation transients were obtained using an oscilloscope, which sampled the current at 250 kHz. The time domain plots are to be compared with simulated data of two cable models outlined in Section II, which has been developed in PSCAD/EMTDC. Further analysis of the corresponding frequency response of cable models considered also presented in the following sub-sections.

A. *Experimental Tests Results*

The measured blue and white phase current transients are depicted in Figure 2. The waveforms were recorded for approximately 30 ms following the energisation of the cable. These signals were then filtered with a third order Butterworth high pass filter with the cut-off frequency set at 200 Hz to remove low frequency components before converting to the frequency domain plots as shown in Figure 3. This process was undertaken to avoid low frequency signals from dominating the frequency spectrum.

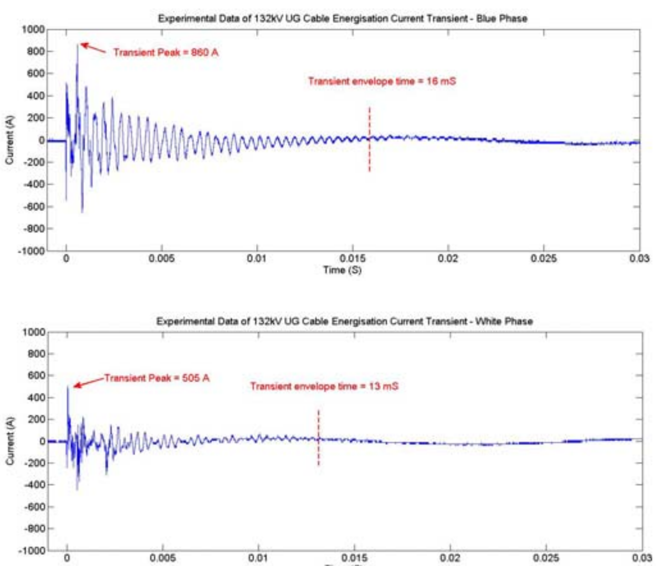

Figure 2.Measured blue (above) and white (bottom) phase current transient

From Figure 2, the transient envelope time for the blue phase is approximately 16 ms whereas the white phase transient envelope is seen to last 13 ms. The blue phase current magnitude peak is around 860 A whereas the white phase peak shows a peak approximately equal to 505 A. Lower peak magnitude for the white phase current is due to the lower instantaneous voltage magnitude during switching.

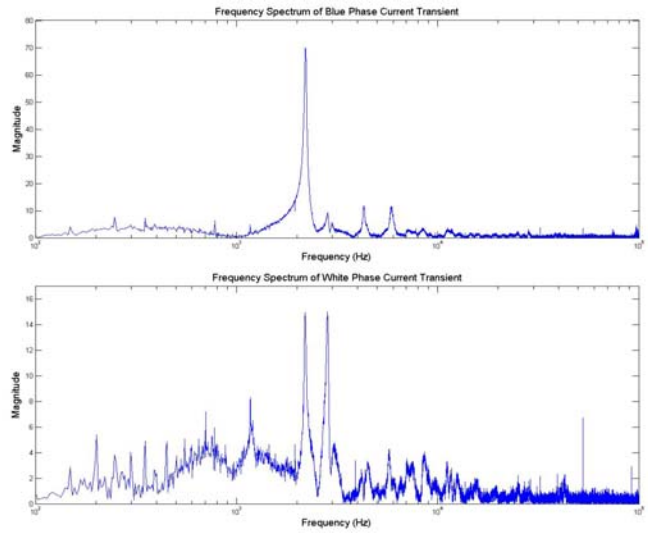

Figure 3.Measured blue (above) and white (bottom) phase frequency spectrum

From Figure 3, it is clear that the frequency spectrum of blue and white phase signals are dominant in the range between 700 Hz to 10 kHz. The major peaks of the signal energy in this range occur at 1.1 kHz, 2.2 kHz, 2.8 kHz, 4.3 kHz and 5.8 kHz.

B. *Circuit Breaker Switching*

In practice, the circuit breaker poles will not close simultaneously. The breaker pole switching times were inferred from the data obtained by measuring voltages at secondary VT. For the simulation length which last in 30 ms, the circuit breaker pole switching times applied are as shown in Table 1.

TABLE I
Circuit Breaker Poles Closing Times

Poles	Red	White	Blue
Closing Times (ms)	0.5288	0.01675	0.5888

C. *Comparison with Simulated FD-Mode Model*

The modal transformation matrix for FD-Mode model was approximated at 10 kHz. This value was based on the assumption made from observed experimental test data. However, the constant transformation matrix assumed may degrade its efficiency as the transient that occurs in underground cable system may vary and increase up to several 100 kHz.

Since only the blue and white phases were measured, the simulated red phase data was not considered for comparison. However, for reference, the red phase current transient waveforms are given in Appendix 2. The simulated current transient data and the frequency spectrum are depicted in the Figures 4 and 5.

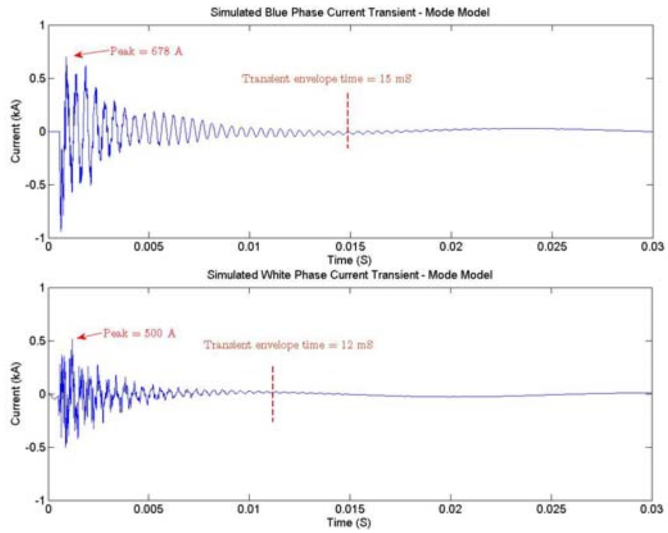

Figure 4.Simulated blue and white phase current transient of FD-Mode model

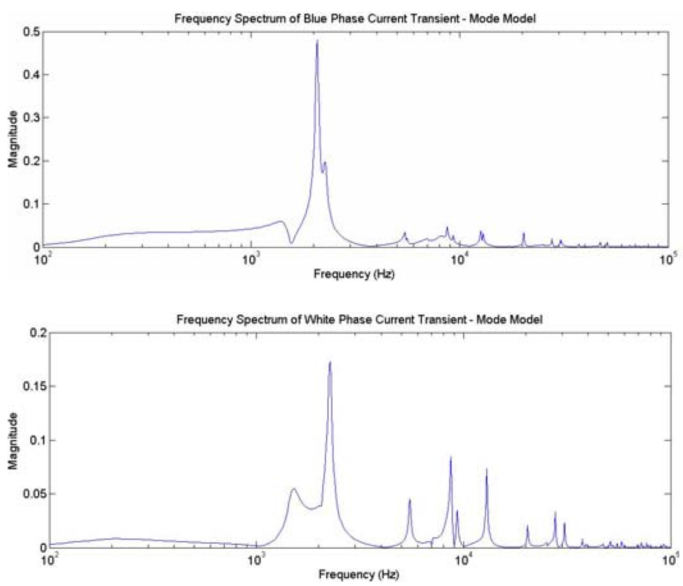

Figure 5.Frequency spectrum of simulated FD-Mode model

From Figure 4, the simulated time domain current transient behaviour gives good agreement of wave shape compared to the measured results. The white phase transient peaks also closely match the measured data. However, the transient peak magnitudes of the blue phase seem relatively low. The blue and white phase current magnitude peak values are 678 A and 500 A respectively. Nevertheless, the FD-Mode model accurately demonstrated the transient envelope time which lasts around 15 ms for the blue phase and 12 ms for the white phase

From Figure 5, the frequency spectrum seems very poor and only several dominant peaks can be seen for both sets of data compared to the measured data in Figure 3. The dominant peaks of both waveforms occur at 2.1 kHz, 5.5 kHz and 8.7 kHz respectively.

D. Comparison with Simulated FD-Phase Model

The FD-Phase model is a robust model currently incorporated in PSCAD/EMTDC. It is theoretically suitable for approximating cable parameters over wide frequency range. It can also be used for the simulation of difficult arrangements of line conditions such as parallel AC and DC lines in close proximity. Furthermore, a reasonable accuracy also can be achieved for unbalanced line or cable conditions using this model. Its efficiency can also be increased by adjusting the curve fitting parameter features. However care should be taken in handling these parameters, because higher demands in accuracy might slow down the simulation time as well as introducing stability problems. This difficulty should be handled carefully when considering rigorous circumstances using this model. The simulated results for this model are depicted in Figure 6 and 7.

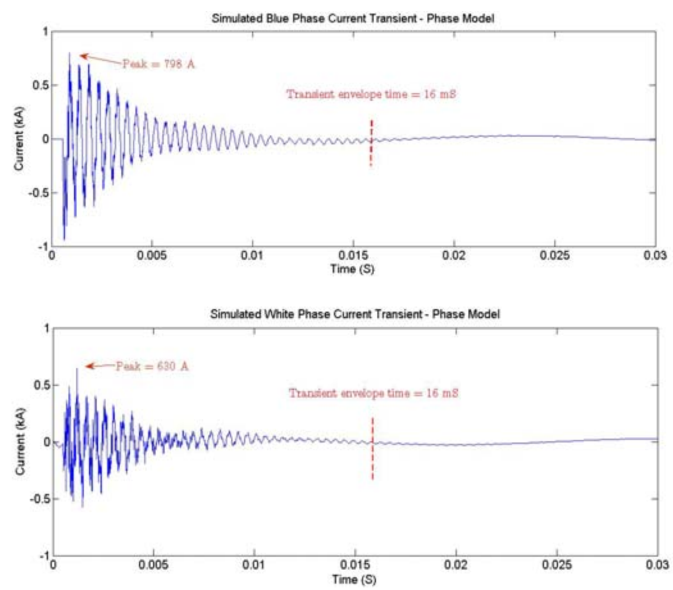

Figure 6.Simulated blue and white phase current transient of FD-Phase model

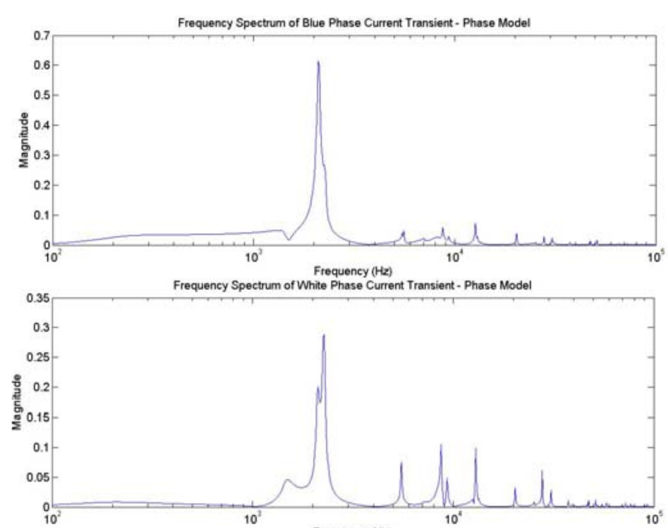

Figure 7.Frequency spectrum of simulated FD-Phase model

From Figure 6, the blue phase current transient peak magnitude value is predicted around 798 A which is slightly lower than the measured blue phase peak. However, it is still a very close prediction compared with the measured results. Its transient envelope time also correlates well to the measured data which is approximately 16 ms before settling down to the steady state condition.

Consequently, the simulated white phase current transient peak predicted a slight higher value than the white phase peak of the experimental result. In contrast, the transient envelope did not decay over similar period to the observed measurement data. The white phase transient peak magnitude and the transient envelope time are 630 A and 16 ms respectively. Nevertheless, these values can be still considered to be in good agreement with the experimental test results. These discrepancies may be due to slight differences in the simulated and actual point on wave at which each circuit breaker closed.

As shown in Figure 7, the simulated FD-Phase model again demonstrated poor frequency response for the result obtained for white phase current transient. Clearly the resonant peaks are at 2.1 kHz, 5.5 kHz and 8.7 kHz which are identical to the data obtained from FD-Mode model. The frequency domain results of both models show no commonality regarding dominant peaks relative to the measured data.

V. Conclusions

Studying the energisation transient behaviour of a HV cable system using simulation methods is attractive provided that the simulation conditions closely matched the real life situations. For such purposes, an investigation of the validity and applicability of existing cable models in an electromagnetic transient simulator were performed.

Two frequency dependent travelling wave cable models, the FD-Phase and FD-Mode models, were assessed through comparison with a measured energisation current transient data of a 132 kV underground cable. Both models had predicted reasonable settling times for the current transient envelope. The FD-Phase model appears to give better agreement with experimental data compared to the results observed from FD-Mode model. Nevertheless, the spectral predictions for these models are very poor with no identical dominant peaks compared to experimental measurement data.

Accordingly, the FD-Phase model is recommended as the model to be used for studying switching transients of underground cable systems. This conclusion is reached purely because of the ability to predict transient magnitudes and settling times more accurately.

VI. Appendix

Appendix 1

The details of cable dimensions and the cross-section of the cable system under test are as shown in Table A1 and Figure A1 [5].

TABLE A1
CABLE DIMENSIONS & MATERIAL DATA

CABLE DIMENSIONS & MATERIAL DATA	VALUE
Core radius (m)	0.01525
Sheath inner radius (m)	0.03725
Sheath outer radius (m)	0.038064
Cable radius (m)	0.042064
Resistivity of the core and sheath (Ω /m)	1.678E-8
Relative permeabilities of core and sheath	1
Relative permittivity inner insulation layer	2.26
Relative permeability outer insulation layer	3.125
Cable length (km)	5.651

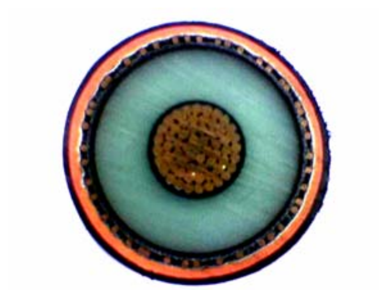

Figure A1.Cable cross-section

Appendix 2

Simulation results of red phase current energisation transients for FD-Mode and FD-Phase models are illustrated here. Figures A2 and A3 depict the corresponding time domain and frequency domain plots.

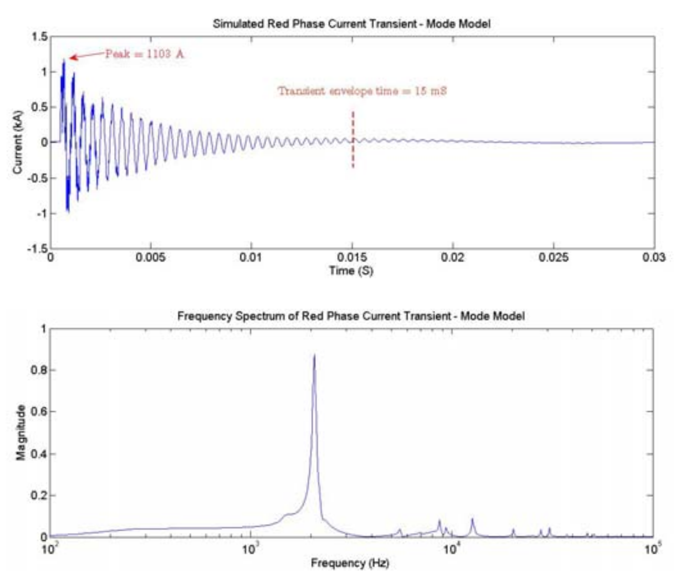

Figure A2.Simulated red phase current transient and the frequency response of FD-Mode model

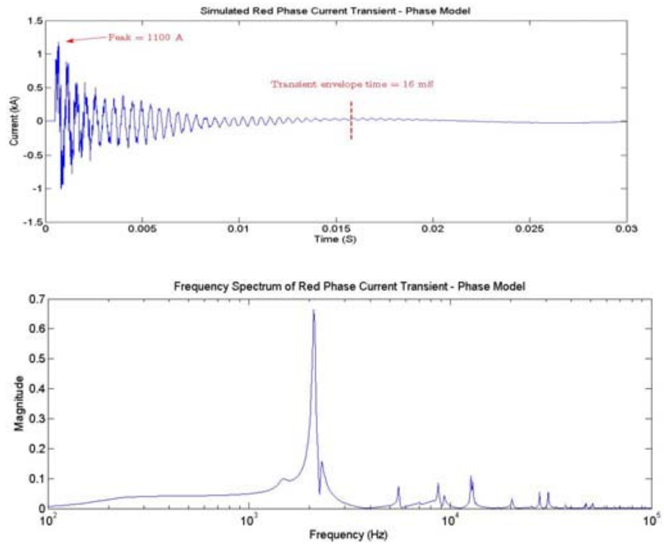

Figure A3.Simulated red phase current transient and the frequency response of FD-Phase model

VII. ACKNOWLEDGMENT

Underground cable, surrounding network and energisation test data provided by Integral Energy (IE) and University of Wollongong Power Quality and Reliability Centre are gratefully acknowledged.

VIII. REFERENCES

[1] J. R. Marti, L. Marti, and H. W. Dommel, "Transmission Line Models for Steady-State and Transients Analysis," *Athens Power Tech, 1993. APT 93. Proceedings. Joint International Power Conference*, 1993, pp. 744-750.

[2] J. R. Marti, "Accurate Modelling of Frequency-Dependent Transmission Lines in Electromagnetic Transient Simulations," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-101, pp. 147-157, 1982.

[3] T. Noda, N. Nagaoka, and A. Ametani, "Phase Domain Modeling of Frequency Dependent Transmission Lines by means of an ARMA Model," *Power Delivery, IEEE Transactions on,* vol. 11, pp. 401-411, 1996.

[4] A. Semlyen and A. Dabuleanu, "Fast and Accurate Switching Transient Calculation on Transmission Lines with Ground Return using Recursive Convolution," *IEEE Transactions on Power Apparatus and Systems,* vol. PAS-94, pp. 561-571, 1975.

[5] P. Nichols, D. Spoor, R. Gangopadhyay, and T. Summers, "A Practical Comparison of a 132kV Cable Energization with ATP Modeling Technique," in *Australasian Universities Power Engineering Conference* Perth, Australia, 2007.

[6] A. Morched, B. Gustavsen, and M. Tartibi, "A Universal Model for Accurate Calculation of Electromagnetic Transients on Overhead Lines and Underground Cables," *IEEE Transactions on Power Delivery,* vol. 14, pp. 1032-1038, 1999.

[7] L. Marti, "Simulation of Transients in Underground Cables With Frequency-Dependent Modal Transformation Matrices," *IEEE Transactions on Power Delivery,* vol. 3, pp. 1099-1110, 1988.

[8] *PSCAD/EMTDC V4.2 User's Guide*. Winipeg, Canada: Manitoba HVDC Research Centre Inc., April 2005.

[9] B. Gustavsen, G. Irvin, R. Mangelrod, D. Brandt, and K. Kent, "Transmission Line Models for the Simulation of Interaction Phenomena between Parallel AC and DC Overhead Lines," *IPST '99 Proceedings, pp. 61-67,* 1999.