Analysis of Very Fast Transient Overvoltages in a proposed 275 kV Gas Insulated Substation

D.T.A Kho, K. S. Smith

Abstract-- **Very Fast Front Transient Overvoltages (VFTO) in a 275 kV gas insulated substation have been analysed using PSCAD-EMTDC. The Gas insulated substation (GIS) components have been represented using equivalent circuits and distributed parameter lines that take into account the GIS high frequency response during transients. Four switching events leading to the generation of possible VFTO are analysed and discussed; i) switching energisation of the main bus and the reserve bus, ii) breaking of small capacitive current via disconnector switching at the bus coupler, iii) energising the transformer bay, and iv) disconnector switching at the incoming and transformer feeders. Transient overvoltages due to transformer bay breaker opening to interrupt the transformer inrush current has also been assessed.**

Keywords: **Very Fast Transient Overvoltage (VFTO), Gas insulated substation (GIS), PSCAD-EMTDC, ETRAN, disconnector switching.**

I. INTRODUCTION

AN existing 275 kV air insulated (AIS) 4-switch mesh substation shown in Fig 1 cannot accommodate additional circuits for expansion. A new 275 kV gas-insulated substation (GIS) has been proposed adjacent to the existing substation. The GIS will be constructed in stages. The first stage will include two incoming and two transformer bays plus one bus coupler as shown in Fig 2. There will be a 275 kV interconnector cable from the mesh corner 4 of the existing air-insulated substation (AIS) to the proposed new 275 kV GIS. The existing feeder H1 connected to the mesh corner 4 will be disconnected and a new 275 kV XLPE cable will be connected from the proposed 275 kV GIS to a transition joint on H1 feeder. The two 150 MVA 275/33 kV transformers will be connected to the proposed 275 kV GIS for the traction supply to a rail company. As part of the design process, studies must be performed to assess the performance of the proposed arrangement, to confirm that no equipment will be subjected to stresses exceeding the equipment limits. This is also to fulfil the utility specification that critical or expensive plant items require additional protective devices and measures, and for non-standard arrangements or complex circuit configurations, an insulation coordination study may be required where specified.

A GIS is significantly more compact than an AIS with shorter bus length and very little electrical damping. Lightning overvoltages entering a GIS can therefore affect more equipment. Damage due to faults within gas-insulated switchgear cannot be inspected without dismantling the GIS. Due to the non self-recovery nature of the gas insulation system, any damage in a GIS usually requires long repair time and subsequently longer outage than the AIS equivalent.

An insulation coordination study has been performed to assess surge arrester requirement at the proposed GIS. All feeders connected to the substation are of underground cables, which have low surge impedance and an attenuation effect on a lightning surge due to the cable capacitance to ground performing a surge suppression function. For the study considered, the possibility of a lightning strike penetrating into the substation is unlikely. Very Fast Front Transient Overvoltages (VFTO) due to switching operations in the GIS and breaker interruption during transformer energisation due to fault and the subsequent re-closing of the breaker after fault clearing have been considered in the insulation coordination study. The modelling methodology and results for the VFTO study to assess the requirement for surge arresters are discussed in this paper.

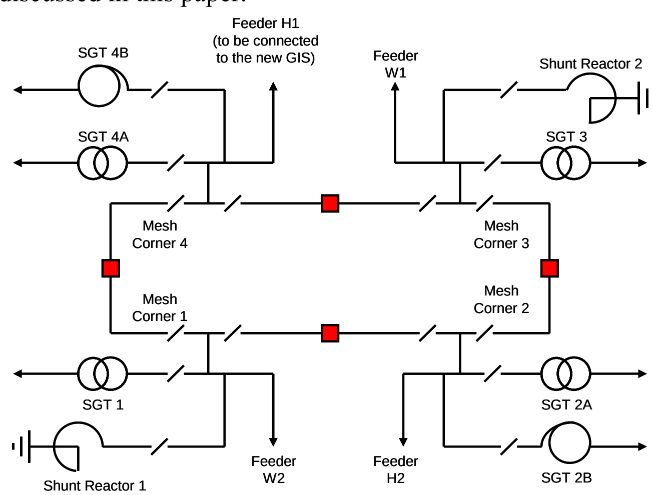

Fig 1: Existing 275 kV air-insulated substation

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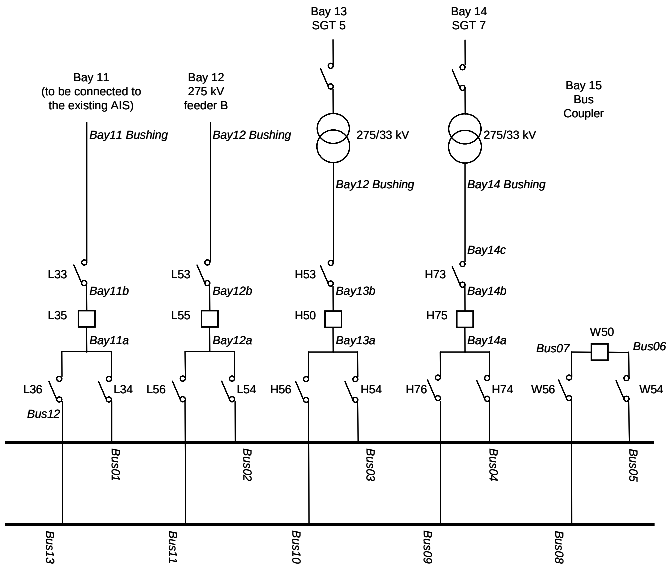


Fig 2: 275 kV GIS substation single line diagram

II. Model Development

Despite the advancement in electrical measurement techniques and equipment, quantifying the VFTO at such high frequencies remains challenging. Actual measurement in the GIS during planning stage is not practically possible. Designers must use numerical tools to calculate the VFTO associated with switching operations in a GIS. This informs the design decision process to achieve a more robust and reliable system with adequate insulation levels for all equipments used. The existing technical literature shows that with good modelling techniques and appropriate assumptions, numerical tools can provide reasonably accurate predictions of the VFTO magnitude and their rate of rise [1], [2], [3], [4], [5], [6], [7]. The simulation studies reported here were performed using PSCAD-EMTDC Ver 4.2.1 developed by the Manitoba Hydro HVDC Research Centre [8].

Switching events in a GIS generates transients with frequencies in the range of hundreds of kHz up to tens of MHz. These transients cannot be calculated if conventional techniques of modelling and simulation are used. Coaxial conductors in gas insulated substations have higher specific capacitance to earth. GIS is also characterized by lower surge impedance and inductance as well as larger gradient of the electric field between pre-strike and re-strike arcs in SF6 under pressure. This causes very fast transients with surge fronts of very short durations. Due to the geometrical structure of GIS and its low surge impedance, travelling waves reflection at the GIS entrance could rapidly result in sizeable over voltages at any open end within the GIS (i.e. due to multiple reflections). To model the impact of fast transients on equipments inside a GIS it is therefore necessary to develop travelling wave models of the GIS as described in the technical literature [9] and [10]. The GIS components used in the PSCAD-EMTDC model are modelled based on data provided by the manufacturer. These are documented in the following sections.

A gas insulated bus is represented by a Bergeron travelling wave model, which is specified by its surge impedance, velocity of surge propagation, and length. The surge impedance of a gas insulated bus can be calculated from the relation.

$$Z = 60 \ln\left(\frac{b}{a}\right) \qquad (1)$$

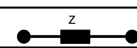
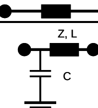
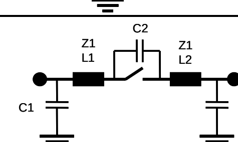
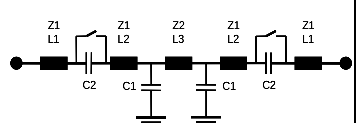
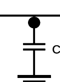
where a is the diameter of the bus and b is the inner diameter of the enclosure. Typically the surge impedance is of the order of 60 to 70 Ω and the surge velocity is assumed be 95% of the velocity of light. A bushing is represented by their capacitance to ground; typically 150 pF. A cross junction is represented by an L circuit with a travelling wave model and a capacitive shunt.

A disconnector is represented by a PI section comprises of two travelling wave models, two capacitors to ground and a capacitor across the breaking contacts as shown in TABLE I. A circuit breaker is represented by a PI circuit with five travelling wave models and four capacitors. The spark used in disconnector re-strike cases is modelled as an exponentially decaying resistance ($R_0e^{-t/T}$) in series with a small resistance, r of 0.5 Ω to take care of the residual spark resistance [11].

$$R = R_0 e^{-(t/T)} + r \qquad (2)$$

The value of R_0 is taken as $1x10^6$ MΩ and T as 1 ns. This gives a resistance whose value varies from very high value (MΩ) to a low value of 0.5 Ω within 30 ns.

TABLE I
List of GIS Components and Their Equivalent Circuit Representations

Component	Equivalent circuit	
Bus bar		Z = 63 Ω
Cross Junction		Z = 35 Ω L = 450 mm C = 25 pF
Disconnector		Z1 = 35 Ω L1 = 640 mm L2 = 450 mm C1 = 25 pF C2 = 2.5 pF
Circuit breaker		Z1 = 58 Ω L1 = 560 mm L2 = 930 mm Z2 = 16 Ω L3 = 400 mm C1 = 20 pF C2 = 620 pF
Bushing		C=150 pF

Transformer winding and bushing capacitance becomes an important factor influencing the transient behaviour of the equipment at high frequency. The transformer winding capacitances provided by the manufacturer are listed in

TABLE II.

The substation outgoing feeders are terminated with Bergeron travelling wave line models with the characteristic impedance of a cable (23 Ω) and the surge velocity of 60% of the speed of light. These are assumed to be reflectionless lines. The voltage level at the instance of switching operation in the GIS is assumed to be at its positive peak and a voltage of -1 p.u due to the trapped charge has been assumed at the load side of the disconnector contact for the worst case scenario.

TABLE II
TRANSFORMER WINDING CAPACITANCES

Transformer	**SGT 5 and SGT 7**
CH	2150 pF
CL	6700 pF
CHL	3020 pF
Transformer	**SGT 3**
CH	5878 pF
CL	3720 pF
CT	19783 pF
CHL	7227 pF
CHT	93 pF
CLT	14910 pF

The second requirement of the insulation coordination study is to determine the maximum switching overvoltage due to circuit breaker operation to break the transformer inrush current. A detailed transformer representation including the saturation characteristic of the transformer core, is required for analysis of transformer inrush transients. The modelling technique used within PSCAD is based on a current source method [12]. The saturation parameters of each 150 MVA, 275/33 kV supergrid transformer were chosen to produce a peak inrush current of 6.9 kA when energised from the 275 kV side against a zero impedance source with a core residual flux that corresponds to 0.8 pu and least favourable switching angle. Underground cables connected to the substation have been represented using the PSCAD frequency dependant (phase) model which is developed based on the methodology presented in [13]. The source equivalent circuits used in the model were derived using ETRAN Ver 1.2.4. This reduces an in-house PSSe model of the transmission system maintained by Mott MacDonald to a lower order equivalent suitable for use in the electromagnetic transient studies. To reduce the computational burden, only the network system within one bus away from the energisation point was kept in the model while E-TRAN equivalent sources were used to represent the network outside the one-bus boundary.

III. VFTO DUE TO SWITCHING EVENTS IN THE 275 KV GIS

Four types of switching events have been considered which lead to the generation of VFTOs:

- Switching on the main busbar or the reserve busbar
- Breaking of a small capacitive current via disconnector switching at the bus coupler bay.
- Switching on the transformer feeder
- Disconnector switching at the incoming and transformer feeders

A. *VFTO due to Bus-charging*

Busbar charging transients have been considered with and without trapped charge. The worst case initial peak instantaneous voltage is assumed on the source side at the instant of circuit breaker closing. The maximum VFTO voltage level of 446.61 kV is calculated at the end of the reserve bus when the circuit breaker W50 at the bus coupler closes to energise the reserve bus with -1.0 p.u trapped charge. The maximum VFTO voltage waveforms along the reserve busbar are shown in Fig 3. The variation of the maximum VFTO levels along the main and reserve busbars for a bus-charging case are shown in Fig 4. The maximum instantaneous overvoltage of 446.61 kV is calculated at the end of the reserve busbar when it is energised via the bus coupler. All other feeders except the incoming feeder from the 275 kV AIS are disconnected. In general, the VFTO increases from the point where the switching occurs (node Bus07) until it reaches an open point (node Bus12). The occurrence of another VFTO peak along the reserve bus suggests that there is a point (node Bus09) where two or more travelling wave peaks coincide. On the contrary, the peak VFTO decreases along the incoming feeder in the direction away from the substation. When the travelling wave reaches the cable termination, which has lower surge impedance compare to the gas insulated busbar, part of the travelling wave will be reflected back to the substation as a negative peak, therefore reducing the peak VFTO at the cable termination point.

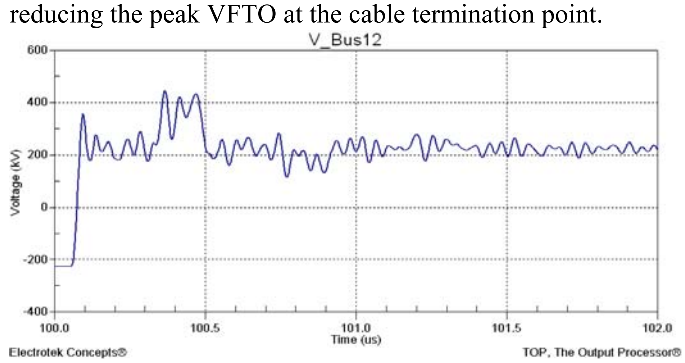


Fig 3: Maximum VFTO waveforms at the reserve busbar

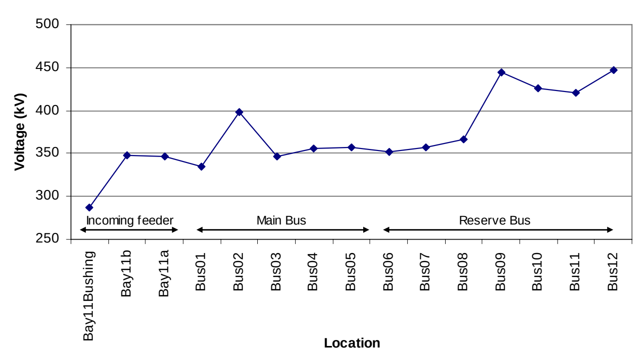


Fig 4: Variation of the maximum VFTO due to busbar charging

B. VFTO due to Busbar De-energisation Re-strikes

IEC 62271-102 (Annex F) [13] describes the requirements for switching of bus-charging currents by disconnectors for rated voltages of 72.5 kV and above. Due to the relatively slow speed of operation of the disconnector switch, numerous re-strikes and pre-strikes will occur when the disconnector opens. The maximum value of the VFTO depends on the voltage drop at the disconnector during re-strike. When the contacts move away from each other, a certain amount of trapped charge remains on the load side. The worst case scenario of -1.0 p.u trapped charge has been considered, which results in the maximum voltage of 2.0 p.u across the contacts during re-ignition. The repeated ignitions cause travelling waves which generate very fast transient overvoltages in the GIS. The study investigates a single re-strike with the worst case scenario of -1.0 p.u trapped charge or 2.0 p.u voltage across the disconnector switch contacts. The maximum VFTO of 531.71 kV is calculated, which considers breaking of capacitive current of the unloaded reserve busbar when only the incoming feeder Bay12 is connected to the substation. The instantaneous voltage waveforms nearest to the bus coupler and at the end of the reserve bus are shown in Fig 5. The figure shows the rate of rise of the travelling wave at the point nearest to the impulse is higher than the one furthest away from the impulse and the VFT voltage peak is doubled as the travelling waves reaches the end of the bus and a full reflection of the voltage wave occurs. The plots of the variation of peak VFTO for one of the busbar de-energisation cases is shown in Fig 6. The results show the maximum overvoltage generally occurs at the open end of the reserve bus and the lowest VFTO is usually at the end of the incoming feeder or the transformer terminals. Note also the high voltage peak which occurs on the GIB at location Bay14c approximately 33 m from the transformer SGT7. The results also show a reduction of the peak VFTO at points on the main busbar where the connected feeder is in service.

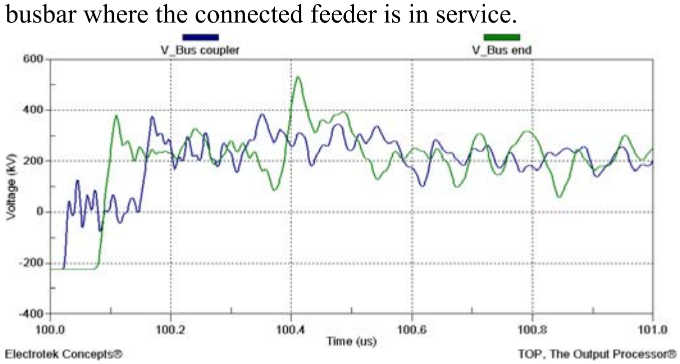


Fig 5: Maximum VFTO waveform nearest to the bus coupler and waveform at the open end of the reserve busbar

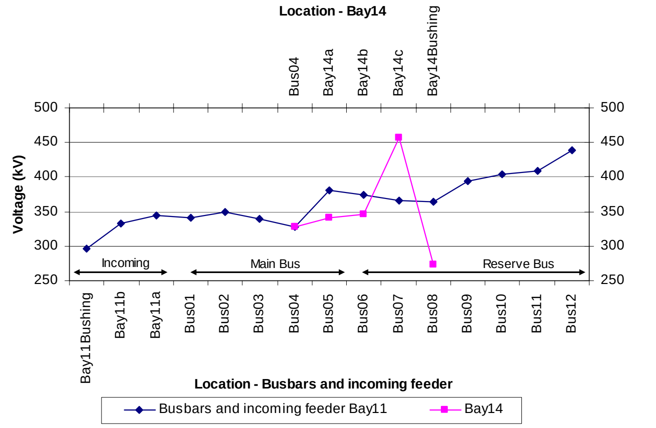


Fig 6: Variation of the maximum VFTO due to busbar de-energisation re-strike

C. VFTO due to Energising the Transformer Feeder

The VFTO at the instant of circuit breaker closing to energise the transformer feeder has been calculated. The maximum VFTO of 341.32 kV is calculated at the location Bay14c approximately 33 m along the feeder to transformer SGT7. This occurs approximately 1 µs after the switching. The VFTO voltage waveforms along the main busbar and the incoming feeder Bay14 are shown in Fig 7.

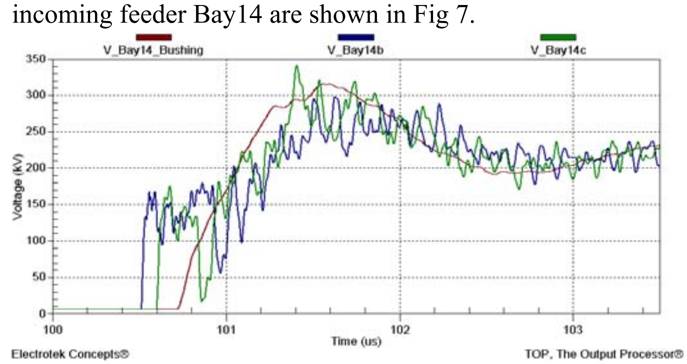


Fig 7: Maximum VFTO waveform when energising a transformer feeder

D. VFTO due to Disconnector Switching with Re-strikes

The maximum VFTO of 580 kV is calculated when the disconnector H54 is opened after the circuit breaker operates to isolate the transformer feeder Bay13 as shown in Fig 8. The transient voltage waveforms at different locations are shown in Fig 9, and the maximum overvoltage along the length of the GIS is shown in Fig 10. As the disconnector switch H54 operates to isolate the circuit breaker from the main busbar, re-strikes may occur across the switching contacts as the electric field rises to exceed the dielectric strength of the SF6 between the small contacts parting distance. Each re-strikes leads to the generation of a VFTO. In this case, the least favourable voltage across the disconnector contacts of 2.0 p.u is assumed. The maximum VFTO in the 275 kV GIS is observed at the end of the main busbar where the travelling waves are reflected back at the open point. The maximum VFTO reduces with the number of feeders connected to the substation.

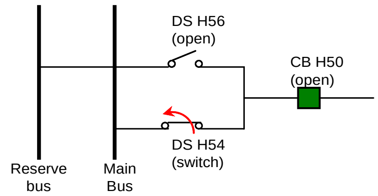


Fig 8: Single line diagram of the disconnector operation

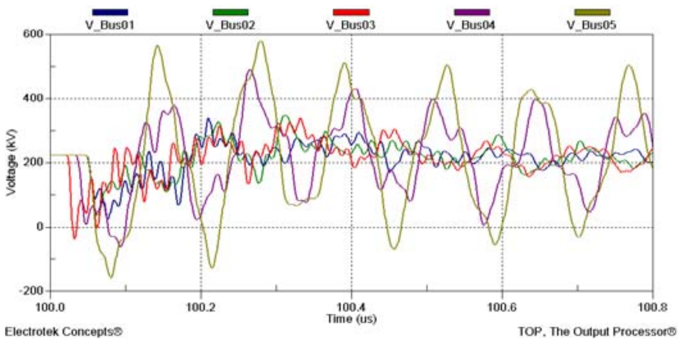


Fig 9: VFTO waveforms along the main busbar

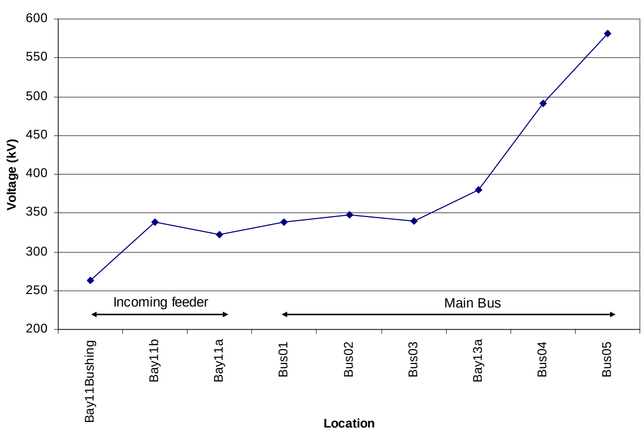


Fig 10: Variation of the maximum VFTO due to disconnector switching with minimum feeder connected to the substation.

IV. Transient Overvoltages due to Breaking of Transformer Inrush Current

The study also investigated the maximum transient overvoltage when protection equipment operates to interrupt the transformer inrush current. For this type of study, a full three phase PSCAD model including transformer core saturation has been used to calculate the maximum transient overvoltage. The maximum inrush current for each transformer is interrupted at different time delays after circuit breaker closing and with different current chopping level. Energising the transformers SGT5 and SGT7 at the most unfavourable switching conditions result in a maximum inrush current of 5.55 kA and 5.58 kA. Different current chopping values have also been considered. The maximum phase to ground voltage of 649.32 kV is observed when breaking the transformer inrush current at a time delay of 150 ms after the circuit breaker H47 is initially closed. Figure 11 shows the instantaneous phase A, B and C to ground voltage waveforms at the transformer SGT7 HV terminals. In general the higher the chopping current, the more severe the transient overvoltages will be at the transformer terminals.

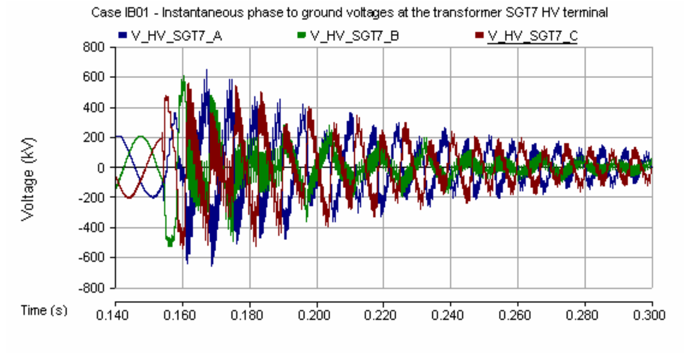


Fig 11: Maximum instantaneous phase to ground voltages at the SGT 7 HV terminals.

V. Discussion of Study Results

The VFTO results show the maximum VFTO due to different switching events considered is 580.76 kV which has a voltage margin of 269.24 kV (31% margin) available compared to the rated switching impulse withstand voltage of 850 kV. The available margin is within the 15% allowance specified by the utility. The analysis shows that the maximum peak VFTO occurs mostly at busbar open ends and the peak VFTO are relatively lower at the end of the incoming and the transformer feeders. It is possible for a high VFTO peak to occur along the long gas-insulated bus. The maximum VFTO peak reduces with the number of feeders connected to the substation.

Interrupting the maximum inrush current causes a transient overvoltage at the transformer HV terminals. When energising the transformer SGT7, the maximum transient overvoltage due to breaking of the inrush current is 649.32 kV. There is a 200.68 kV voltage margin available (23% margin) compared to the rated switching impulse withstand voltage of 850 kV. This is within the 15% allowance specified by the utility.

As all the overvoltages predicted are within the rated voltages and coordination margins specified by the utility, the study demonstrates that surge arresters to protect the equipment from VFTO are not required for this installation.

VI. Conclusions

This paper has described the development of a PSCAD-EMTDC model to assess the maximum transient overvoltage in a proposed 275 kV GIS. The key elements of the modelling methodology are described along with typical simulation results and the principle conclusions drawn from the analysis. The paper demonstrates how such computer simulations are used as a tool in the design and planning process to predict the maximum very fast transient overvoltage in a GIS for the insulation coordination of the equipments.

Many factors, such as technical compliance (as demonstrated for VFTO in this paper), as well as future expandability, cost effectiveness and efficiency need to be considered when evaluating options for new infrastructure works such as the proposed 275 kV GIS. This study is one of many that demonstrate the technical feasibility of this option, allowing it to be evaluated against alternative options. The final chosen option will depend upon a number of factors, and studies such as this are an important part of the option selection process.

VII. References

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VIII. Biographies

Denis Kho obtained his B.Eng in Electrical Engineering from Multimedia University, Malaysia in 2001. He worked for Sarawak Electricity Supply Co. and Advanced Power Solutions in Malaysia before joining Mott MacDonald’s Transmission Distribution Division, Glasgow, UK in 2007 as a power system analysis engineer. His experience includes large electrical utility networks using computer simulations, breaker TRV, switching overvoltages, fast front and very fast front overvoltages.

Kenneth S Smith studied Engineering Science at University of Aberdeen, UK (1984-1988) and was awarded his Ph.D. in 1992. He worked as a lecturer at the University of Aberdeen between 1991 and 1996 and then at Heriot-Watt University, Edinburgh, UK. He joined Mott MacDonald’s Transmission and Distribution Division, Glasgow, UK in 2002, where he is a Senior Engineer in the Power Systems Analysis Group. Dr Smith is a Chartered Electrical Engineer (UK), a Fellow of the IET, and a Senior Member of the IEEE. He is an Honorary Professor in Electrical Engineering in the School of Engineering and Physical Sciences at Heriot-Watt University, Edinburgh, UK, and is an Associate Editor of the IEEE Transactions on Industry Applications (Power Systems Committee).