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Investigation of Transient Overvoltages on GIS Busbars and External Enclosures

Hussam Saeed Alamoudi
Master of Science, Electrical Engineering, King Abdulaziz University, Jeddah, Saudi Arabia

Dr. Abdulaziz Uthman Alghamdi
Associate Professor, Faculty of Engineering, King Abdulaziz University, Jeddah, Saudi Arabia

Abstract
Fast Front Transient Overvoltages and Very Fast Transient Overvoltages in a 380kV gas-insulated substation (GIS) located in Jeddah City have been studied and analyzed using PSCAD Software. The Gas insulated substation (GIS) components and equipment's inside substation have been modeled using their equivalent circuits and distributed parameter lines that take into account during transients. Two Lighting events leading to the generation of possible Fast Transient Overvoltages are analyzed and discussed: i) Direct Strike, ii) Back Flashover. One switching operation event leading to the generation of possible Very Fast Transient Overvoltages inside GIS is analyzed and discussed: i) disconnector switching of outgoing diameter. Transient ground potential raise has also been investigated.
Keywords: Fast Transient Overvoltages, Very Fast Transient Overvoltages, PSCAD software

1. Introduction

The influence of lightning strikes and switching operations that are inevitable, cause transient over voltages in electrical transmission networks. Their duration is quite short (microseconds to milliseconds) and could be of large magnitude. As issued in IEEE, Transient over voltages cause losses of over billions of dollars every year worldwide because of damaged equipment and operation breakdown. The selected substation for this study is under construction and will connect the 380 kV Saudi Electricity network through underground cables and overhead transmission lines to different 380 kV substations in the western operating area of Saudi Network as shown in Figures. 1a and 1.b. It will also be connected to 110 kV network through underground cables to different substations. Furthermore, the selected substation consists of the followings:

380 & 110 GIS, 13.8 SWG,380 kV/110 kV Transformers,110 kV/13.8 kV Transformers, Capacitor Bank and Bus Shunt Reactors as a major equipment, will be considered in the study.

As part of the design stage, studies must be performed to ensure the reliability and the efficiency of the system, to prevent and lessen the damage of transient overvoltage on the utility system, to confirm that no equipment will be subjected to stresses exceeding the equipment insulation withstand limits.

Transient overvoltage's entering a GIS can therefore affect more equipment's and any damage due to transients within gas-insulated switchgear cannot be fixed without dismantling the GIS at all due to the non-self-recovery nature of the gas insulation system Sulfur hexafluoride (SF6).Any damage in a GIS usually requires long repair time and subsequently longer outage than the Air Insulated Substation.

A Transient study has been performed to assess protective devices requirement on the proposed GIS and to confirm that the insulation strengths have to be fulfilled the major possible over voltages occurred in the system. Fast Front Transient Overvoltage’s due to striking the phase conductor and striking the earthing wire on the top of the transmission tower have been considered in the study. Very Fast Front Transient

Overvoltages (VFTO) due to switching operations inside GIS such as disconnector interruption during normal operation condition has been considered in the transient study. The modeling methodology and results for the Transient study are discussed in this paper.

2. Methodology

Electrical measurement techniques quantifying the transient overvoltages at high frequencies remains challenging even with the advancement in power system. Real measurement in the GIS during the designing stage is not practically possible. Designers must use software and numerical tools to measure the transient overvoltages at high frequencies related to lightning surges and switching operations of GIS equipments. This will confirm the designer decision to achieve a reliable system and strong network with adequate insulation levels for the equipments. There are considerable existing literatures with regards to Transient overvoltage, the literature on the investigation of Transient Overvoltage in GIS substations is notably rare in Saudi Arabia. This analysis shows previous and related literature on the Transient Overvoltage as relevant in several contexts all over the world with good modeling methods, appropriate hypothesis and numerical tools can provide reasonably accurate results of the transient magnitude and their rates [1], [2], [3], [4]. The simulation studies reported here were conducted by using PSCADTM a time domain simulation program version 4.2.0, developed by

MANITOBA HYDRO for the transient investigation. The inception of an insulator flashover by a lightning stroke is a very complicated electromagnetic event. The basic concepts that appear in any computation of lighting flashover of transmission line divide widely into the concept of appearance of lighting on the line and the idea of the voltage created on the line by the flash when it happens. Lighting Stroke could be categorized into two types: i) Direct stroke ii) Back Flashover. This surge generates transients with frequencies in the range of hundreds of kHz.

The second type of the transient covered in the study is Very fast transient overvoltages. The disconnector in GIS is generally used for shutting and breaking off- load bus. In this situation, a number of strikes and re-strikes are going to happen because of the slow moving speed of disconnector contacts and poor arc extinguishing capability, which causes high-frequency oscillations and produce very fast transient overvoltages with electromagnetic nature [1]. This surge generates transients with frequencies in the range of hundreds of MHz. These transients cannot be calculated if conventional techniques of modeling and simulation are used.

To model the impact of transients overvoltages on equipments inside substation it is necessary to develop travelling wave models of the GIS as described in the technical literature and IEC 60071-2 [5]. The substation components used in the PSCAD are modeled based on data provided by the manufacturer for each equipment's. The equipment's models are documented in the following sections. Lightning stroke value in case of the direct or backflashover case is calculated and taken as 20 kA and 200 kA respectively [6], [7]. The surge impedance of the gantry (Zt) is calculated as 76.88 ohms [8], Transmission line it is composed of four sections that represent the tower sections between cross-arms. Each section consists of a lossless line in series with a parallel RL circuit as shown in fig.2 included for attenuation of the traveling waves, the surge impedance is calculated as 220 Ω and 300 m/us is the surge propagation velocity. The damping resistances and inductances are calculated according to [9]:

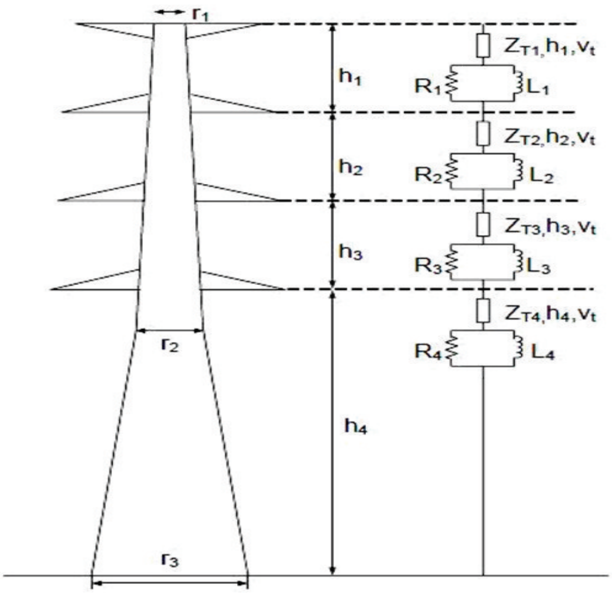


Figure 2. Multistory model of transmission line

R1=8.18 Ω, R2=8.18 Ω, R3=8.18 Ω, R4=16.7 Ω

L1=3.06×10^{-6} H, L2=3.06×10^{-6} H, L3=3.06×10^{-6} H , L4=6.24×10^{-6} H

The GIS bus bar is modeled as loss-free distributed parameter line with surge impedance of 86 ohm and velocity of propagation of 300,000 km / Sec. The GIS bus bar is modeled as loss-free distributed parameter line with surge impedance of 50 ohm and velocity of propagation of 300,000 km / Sec. SF6 Bushings have been represented by means of phase-to-ground capacitance of 500 pF according to manufacturer data. VT is modeled as a capacitance to ground the capacitance value is 50 pF. The power transformer at high frequency is represented as a lumped capacitance provided by the manufacturer. The frequency-dependent surge arrester model proposed by IEEE WG takes into account its dynamic behavior and it modeled as shown in fig.3

Where

L0=0.912, L1=68.4, R0=456, R1=296.4, C=21.92 for Air Surge Arrester Type

And

L0=0.534, L1=40.05, R0=267, R1=173.55, C=37.45 for GIS Surge Arrester Type

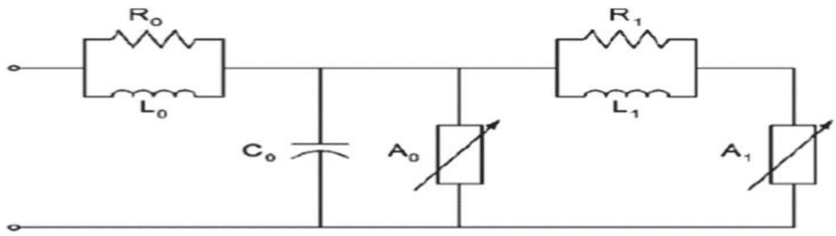


Figure 3. Surge arrester model proposed by IEEE working group

The modeling of each elements for the VFTO analysis is carried out in accordance with IEC standard [1]. A disconnector is represented by a PI section comprises of two traveling wave models, two capacitors to ground and a capacitor across the breaking contacts. A circuit breaker is represented by a PI circuit with two traveling wave models and four capacitors.

3 Fast Transient Overvoltage's due to Lightning strikes

3.1 Fast Transient Analysis

A Lightning surge of peak value 20 kA is considered to hit the phase conductor near the last tower in case of a direct strike and 200 kA when the surge hit the earhing conductor .The lighting study has been performed for the selected substation in order to find the maximum generated lighting surge transferred to system equipment's inside substation.

Table1.Lighting Surge transferred to system due to Lightning strike without using protective devices

Measured Overvoltage (location)	Reference voltage	Overvoltage due to Direct Strike	Overvoltage due to BackFlash	Withstand BIL
On gantry	380	3771	3965	1425
Entry of Substation	380	3741	4051	1425
Bus Section of GIS	380	3736	4057	1425
At the end diameter of GIS	380	3733	4046	1425
Line 2 on the same tower and gantry	380	3711	4088	1425
HV side of 502 MVA TR	380	3722	4986	1425
LV side of 502 MVA TR	110	2340	3206	650
TV side of 502MVA TR	13.8	2456	3278	95

The maximum fast transient overvoltage in case of direct strike without using any protective device against lighting strike is 3771 kV on the gantry side is shown in Fig 4.

The acceptable overvoltages must be within 87% of BIL values [1]. It is seen that the obtained result care high and beyond the recommended BIL levels. Its required to limit the overvoltage's to safe levels by using Surge Arresters in the proper locations. The maximum fast transient overvoltage in case of a direct strike with surge arresters is reduced to 720 kV on the gantry side as shown in Fig 5.

Table2.Lighting Surge transferred to system due to Lightning strike when installed protective devices

Measured Overvoltage (location)	Reference voltage	Overvoltage due to Direct Strike	Overvoltage due to BackFlash	Withstand BIL
On gantry	380	720	811	1425
Entry of Substation	380	803	862.5	1425
Bus Section of GIS	380	808	870	1425
At the end diameter of GIS	380	809	875	1425
Line2 on the same tower and gantry	380	887	931	1425
HV side of 502 MVA TR	380	703	710	425
LV side of 502 MVATR	110	174.5	175	650
TV side of 502MVA TR	13.8	32	32	95

3.2Effect of Location of Surge Arrester

The Surge arresters that used to protect power transformer has to be installed in two locations. Location A closer to the power transformer and Location B far away from power transformer as shown in fig.6 and the result is tabulated in Table 3.

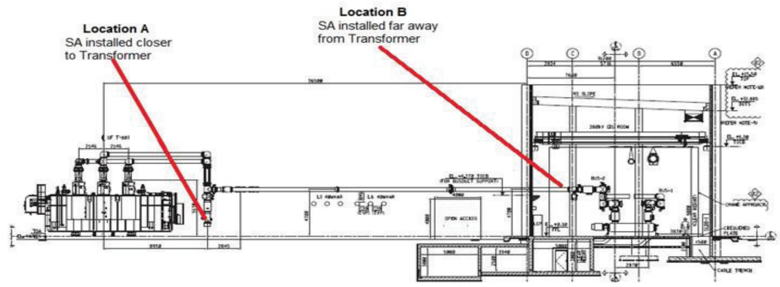


Figure 6.Effect of Location of Surge Arresters

Table 3. Shows the effect of location of surge arresters on GIS substation.

Measured Overvoltage (location)	Overvoltage SA Closer to protected object	Overvoltage SA far away protected object
On gantry	811	825
Entry of Substation	862.5	896
Bus Section of GIS	870	903
At the end diameter of GIS	875	908
Line 2 on the same tower & gantry	931	965
HV side of 502 MVA TR	710	1210
LV side of 502 MVA TR	175	175
TV side of 502MVA TR	32	32

3.3 Effect of Tower footing resistance of transmission Tower

Tower footing resistance of 20 ohm has been considered in the previous section and the reduction of the footing resistance as 0.5 ohm will be assumed. The comparison between the different footing resistance values is shown in table 4.

Table 4. Shows the effect of location of surge arresters on GIS substation.

Measured Overvoltage (location)	Footing Resistance 20 ohm	Footing Resistance 0.5 ohm
On gantry	811	790
Entry of Substation	862.5	827
Bus Section of GIS	870	830
At the end diameter of GIS	875	828
Line 2 on the same tower& gantry	931	883
HV side of 502 MVA TR	710	706
LV side of 502 MVA TR	175	173
TV side of 502MVA TR	32	31

3.4 Effect of Current Amplitude of Lightning Strike

The effect of the current amplitude of lightning strike to the equipment's and HV substations in this section is the main concern. Hence, simulations were performed for two situations in terms of the current amplitude of lightning strike 20 kA and 200 kA for back flashover and the reflected current into the substation was 25 kA for the shielding failure. Figures [7] [8] illustrate that maximum voltages, observed at the GIS entry when the lighting stroke the phase conductor and when the lighting stoke the ground wire.

4.1 Very Fast Transient due to switching operation of disconnector Switch

Due to the relatively slow speed of operation of the disconnector switch number of re-strikes and pre-strikes will occur when the disconnector opens. The maximum value of the very fast transient 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 and the maximum generated Very fast transient Overvoltage is shown in figure [9]

Table 5. Measured Very Fast Transient Overvoltage on GIS

Measured Overvoltage (location)	Reference voltage	Overvoltage
Disconnector	380	690
Voltage Transformer	380	765
Current Transformer	380	678
Earthing Switch	380	731
Circuit breaker	380	675
Transformer Terminal	380	759
Air Terminal/ Cable Bushing	380	867
BusBar	380	688

4.2 Transient ground potential raise

The phenomena of transient enclosure voltage (TEV), also known as the transient ground potential rise (TGPR), consists of short duration high voltage transients appearing on the external surface of the GIS enclosure associated with an internal voltage collapse (SF6 breakdown), internal restrikes across the contacts of operating circuit breakers and disconnectors. In any case, the voltage collapse produces traveling waves which propagate in all possible directions from the point of breakdown, depending on the number of paths departing from this point. It calculated by using the factor that is obtained from calculates the TEV voltage by multiplying the voltage that appears near to the cable bushing. From the above case, the maximum voltage that is observed across the cable head is given by 867 kV (peak).

When

Ze = 86 Ω, Z1 = 50 Ω, Z2 = 220 Ω (according to manufacturer data)

$$S = \frac{-Z \times Z_e}{(Z_1 + Z_2 + Z_e)}$$

Then **S= 0.483**

The enclosure voltage is given by Ven= 867*0.483 = 418.88 kV (peak).

5 Cost Analysis

Cost-benefit analysis is used to help people make decisions and involves comparing the values of an activity by providing SA in the substation. The Surge arrester cost includes items, such as the cost of the structural system (e.g. structural installation, Foundation, Support) and the electrical system costs (e.g. Surge arrestors, Surge counter, Surge arresters accessories and Connection cable) and others such as maintenance and commissioning. The required data of the cost analysis has been taken from the manufacturer and contractor. The estimated cost for the Surge Arrester is as follow:

Table 6. Showing the estimation cost for each unit

Estimation Cost for single phase in $							
Level KV	Type	Location	SA price with the accessories	Foundation	Construction	Testing for all units	Total $
380	Air	Gantry	29,484.27	1,600.00	1,200.00	12,000.00	44,284.27
380	GIS	Near TR	27,209.87	NA	1,096.53	4,000.00	28,306.40
13.8	indoor	Inside TRTV box	2,556.00	NA	133.33	1,600.00	4,289.33

Table 7. Total cost to protect substation against Transient

Estimation Cost for all units in $					
Voltage Level KV	Type	Location	Price/Unit	Quantity	Total
380	Air Type	Gantry	44,284.27	9	398,558.40
380	GIS	Near TR	28,306.40	4	113,225.60
13.8	Indoor	Inside Transformer TV box	4,289.33	4	17,157.33

The total estimation cost for 380 kV GIS system is 528,941.33 $ in order to protect the GIS substation against Transient overvoltages.

6 Discussion

It is observed that the overvoltage's at the different locations of the substation without using SA are exceeding withstand limits and After installed the lighting arrester in the proper locations the observed overvoltage has been decreased to the acceptable range. The study demonstrates that surge arresters to protect the equipment from lightning surge are required for this installation. The lightning overvoltage's in substations and their rates of occurrence depend on: the lightning performance of the overhead lines connected to it, the substation layout, size, the instantaneous value of the operating voltage (at the moment of the stroke), the parameters of the substation equipment's, the value of the lighting stroke, the severity of lightning overvoltage's for the substation equipment is determined from the combination of the mentioned factors. The reflected wave and the waveforms of the lighting induced voltages vary widely and are particularly affected by the: Magnitude and the front time of the stroke current, Distance between the line and the lighting strike point, Soil resistivity, Surge impedance of Transmission line, Heights of the conductor, Line configuration, Earth resistance. The surge can be transferred between the phases which can increase the stress in an adjacent phase subjected to a direct surge and it can damage transformer if the transferred surge exceeds protection level of transformer. Capacitive transferred surges are usually critical only when they are transferred from the high-voltage side to the low-voltage side. The capacitive transferred surge originates from the potential rise of the primary winding caused by incoming fast-front and transferred to the secondary / tertiary through the winding capacitance as in the case of unbalanced primary voltages but an important difference is caused by the fact that in the case of rapid primary voltage variations only those parts of the windings which are near the terminals take part in the surge transference.

7. Conclusion

Based on lightning stroke studies performed, by injecting current of 20 kA on one of the phase conductor in the first tower near the gantry of MHR line and 200 kA on the shielding wire, it is observed that the voltages at the different locations of the substation without using SA are exceeding limits of respective BIL levels. Hence, the proposed surge arresters, one at gantry of the transmission line, one at near to each HV, LV and TV terminal of transformer are required in order to protect the GIS substation against direct strokes.

Results obtained from this study are in line with the existing literature and previous studies in this field. Maximum overvoltage's without using surge arresters are below 6 pu for lightning cases and below 3 pu for a very fast transient case.

Studies have been conducted for one with surge arrester in service at the Gantry side (entry of substation) as well as one near the HV side of Transformer and one near the Tertiary winding side. it is observed that the overvoltage's at the substation during direct stroke and back flashover is much below the BIL value and sufficient safety margin is available, and therefore no additional surge arresters are required at 380kV level.

The overvoltage developed at the point of impact on the Transmission Line has been shown in section3. Theoretically, these can be calculated by using the lightning current (I0) and Surge Impedance of the Transmission Line (Z0) mentioned in section3. For 20kA Lightning Current, the overvoltage calculated as $V_0 = \frac{1}{2}I_0Z_0 = 2200\ kV$ while the obtained result based on the parameters is in the range of 3700 kV.

It has been observed that the location of the protective device should be installed closer to the protected equipments to reduce the path from the Surge arresters to the protected units. The location of arrester shall be placed so that the minimum distance between any part of it and any protected object is not less than one-half of the length of the arrester to maintain the phase to phase, phase to ground and safety/ maintenance clearances.

Lightning overvoltage occurrences can be limited by appropriate design for the overhead lines. Back flash over can be limitation by reducing the tower footing earthing resistance. While the current amplitude of the applied lightning strike increases, substation equipment's and GIS are exposed to higher voltages. This is an expected result since there is a linear correlation between the current amplitude of the lightning strike and maximum voltages observed at the equipment's and GIS.Based on VFTO study performed, by switching operation of the disconnector switch of diameter D8 of the GIS, it is observed that the measured overvoltage's at the several locations of the GIS are within limits of respective BSL levels. Hence, the proposed GIS can withstand the VFTO generated from the normal operation condition of GIS VFTO.This analysis is required to cater for the control relay malfunction.

References

[1] Standard IEC 60071-4, ‘Insulation coordination’ part 4 ‘Computational guide to insulation coordination and model, 2004

[2] Chang-Hsing Lee and Shi-Lin Chen, power system design for NPP, 2012

[3] A. Tavakoli, A. Gholami,” Mitigation of Transient Overvoltages Generated Due to Switching Operations and Lightning in Gas-Insulated Substation (GIS) Without Extra Limiter”, Iranian Journal of Electrical & Electronic Engineering, Vol. 7, No. 3, Sep. 2011

[4] Dr Sukhdeo Sao, K Prasada Rao, “Effect of Very Fast Transient over voltages at high frequency in a Gas Insulated Substation during switching operations”, International Journal of Scientific and Research Publications, Volume 3, Issue 3, March 2013

[5] Standard IEC 60071-2, 'Insulation coordination' part 2 'application guide, 1993
[6] Andrew R.Hileman, Insulation Coordination for Power Systems, 1999
[7] IEEE Modelling and System Transients Working Group, Modeling Guidelines for Fast front transients, IEEE Trans. on PD, 1996, vol. 11, p. 493-506
[8]Allan Greenwood,Electrical Transient in Power Systems , Second edition, 1991
[9] Juan A. Martinez-Velasco, Power system transients parameters determination, 2010

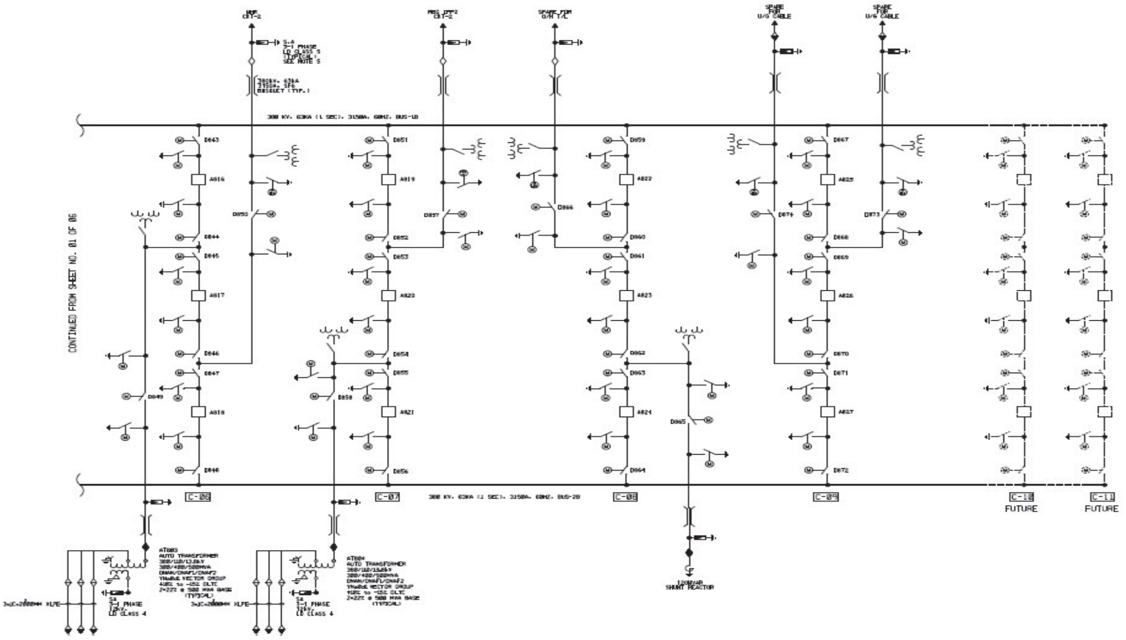


Figure 1a. 380 kV GIS substation single line diagram part a

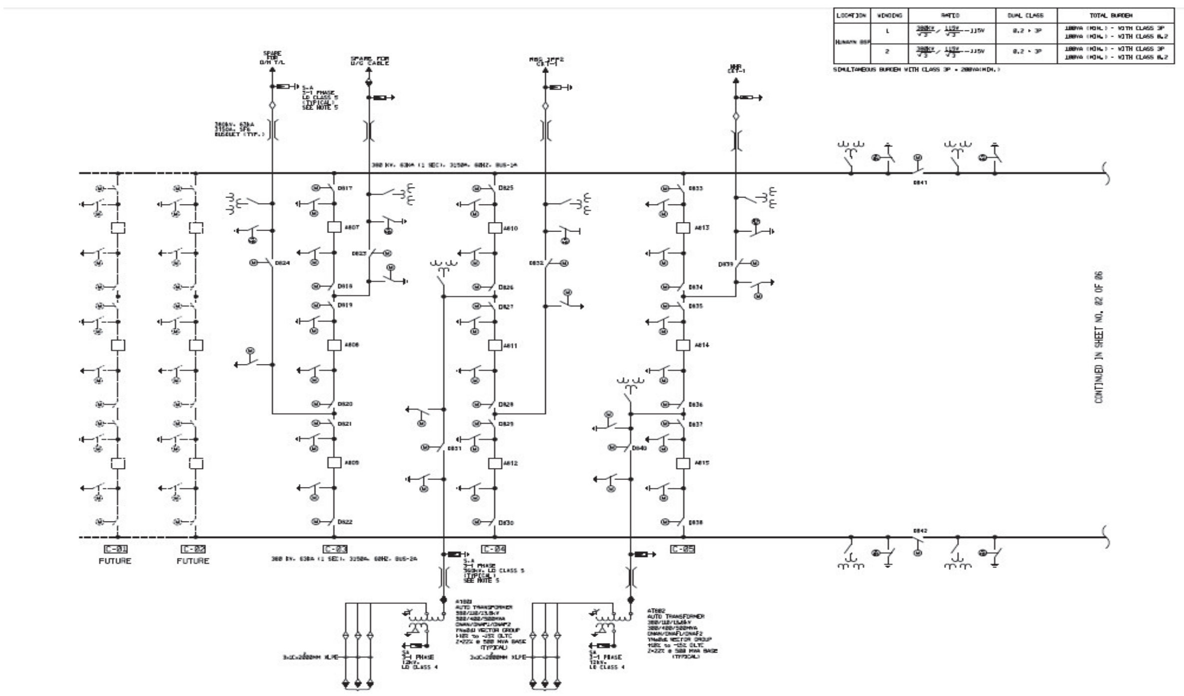


Figure 1b. 380 kV GIS substation single line diagram part b

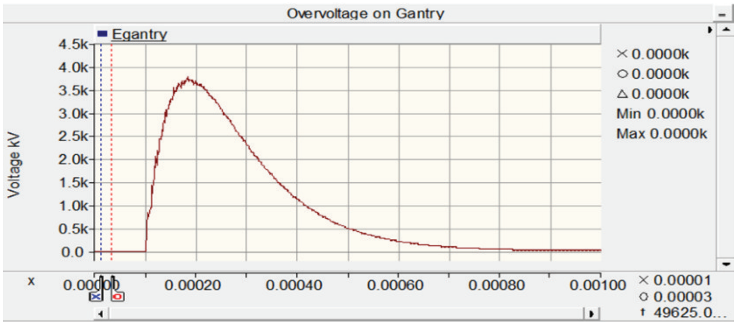
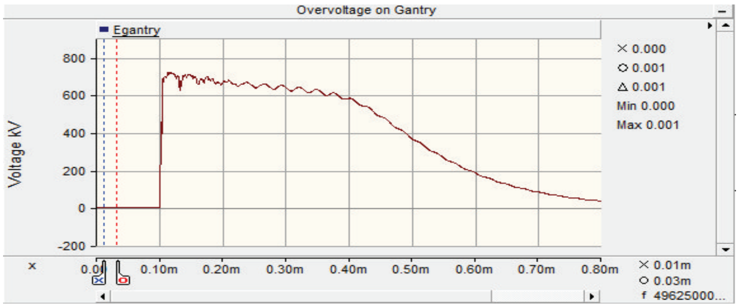


Figure 4. Maximum Fast transient overvtoltage due to direct strike case without Surge arresters inside substaion



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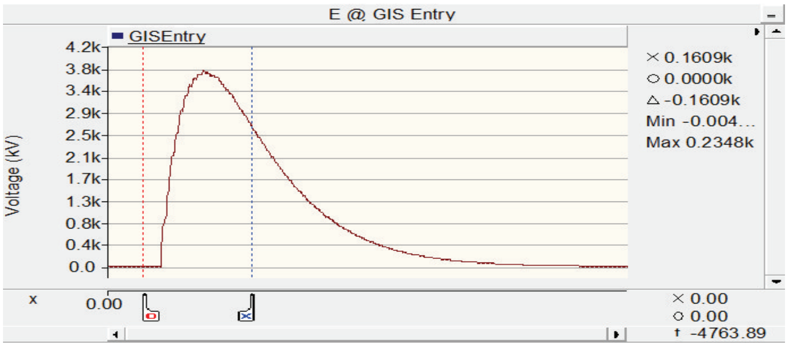

Figure 7. Overvoltage on GIS entry when the injected current is 20 kA

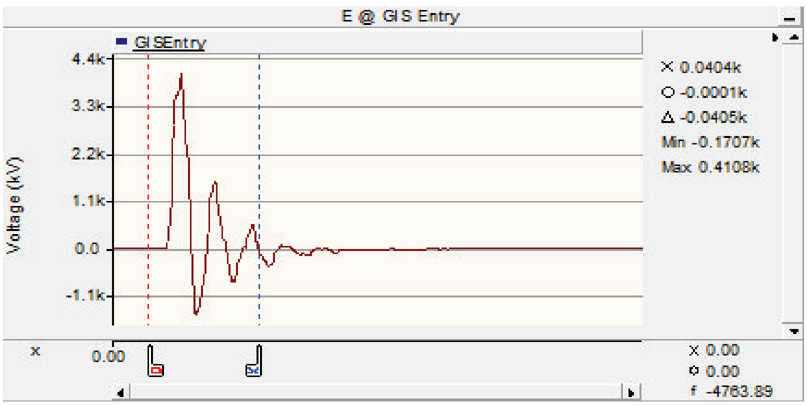

Figure 8. Overvoltage on GIS entry when the injected current is 200 kA

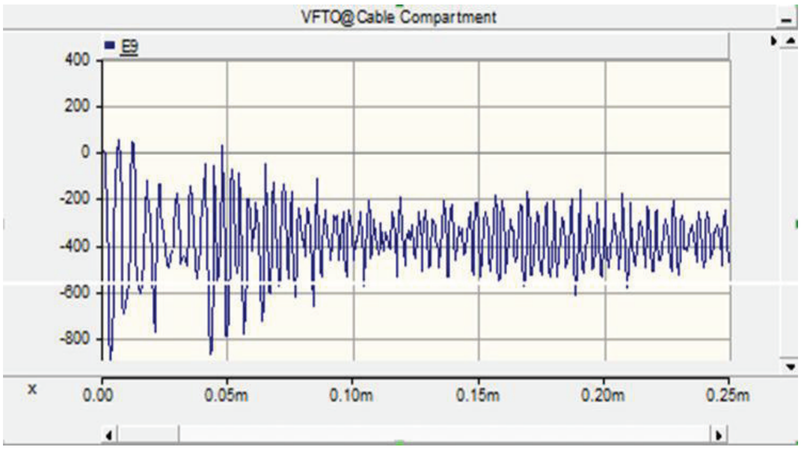

Figure 9. Maximum VFTO on Air Terminal