A Transmission Utility Approach to Electromagnetic Transient Analysis

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***Abstract* -- National Grid Electricity Transmission (NGET) is constructing a number of reinforcements and extensions to the transmission network in the London area: installing new cable circuits and transformers. To support this, a number of Electromagnetic Transient (EMT) studies need to be conducted.**

A collaborative approach was employed by NGET for delivery of these studies whereby NGET commissioned a consultancy to assist with development of a regional model, to an agreed engineering specification, that was suitable for a variety of study types. This paper presents the model development, an example case study of the model's use by NGET and the lessons learned in the collaboration.

***Keywords*: EMT, utility, electromagnetic transients, modelling.**

I. INTRODUCTION

As the onshore transmission utility for England & Wales, National Grid Electricity Transmission (NGET) is responsible for the planning and delivery of a safe, reliable and efficient network. Changes to demand and generation patterns required the design and construction of a series of network reinforcements throughout the Greater London region.

To support this, a number of Electromagnetic Transient (EMT) studies need to be conducted by NGET to ensure that the transmission network can be operated without subjecting new or existing plant to undue stress from the high voltages and high currents that may occur during switching.

This paper discusses the new approach taken by NGET for the creation of an extensive base study model for EMT simulation, using ATP-DRAW software. The modelling methodologies adopted by the consultants to deliver the model are discussed and the importance of data management is highlighted. An example of NGET's use of the model is then presented with lessons learned.

The example looks at a 275 kV substation site, where a through-wall bushing is to be installed. Current NGET policy mandates that a bushing with a rated Switching Impulse Withstand Voltage (SIWV) of 850 kV is used. However, practical concerns at the site mean that a bushing with a rated SIWV of 650 kV can be more readily installed. The example study was conducted to examine the proposed deviation from NGET policy.

The approach presented is an example of how collaboration between utility and consultant can benefit the utility by enabling faster completion of time-critical study outputs. Lessons learned from the process of model building from specification through to validation and acceptance will benefit other utilities that adopt this approach.

II. MODEL DEVELOPMENT

The consultancy have previously undertaken EMT studies using PSCAD-EMTDC software on behalf of NGET, to provide engineering guidance on issues related to the installation of new equipment. As an example, Reference [1] describes such a study to ensure technical compliance with NGET standards for a proposed modification to an existing 275 kV Gas Insulated Switchgear (GIS) substation. More recently, initial design studies were undertaken for the ongoing London Cable Tunnel (LCT) project. As the project approached the commissioning stage it became apparent that NGET would require a more geographically extensive in-house EMT model for plant specification, design and operational studies of the new LCT circuits. EMT analysis is required to assess transient voltages and currents and to evaluate their impacts on the existing and future equipment, taking into account the changes of network configuration and operating conditions. This required an extensive ATP model of the transmission network around the central London area to be developed.

A detailed technical specification for the required ATP model was jointly developed by NGET and the consultant, and project timescales agreed. The base model covered an area of 160 square-km, including 31 substations at 275 kV and 400 kV, 13 boundary equivalents, 150 Supergrid Transformers (SGTs), over 60 basic line and cable circuits and 11 detailed cable models.

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The extent of the model is illustrated geographically in Figure 1 showing the approximate location of the eight boundary busbars.

Fig. 1. Geographical extent of the base ATP model

Procedures were developed to record the sources of all input data, and all sub-components were tested individually in terms of their power-, switching-, and fast front-response before being incorporated into the larger base model. Where modelling assumptions were necessary based on technical literature and published modelling guidelines [2-4] these were recorded. Documentation was developed for each sub-model by an originator, then reviewed and challenged where necessary by a checker, and finally approved by the project manager. This ensured an ISO 9001-2008 compliant system with full traceability of all data used in the ATP model, traced back to the source of data provided from NGET. Data sources included information from NGET's own DIgSILENT and ATP models, and data held by the consultant on behalf of NGET from earlier PSCAD-EMTP studies. Full traceability of input data and modelling assumptions permitted rapid answering of technical questions and queries when the model was transferred to NGET. The following sections briefly discuss the modelling approach adopted for a number of the key network elements.

A. *Cable Circuits*

There are 53 cable circuits within the network modelling boundaries. The 400 kV cable circuits under study are represented based on detailed cable geometry and material property data provided in the manufacturer's datasheet, which includes cable sheath cross-bonding, transpositions and sheath voltage limiters (type 92 non-linear resistor). As an example, the cable circuit between Node_M and Node_N is shown in Figure 2. The cable core details are shown in Table I.

The conductor screen, main insulation layer, insulation screen and the binder were merged into a single insulator layer. The insulator relative permittivity was adjusted to give the design capacitance of 0.25 μF, based on the methodology presented in [5].

All cables were modelled using a constant parameters model with PPS and ZPS parameters. For cables far from the point of evaluation, 50 Hz parameters in a Clarke model were used due to ease of availability of 50 Hz data. The Clarke model is a constant parameter ideally transposed model where all phase impedances are identical.

Cables located close to the point of evaluation of a study were modelled in detail, including sheath bonding arrangements and transpositions, using a Bergeron model with a frequency of calculation of cable parameters set to 5 kHz (suitable for typical slow-front transients) or to the specific frequency of interest, depending upon the study. The Bergeron model is a constant parameter, un-transposed model.

Limitations in the number of components available in ATP-DRAW software and a desire to have short calculation time restricted the use of detailed Bergeron models to the region around the point of evaluation.

The cable energisation (against an ideal source) and lightning impulse test has been simulated to test the cable model as shown in Figure 3 and Figure 4. The impulse test confirms the speed of wave propagation in the cable is about 60% of the speed of light with a surge impedance of 25 Ω. The positive- and zero-sequence impedances calculated from the ATP cable model and the NGET DIgSILENT cable model for each new cable circuit have been compared and the results show good agreement.

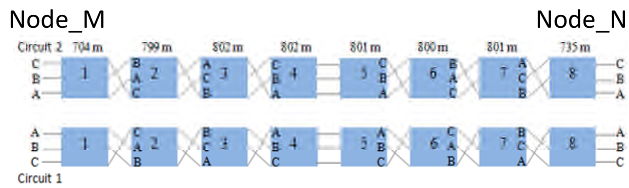

Fig. 2. Cable sectional length and transposition configurations between cable sections of Node_M – Node_N circuits

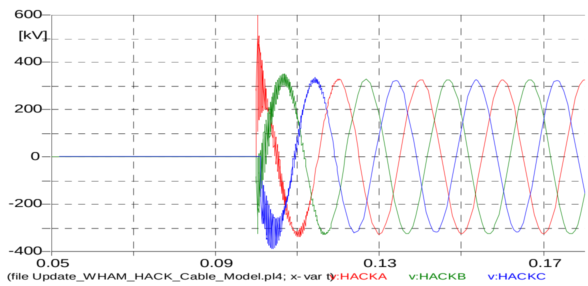

Fig. 3. Energisation test on Node_M – Node_N cable model

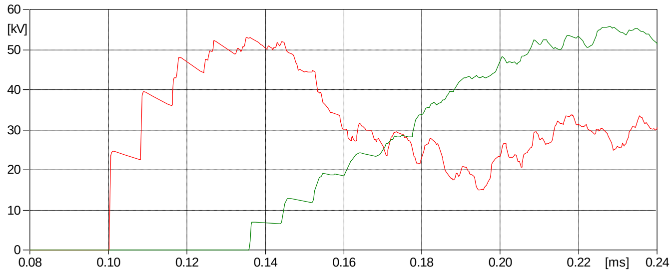

Fig. 4. Current impulse test – instantaneous phase-ground voltage plots: Node_M end phase A (phase-ground) voltage compared to that observed at Node_N end of circuit 2

TABLE I

400 KV XLPE CABLE CROSS SECTIONAL BUILD-UP AND THE ATP MODEL REPRESENTATION

Layer Description	Radius [mm]	Material	ATP layer
Central rod	6	Aluminum	C1
Conductor	32.45	Copper	
Conductor screen	35.9	Semi-conducting polymer	I1
Main insulation	61.4	XLPE	
Insulation screen	63.05	Semi-conducting polymer	
S/C Water Barrier	64.15	Hygroscopic Tape	
Metallic Sheath	65.65	Longitudinally welded Aluminum	C2
Finish	71.4	Flame retardant Polyethylene	I2

B. Supergrid Transformers (SGTs)

There are 150 SGTs within the network boundary; most of them are three-winding auto-transformers. These have been represented using the ATP BCTRAN model, with the correct short circuit characteristics, and with their winding capacitances and core saturation characteristics (represented by star-connected type-96 non-linear inductors located at the transformer LV side) as shown in Figure 5 in order to enable the model to be used for transformer energisation studies. The procedure used to develop the saturation curve applied to the non-linear inductors is shown in Figure 6.

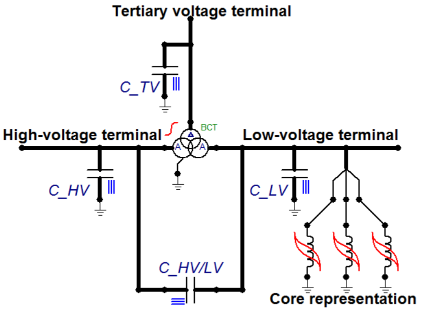

Fig. 5. Configuration of SGT model

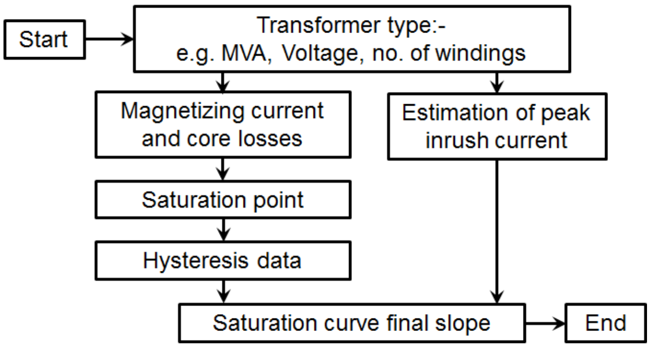

Fig. 6. Procedure for producing transformer core saturation curve applied to type-96 non-linear inductor

C. Quadrature Boosters (QB)

QBs are represented by a two-winding transformer connected in series with transmission lines. It contains two blocks. Block_1 contains one transformer SC_T (modelled by a BCTRAN object) used to represent the QB's short-circuit characteristics. Block_2 contains two transformers Shunt_T and Series_T (both are modelled by a BCTRAN object); they are used to represent QB's phase-shifting function and core-saturation characteristics. Figure 7 shows the ATP single line diagram of a QB.

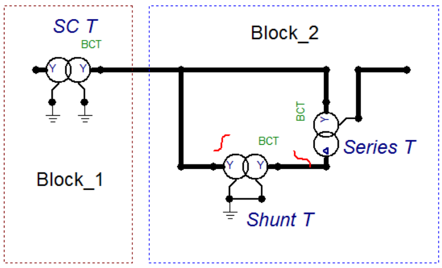

Fig. 7. ATP single line diagram of the QB model

D. Traction Transformers

Traction transformers as shown in Figure 8 are represented using single phase three-winding BCTRAN transformer model. A type-96 non-linear inductor is connected between one of the LV terminals and the grounding point to represent core magnetization behavior (the final-slope of the inductor's saturation curve is adjusted to give an air-core inductance of twice the transformer short-circuit inductance).

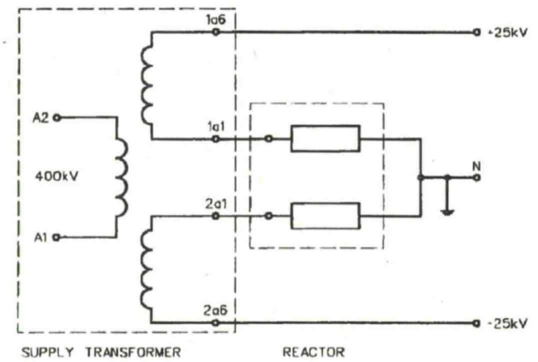

Fig. 8. Single line diagram of a traction transformer

E. Shunt Reactors

Shunt reactor representation is shown in Figure 9, which includes the core inductance and its non-linear core saturation, winding capacitance, copper losses and iron losses. Typical shunt reactor characteristics used in the study are based on [6]. The winding capacitances are based on values given in [7, 8].

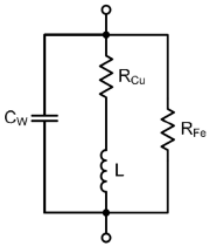

Fig. 9. Representation of an iron core shunt reactor (single phase) [9]

F. Overhead lines

Overhead lines are represented by the J-Marti model (a frequency-dependent traveling-wave model), taking into account line length, sag, geometrical dimension, conductor material, bundling and phase transposition. These are modelled using the ATP line templates. The ATP-calculated 50 Hz PPS and ZPS line impedances were verified against the NGET DIgSILENT model.

G. Loads

Frequency dependent loads based on the NGET harmonic load model are used for loads one bus away from the switching location. Parallel real and reactive loads are used elsewhere. The harmonic load model divides the total power proportionally into resistive, inductive and capacitive components and takes into account the impedance of distribution transformers as shown in Figure 10. This model attempts to re-create typical resonance conditions in the downstream network.

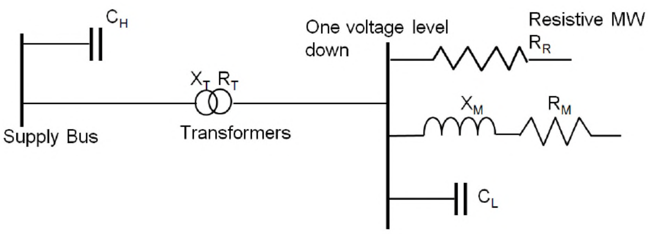

Fig. 10. Configuration of NGET harmonic load model

H. Network Equivalents

The network boundaries were set at the vertices of the 'model extent' polygon shown in Figure 1. The network exterior to the network boundary is represented by Thevenin equivalent sources with self impedance and mutual transfer impedances. These were computed from the NGET DIgSILENT model of the full GB system: positive and zero sequence of the self and mutual impedances for the set of required network boundary nodes were generated using the DIgSILENT network reduction function.

III. Model Verification

The sub-components in the model were individually tested to confirm their power-, switching-, and fast front-response. When combined into the full ATP-EMTP model it was necessary to verify that the power frequency load flow and short circuit levels matched those of the NGET DIgSILENT model to ensure correct initial conditions before carrying out any EMT studies. As an example, the steady state voltage and short-circuit profiles of the 2015 network scenario under maximum load condition have been calculated and compared with the values generated from the NGET DIgSILENT model (50 Hz) of the full GB system. This comparison is shown in Figures 11- 13. The calculated voltage profiles show good agreement between the two models. The RMS break currents calculated by the ATP model are consistent with those obtained from the DIgSILENT steady state model. Slightly lower initial peak current values are calculated in the ATP model due to different calculation methods being employed: ATP calculates peak current through solution of differential equations whereas DIgSILENT calculates peak current using the IEC Method C to approximate X/R ratio.

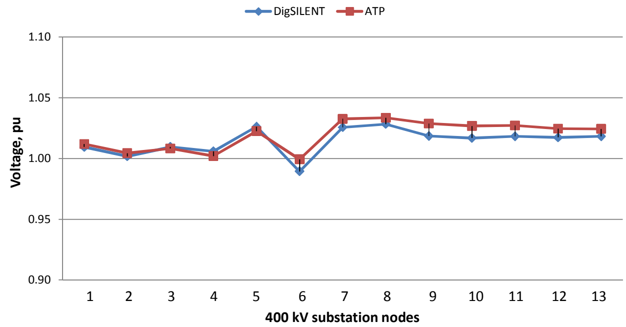

Fig. 11. Comparison of 400 kV busbar voltage profile between DIgSILENT and ATP model.

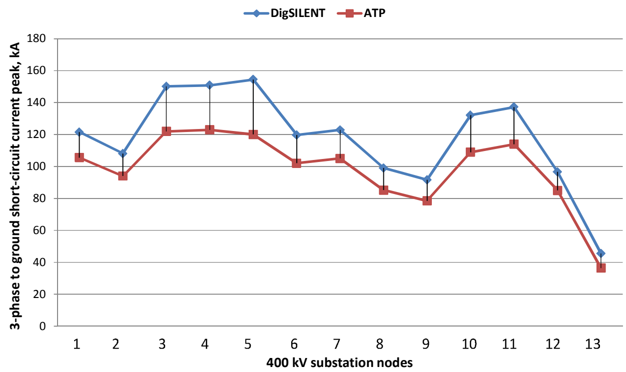

Fig. 12. Comparison of 400 kV 3-phase-ground fault initial peak current between DIgSILENT and ATP model

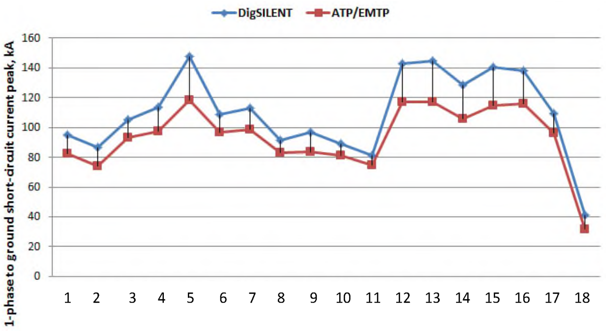

Fig. 13. Comparison of 400 kV 1-phase-ground fault initial peak current between DIgSILENT and ATP model

IV. STUDY PERFORMED

A. Study Objective

NGET will install 2 x 950 MVA, 400/275 kV transformers at Node_1 under a major infrastructure reinforcement project to connect Node_2 400 kV and Node_1 275 kV substations using 2 x 400 kV cable circuits. One of the transformers is proposed be connected to the 275 kV indoor busbars using a through-wall bushing which has 650 kV phase – ground Switching Impulse Withstand Voltage (SIWV) due to limitations in physical space at the substation site. Figure 14 provides details of the network at Node_1 substation. The NGET technical policy requires it to be rated at 850 kV and this study is commissioned to confirm the suitability of a 650 kV rated through-wall bushing for the project.

B. Network Model

The model represents the transmission network configuration in years 2016/17 with 2 x 400 kV cable circuits from Node_2 to Node_1 commissioned and energized in cable tunnels. The Node_2 – Node_1 circuits are modelled as Bergeron elements tuned to 2.5 kHz (the dominant frequency) while other circuits are represented using the Clarke model. At Node_1, 2 x 950 MVA 400/275 kV transformers are represented as BCTRAN elements with a non-linear core model. The 2 x 150 m cables that connect the transformers' low-voltage terminals and the 275 kV through-wall bushing are modelled as Bergeron elements at 2.5 kHz. The Node_1 – Node_3 and Node_1 – Node_4 circuits are existing 275 kV cables with quadrature boosters at the Node_1 end.

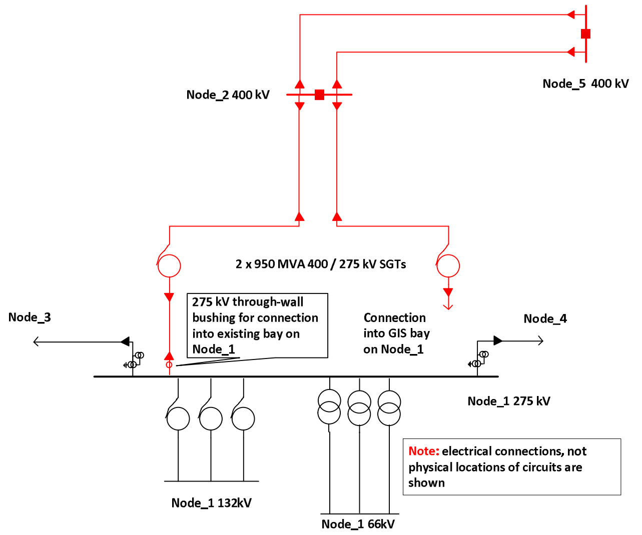

Fig. 14. Single Line Diagram of the Network at Node_1 Substation

C. Study Cases and Results

The study considered different network running configurations and considered closing on different points on the voltage waveform to find the maximum overvoltage at the 275 kV through-wall bushing. The simulations are performed using a simulation time step that is 0.5 µs lower than the travel time of the 150 m cable. Table II provides a summary of the study cases and the maximum phase–ground peak voltage values predicted by the ATP model. It is observed that the overvoltage at the bushing location is highest when the other 400 kV cable circuit is out of service. The results presented are therefore for the condition when the first Node_2 – Node_1 400 kV cable circuit is switched while the other cable circuit is out of service.

The highest phase–ground voltages for switching at Node_2 400 kV are observed when either Node_2 400 kV substation runs split or one of the 400 kV Node_2 – Node_5 cable circuits is out of service. Similarly for switching from the 275 kV side at Node_1, the highest phase voltages occur when either of the Node_1 – Node_3 or the Node_1 – Node_4 275 kV cable circuits is not available. This suggests that the switching overvoltage is highest under low system fault levels when the network is at greater level of depletion, with more circuits out of service and is in line with expectation and experience.

The switching studies are performed for closing on different points on the voltage waveform in combination with different levels of residual flux in the transformer core. The study also considered different cases of fault inception at the Node_1 275 kV busbar and fault clearance within normal protection clearance time. The results for these cases are not provided as these differ only slightly from the results presented in Table II.

TABLE II
MAXIMUM PHASE – GROUND SWITCHING OVERVOLTAGE FOR NODE_1 275 KV THROUGH-WALL BUSHING

Cable Switched at	Network Configuration	Phase – Ground	
		kV peak	% of 650 kV
Node_2 400 kV	Node_2 solid with Node_5 – Node_2 both circuits IN	500	77
	Node_2 solid with One Node_5 – Node_2 circuit OUT	585	90
	Node_2 split with Node_5 – Node_2 both circuits IN	585	90
Node_1 275 kV	Node_1 solid with Node_1 – Node_3 and Node_1 – Node_4 both circuits IN	277	43
	Node_1 solid with Node_1 – Node_3 circuit OUT and Node_1 – Node_4 circuit IN	286	44
	Node_1 solid with Node_1 – Node_3 circuit IN and Node_1 – Node_4 circuit OUT	280	43

The results of this study were made available in a short timescale to the project team for consideration in their selection of the appropriate bushing for this project.

V. LESSONS LEARNED

The collaborative approach employed highlighted areas where, if we were to repeat the task, we would make some changes. Likewise, there were some aspects that went particularly well.

The study outlined in section IV is a strong example of how a pre-existing base model enabled the utility to quickly provide a study output in time-critical conditions.

Specific learning points around the process and interaction of the parties were found upon reflection. It is desirable to appoint a single point of contact from both parties and, where practicable, to ensure continuity of the role this person has in the project. Collaboration between parties is best performed face to face, as email contact can lead to delays. When resolving queries related to technical data provision, it is important for both parties to seek time-bound resolutions and avoid open-ended technical enquiries or open forum debate – the appointment of and deferral to a technical authority from the client side is beneficial.

Learning points about model reliability were found: data provided by the utility is sometimes estimated and the utility can manage the risk of this; some data is estimated by the consultant – this requires utility verification and discussion early in the model building process; the breadth of the model means that an extensive verification process is needed by the utility – it can occur that the required level of attention to detail in a specific area is only provided when that part of the model becomes the point of evaluation for a study. This can slow down the utility's pace of study output and risk negating some of the benefits of the approach.

Specific learning points around the approach of producing an extensive base model in ATP software were found. The limitations of ATP software were not anticipated to be exceeded by the base model, but when two or more detailed cable circuits were included then the limit of components in ATP-DRAW was reached and the use of boundary equivalents to reduce the network was necessary. This had no impact on result reliability but did impact on the time needed to complete a study. Studies on the large model took longer to simulate – 1000 statistical switching runs for six cases of a subsequent study, similar to that of Section IV, were performed using six parallel laptops over three days; a smaller network would complete quicker. The initial overhead of time required to validate the large base model was significant, whereas a high-priority time-critical study could have been performed sooner if a dedicated, smaller model had been provided.

Reducing the number of components that are not influential in the study, (such as transformers with nonlinear magnetizing reactance and load models remote from the point of study) reduces the execution time significantly. When calculation time is a concern, the components that do not directly and significantly affect the results can be further refined, for example, if switching overvoltages on the conductor and at the busbar are of interest then the sheath model can be simplified by reducing the number of non-linear Sheath voltage Limiter (SVL) components. The sheath solid earth points are important and should be correctly included. This applies to the cable models around the point of study and even the cable under study provided the focus of the study is not the sheath voltages and currents.

The determination of appropriate level of detail for component modelling is a decision that the utility can make through subsequent modification of the base-model.

VI. CONCLUSIONS

A collaborative approach for a utility to deliver a suite of EMT studies employing an extensive base model provided by a consultant has been presented.

Details of the modelling aspects and techniques for verification and data handling have been presented, along with lessons learnt from this process. A study performed using the model has been presented, with the key message of how a quick study outcome was enabled by the utility's use of an extensive base model. Some aspects of the model size and detail have been highlighted for careful consideration, ideally at the scoping stage of the collaboration.

This paper has presented the approach taken, detailed the process for building the model, provided an example study that used the model to beneficial advantage and drawn learning points from the process.

This paper can benefit a utility considering using a large base model for a number of EMT studies in different locations within the model and different frequencies and phenomena of interest.

VII. Acknowledgment

The authors would like to acknowledge the contribution made by Ben Marshall of NGET to this project.

VIII. References

[1] D.T.A Kho, K. S. Smith, “Analysis of Very Fast Transient Over-voltages in a proposed 275 kV Gas Insulated Substation”, International Power System Transient Conference 2011, Delft, The Netherlands, June 14 – 17, 2011.

[2] “Guidelines for representation of network elements when calculating transients”, CIGRE Working Group 02, Study Committee 33 (Over-voltages and Insulation Coordination)

[3] “Modelling and Analysis of System Transients Using Digital Programs”, IEEE Power Engineering Society Special Publication, Working Group 15.08.09.

[4] IEC 60071-4, Insulation co-ordination, Part 4, Computational guide to insulation co-ordination and modelling of electrical networks, 2004.

[5] J. Marti, "Accurate Modelling of Frequency Dependent Transmission Lines in Electromagnetic Transients Simulation," PAS-101, No 1, Jan 1982 pp 147-155.

[6] Zoran Gajić, Birger Hillström and Fahrudin Mekić , “HV Shunt Reactor Secrets for Protection Engineers”, conference paper presented at the 30th Western Protective Relaying Conference, Spokane, Washington, October 21-23, 2003.

[7] IEEE Guide for Shunt Reactor Switching, IEEE Standard C37.015-1993.

[8] IEEE Application Guide for Transient Recovery Voltage for AC High-Voltage Circuit Breakers, IEEE Standard C37.011-2005.

[9] M. Kizilcay, K. Teichmann, A. Agdemir and G. Kaflowski, "Flashovers at a 33-kV Filter Reactor during Energization", in International Conference on Power Systems Transients (IPST'07), Lyon, France, June 4-7, 2007.