The Lightning Current Parameters that Impact on the Surge Analysis of the EHV Gas Insulated Substation by EMTP

Eung-Bo Shim† and Sang-Ok Han*

Abstract - This paper describes the lightning surge analysis model of extra high voltage GIS using EMTP. Various lightning current parameters were investigated in order to confirm the impact on the lightning surge analysis such as lightning current amplitude, waveform, size of GIS, tower footing resistance and surge arresters. The multi-story tower model and EMTP/TACS model were introduced for the simulation of dynamic arc characteristics. The margin between the maximum overvoltage and BIL of the GIS was about 10 percent and the margin between the maximum overvoltage and BIL of the transformer was 21 percent.

Keywords: BIL (Basic Insulation Level), EMTP, GIS (Gas Insulated Substation), Lightning Surge, TACS (Transient Analysis of Control Systems)

1. Introduction

In the 1960's, the extra high voltage substation was constructed as an outdoor type of equipment using the air as its insulating material. Recently, SF6 gas has taken precedence as the insulating material for substation facilities in order to minimize both the environmental impact and the installation area[1]. Despite these benefits, if insulation failure occurs, a longer time is required to re-establish the equipment because the SF_6 gas is incapable of self restoration. As such, we must carefully examine and review the insulation characteristics of the equipment from the initial stages of its design[2]. In this paper, we analyzed the influence of lightning overvoltage, such as arrangement of the substation equipment by EMTP and lightning current parameters to the substation, transmission and substation equipment. Based on the analysis results, we determined whether or not the characteristics of the equipment satisfy the BIL.

2. Outline of Lightning Analysis Model

We can assume that lightning current reaches the substation in either of two ways; one is direct lightning stroke from the power line and the other is back flashover of the transmission tower by a lightning stroke on the top of the tower. The commercial transmission line has ground wires to prevent any direct lightning stroke, so we only consider the back flashover case here. The objective substation has four (4) circuits of 345 kV transmission lines, one (1) transformer bank and 1.5 circuit breaker systems. The analysis parameters are affected by the following: lightning conditions, transmission facility, power generation and substation facilities.

2.1 Lightning Current Assumption

We assumed that the lightning stroke is on the first tower, which is nearest to the substation. In this case, the lightning surge would travel to the substation if the back flashover occurs in the tower. The assumed lightning current has a peak of 120 kA, wave front of 2 micro-seconds and a 70 micro-second wave tail. The probability of lightning bigger than 120 kA is less than 3 percent in such a case[3].

2.2 Transmission Line and Transmission Tower

The transmission is modeled as an 8-phase type, which represents two overhead ground wires and six phase power line conductors. The transmission tower is arranged up to 5 towers from the substation, and the remainder of the towers is replicated to match the resistance matrix to prevent reflection of the traveling wave.

If we assume the surge Z_1, Z_2 as surge impedance of different conductors, the reflection co-efficient can be expressed as the following equations;

$$\lambda = (Z_2 - Z_1)/(Z_1 + Z_2) \tag{1}$$

If we set $Z_1 = Z_2$, the reflection co-efficient will be zero, signifying that no reflections are occurring in the circuit. In the calculation, we obtained the resistance matrix value by EMTP/LINE CONSTANTS as follows;

---

† Corresponding Author: Power Systems Laboratory, Korea Electric Power Research Institute, Korea. (ebshim@kepri.re.kr)

* Dept. of Electrical Engineering, Chungnam National University, Korea. (sohan@cnu.ac.kr)

Received May 29, 2004 ; Accepted June 19, 2004

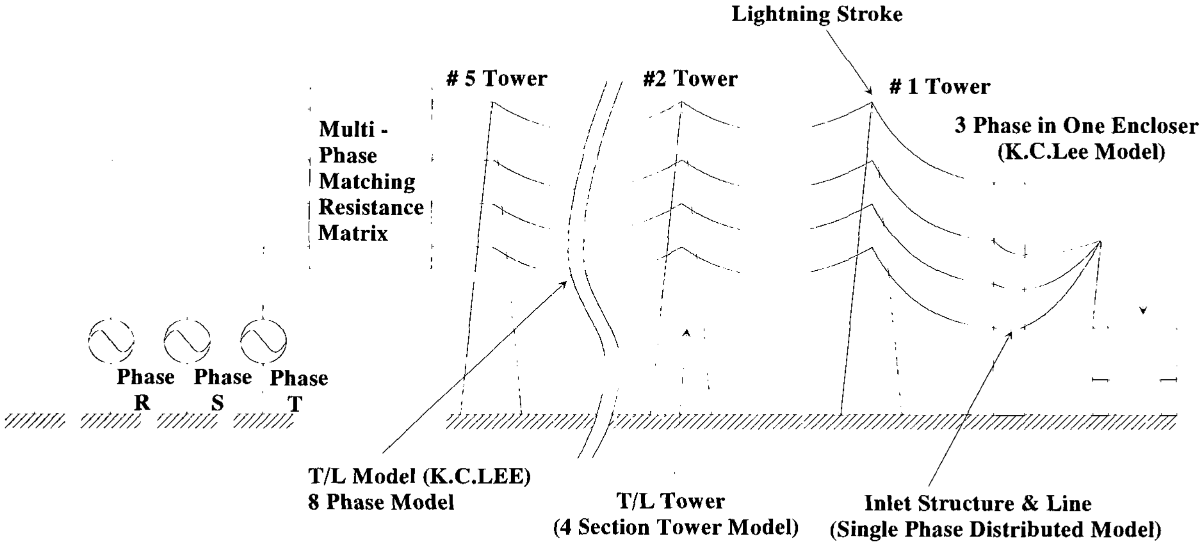


Fig. 1 Concept on the modeling of transmission line

$$\begin{bmatrix} 565.61 & & & & & & & \\ 178.76 & 561.19 & & & & & & \\ 173.90 & 142.77 & 418.57 & & & & & \\ 122.86 & 109.54 & 162.10 & 412.19 & & & & \\ 97.60 & 92.38 & 124.66 & 166.96 & 409.19 & & & \\ 104.52 & 110.95 & 112.54 & 121.28 & 129.37 & 399.63 & & \\ 122.65 & 132.57 & 126.23 & 123.23 & 117.71 & 162.30 & 410.40 & \\ 117.25 & 128.70 & 127.07 & 129.25 & 127.22 & 181.80 & 223.55 & 409.20 \end{bmatrix}$$

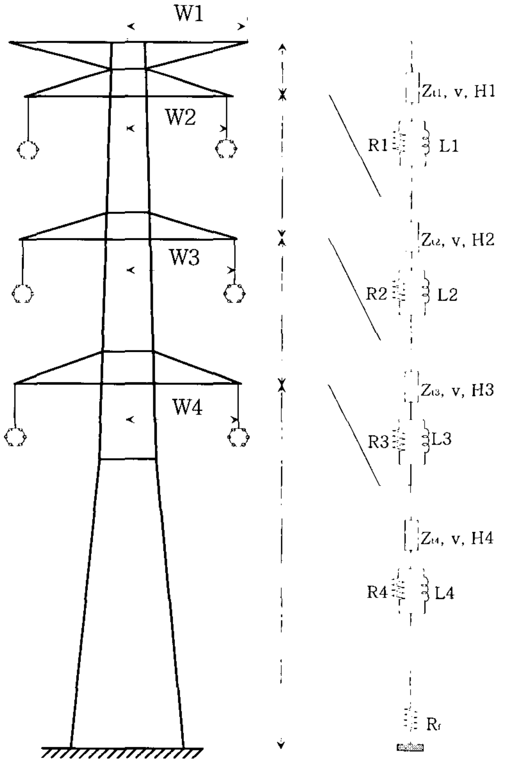


Fig. 2 Four section tower model

The frequency independent K. C. Lee model is used because the surge frequency is very high in the lightning phenomena and the calculated result is identical to that of the frequency dependent model.

Fig. 1 depicts the overall concept on the modeling of the transmission line. The tower height is 56 meters, which consist of a 483 square millimeter cross section of 4 bundle conductors for power lines, and a 120 square millimeter cross section of 2 ground wires. The standard of tower footing resistance is 20 ohms. The tower model directly affects the wave shapes of lightning surges that appears on the arcing horn gap. A four section tower model with a distributed line parameter is used for the high accuracy transmission tower model.

In Fig. 2, the electrical parameters are as follows[4];

- tower heights between arms (H1, H2, H3, H4) are 7.3, 8.6, 7.7 and 32.4 meters, respectively.
- equivalent resistance between arms (R1, R2, R3, R4) are 15.18, 17.89, 16.02 and 33.37 ohms, respectively.
- equivalent inductance between arms (L1, L2, L3, L4) are 5.7, 6.7, 6.0 and 12.5 micro-Henry, respectively.
- tower surge impedance between arms ($Z_{t1}=Z_{t2}=Z_{t3}$) is 220 and Z_{t4} is 150 ohms.

2.3 Arcing Horn Gap Model with EMTP/TACS

The arcing horn gap can be modeled as a time-controlled switch, linear arc inductance with time-controlled switch or nonlinear arc inductance with controlled switch.

Among these models, the nonlinear arc inductance model is the most accurate one able to represent the dynamic arc characteristics of the arcing horn gap. Since we do not have any experimental data for that, we used the linear inductance model.

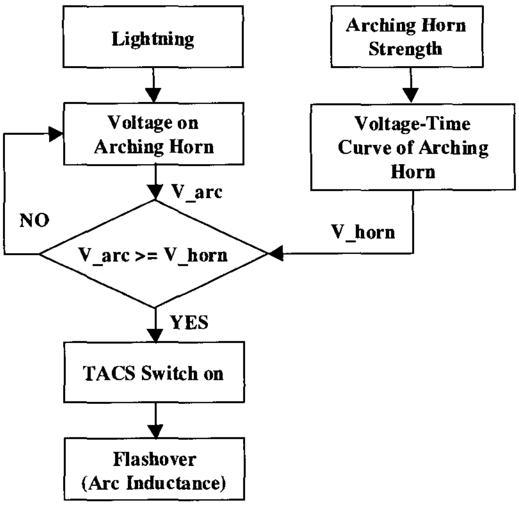


Fig. 3 Flow chart of arcing horn and TACS

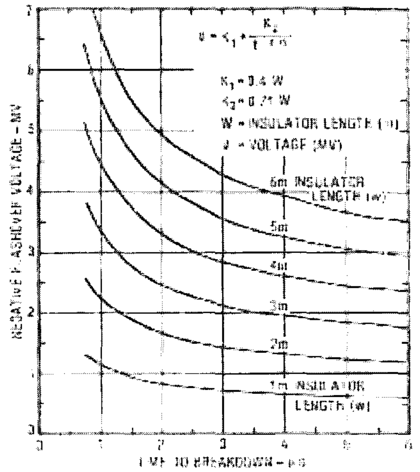


Fig. 4 CIGRE volt-time characteristics for flashover of line insulators

2.4 Calculation of Surge Impedance of GIS

There are two (2) types of GIS, one is a single phase arrangement in one encloser, and the other is a three (3) phase arrangement in one encloser. We calculated the surge impedance of the GIS according to the manufacturer by EMTP/CABLE CONSTANTS.

Fig. 5 shows the layout of the 345 kV class GIS, which is a one (1) phase in one encloser type, used for the bus inter connection. In the Fig., a_1=43 mm, a_2=60 mm, b_1=248 mm, b_2=254 mm and H is 2.7 meters.

In Fig. 5, sheath radius is b_1 and conductor radius is a_2. The capacitance of the GIS is represented as equation 2.

$$C_0 = \frac{2\pi\varepsilon_0}{\ln\frac{b_1}{a_2}} = \frac{55.6}{\ln\frac{b_1}{a_2}} \tag{2}$$

whereas ε_0 is dielectric constants of the vacuum.

The surge impedance Z is expressed as equation 3.

$$Z = \frac{1}{v \cdot C_0} = 60\ \ln\frac{b_1}{a_2}\,[\Omega] \tag{3}$$

whereas v is surge propagation velocity.

Considering the actual size of domestic manufacturer's GIS lay out, the calculated surge impedance of single phase GIS is between 55 ohms and 85 ohms.

Fig. 6 indicates the layout of the 345 kV class GIS[5-7], which is a three phase in one encloser type, used for the buses. In this Fig., a_1=43 mm, a_2=60 mm, b_1=450 mm, b_2=459 mm, r=250 mm and H is 2.2 meters. Equation 4 shows the surge impedance matrix for the three (3) phase in one encloser type GIS. The propagation velocity is 270 meters per micro-second for single phase enclosure as well as three phase in one encloser type GIS.

$$Z_c = \begin{vmatrix} 90.9 & 11.5 & 11.5 \\ 11.5 & 90.9 & 11.5 \\ 11.5 & 11.5 & 90.9 \end{vmatrix} \tag{4}$$

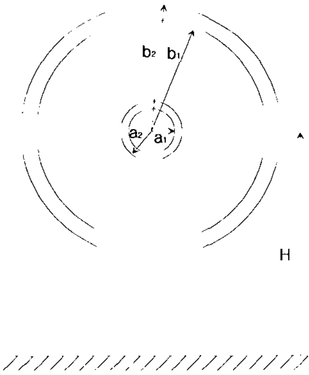


Fig. 5 Arrangement of one (1) phase in one enclosure type GIS

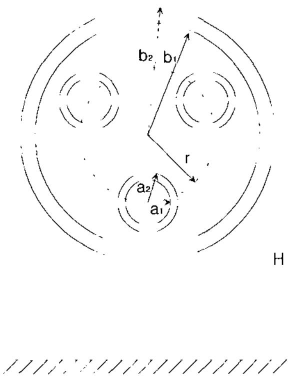


Fig. 6 Arrangement of three (3) phase in one enclosure type GIS

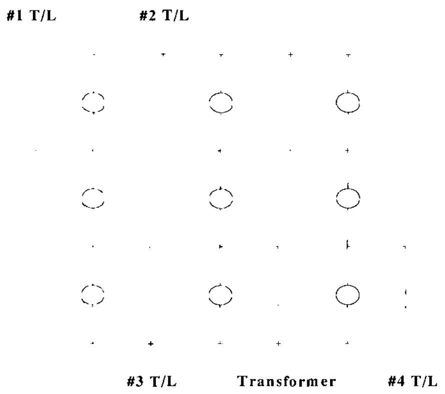


Fig. 7 GIS Layout for model scheme

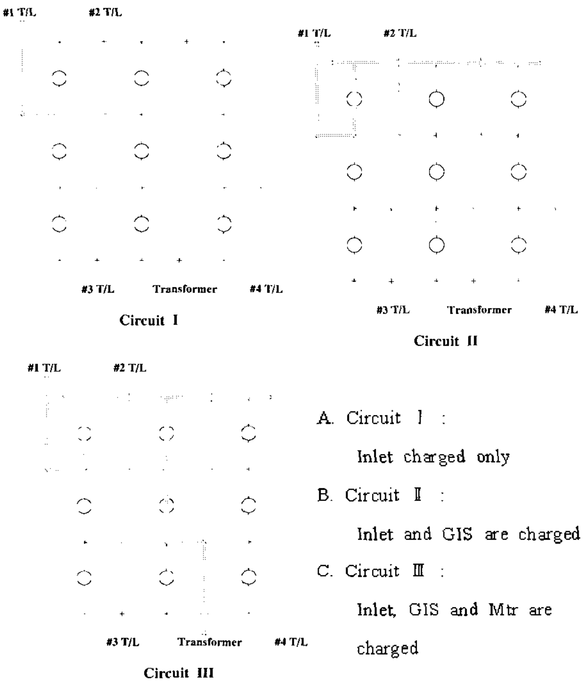


Fig. 8 Operation conditions of the GIS

2.5 GIS Layout and Operating Condition

The type of the model substation is full GIS, 1.5 circuit breaker system, which has four transmission lines and one transformer bank. The buses of the GIS are of the three phase in one encloser type, and the circuit breakers are single phase type as shown in Fig. 7.

To investigate the most severe operation condition, we classified it as three circuit conditions; the one is for protecting the incoming of GIS, which includes the surge arresters, the second one is for buses and circuit breakers and the last one is for the main transformer. Fig. 8 is the example of each operating condition.

2.6 Tower Footing Resistance

We represented the earth resistance as a concentrated pure resistance considering the most severe condition, because the transient voltage-time characteristics of the tower footing resistance are not yet specified. The represented value of the tower footing resistance of transmission tower is 20 ohms, however 10 to 50 ohms are used for comparing the result with another whereas the resistance of the mesh of substation is set to 1 ohm.

2.7 Surge Arrester Characteristics

Table 1 V-I Characteristics of Surge Arresters

Unit: kV

Manufacturer	MCOV (rms)	Impulse (8/20 μs)			
		5 kA	10 kA	20 kA	40 kA
M	224	605	645	700	780
H	-	584	637	702	768
A	224	687	715	787	866

The surge arrester characteristics and its location are very important to simulate the lightning surge. Table 1 shows the voltage-time characteristics of ZnO surge arresters, which are installed in the site.

2.8 Other Equipment

In the lightning overvoltage analysis, the substation equipment can be modeled as a concentrated capacitance. It does not affect the calculated results because the wave front of a lightning surge is in a several micro-seconds.

The representative capacitance of a transformer, potential transformer and bushings are shown in table 2. The circuit breakers are modeled identical to the GIS when the circuit is in closed state, as pi circuit of capacitance as in Fig. 9 when the circuit is in opened state.

Table 2 Representative Capacitance of Equipments

Transformer [pF]	PT [pF]	PD [pF]	Bushing [pF]
2,500	200	2,000	200

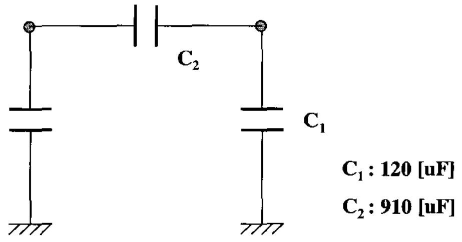


Fig. 9 Circuit Breaker Modeling (opened state)

3. Analysis Result

3.1 Effect of Lightning Current Parameters

Table 3 Overvoltage variation due to lightning current parameters

Item	Base Index	Comparative Index	Variation of Overvoltage (%)
Amplitude	120 kA	140, 160 180, 200	+3.7 ~ +23.6
Wave front/ Wave tail	2/70 ㎲	Wave front (1, 2, 3 ㎲)	-11.9 ~ +32.6
Superposition of power frequency	Negative	Positive, None	-42.0 ~ -2.7

The overvoltages at the substation are increased according to the steepness of the wave front, amplitude of lightning current and supposition of power frequency voltage. We examined the variation of overvoltage at the substation according to the above listed items, results are shown in Table 3, and wave forms are shown in Fig.s 10 and 11.

When the lightning peak current is varied from 120 kA to 200 kA, the overvoltages are raised up to 23.6% according to the increase in current. When the wave front of the lightning current is changed to one (1) micro-second, the overvoltage is increased up to 32.6%, whereas when the wave front of the lightning current is altered to three (3) micro-seconds, the overvoltage is decreased to -11.9%. If the negatively superposition of power frequency is neglected, the overvoltage is decreased to - 42.0%.

3.2 Effect of Transmission Line Equipment

Table 4 Overvoltage variation due to transmission line equipment

Item	Basic Index	Comparative Index	Variation of Overvoltage (%)
Tower footing resistance	20 Ω	10, 20, 30, 40, 50	-2.7 ~ +3.9
Length of line between inlet and 1st tower	100 m	50, 150, 200	-17.2 ~ +2.9
Arcing horn gap length	2.34 m	2.0, 2.1, 2.2	-4.0

We examined the variation of overvoltages at the substation according to the transmission line equipment such as tower footing resistance, length of line between the inlet structure and the nearest transmission tower from the substation, and arcing horn gap length.

The 10 ohms of tower footing resistance reduce the overvoltage by -2.7 percent whereas 50 ohms of tower footing resistance increase the overvoltage by +3.9 percent.

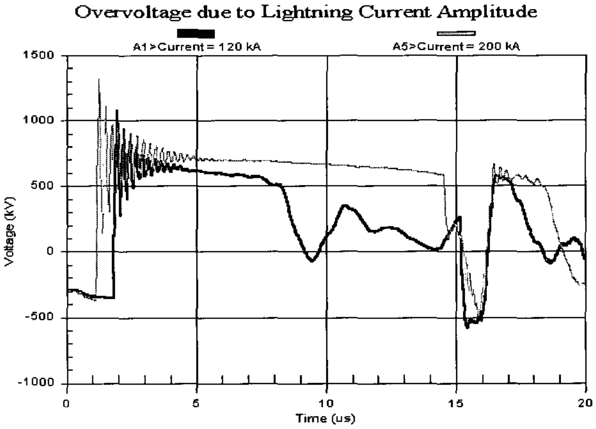


Fig. 10 Typical waveform by EMTP (Overvoltage due to lightning current amplitude)

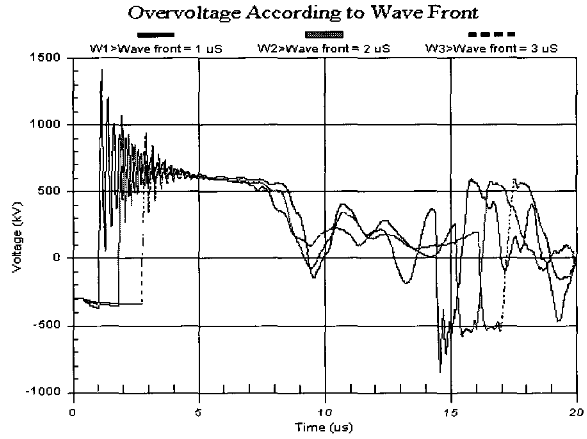


Fig. 11. Typical waveform by EMTP (Overvoltage according to wave front)

The simulated results are shown in Table 4, and waveforms are shown in Fig. 12.

3.3 Effect of Substation Equipments

Table 5 Overvoltage variation due to substation equipment

Item	Basic Index	Comparative Index	Variation of Overvoltage (%)
Surge impedance	80 Ω	60, 70, 90,	-5.9 ~ +3.7
Length of GIS between inlet and bus	10 m	20, 30, 40,50	+11.0 ~ +16.1
Surge arrester characteristics	Maker (M)	Maker (H) Maker (A)	-2.2 ~ +6.1

We examined the variation of overvoltages at the substation according to the substation equipment such as surge impedance of the GIS, length of the GIS between the inlet and main buses, and characteristics of surge arresters. The 40 meter lengths of the GIS inlet increase the overvoltage by +16.1 percent compared with the length of 10 meters. However the surge impedance of the GIS and surge arrester characteristics does not affect the over-voltage variation. The simulated results are shown in Table 5.

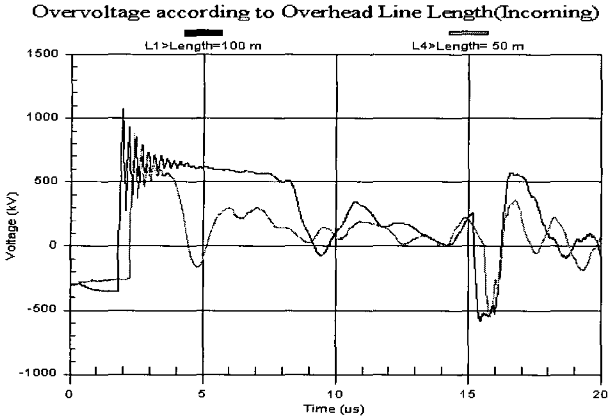


Fig. 12 Typical waveform by EMTP
(Overvoltage according to overhead line length)

3.4 The Analysis Result and Test Requirement

We compared the analysis result with test requirements of each piece of equipment for the buses and transformer in the GIS. The calculated margin of the equipment was 10.0 percent and 21.2 percent, respectively. The margin is shown in Table 6 using equation 5.

Table 6. The Analysis Result and Test Requirement

Measuring point	Overvoltage [kV]	Test Voltage [kV]	Margin [%]
Inlet of GIS	1,068	1,175	10.0
Bus (with LA)	850	1,175	38.2
Transformer (30 m from LA)	866	1,050	21.2

$$\text{Margin} = \frac{\text{Test Volt.} - \text{Max Volt.}}{\text{Max.Voltage}} \times 100 \ [\%] \qquad (5)$$

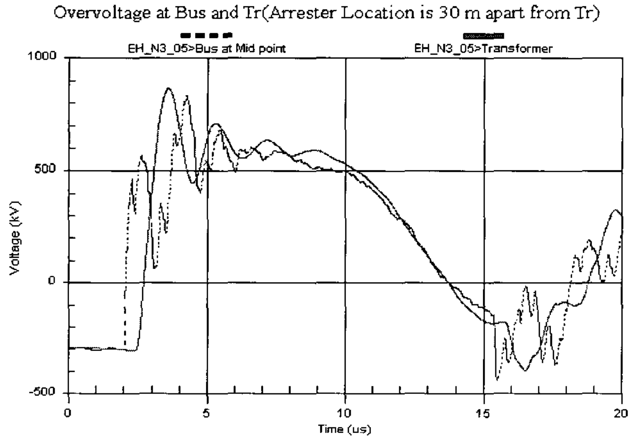


Fig. 13. Typical waveform by EMTP
(Overvoltage at bus and transformer)

4. Conclusion

It was found from the simulation result that the overvoltage varies according to the various parameters such as lightning current parameters, transmission facility and substation & power station facility. As well, the overvoltage does not exceed the present insulation level for lightning surge with proper margin to the test voltage.

- Overvoltage variation is -42~+33% according to the lightning current parameters.
- Overvoltage variation is –17~+4% according to the effect of the transmission facility.
- Overvoltage variation is –6~+16% according to the effect of the power station & substation facility.
- The maximum overvoltage that appears on the GIS is 1,068 kV, which has a 10.0 percent margin to the test voltage of 1,175 kV.
- The maximum overvoltage that appears on the transformer is 866 kV, which has a 21.2 percent margin to the test voltage of 1,050 kV.

References

[1] A. R. Hileman, “Insulation Coordination”, ABB Power Systems Inc., 1991

[2] EPRI, “Transmission Line Reference Book 345 kV and Above”, 2nd Edition, 1982

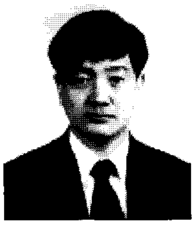
[3] EMTP Rule Book, ATP Salford Version, Ⅰ, Ⅱ, 1987

[4] Akihiro Ametani, “Distributed Parameter Circuit Theory”, Tokyo, Japan, 1990

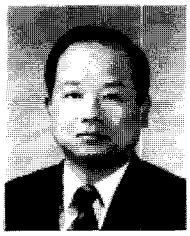
[5] CRIEPI Report, “Guide to Lightning Protection Design of Power Stations, Substations and Underground Transmission System”, 1995

[6] J. G. Choi, S. H. Yi, K. H. Kim, I. S. Kim and J. C. Kim, “Detection Characteristics of a Novel Coupler for GIS PD Detection”, KIEE Int. Trans. on EA., Vol. 3-C, no. 6, pp. 224-229, 2003.

[7] I. K. Song, J. W. Jung and H. R. Kwak, “Dielectric and Electrical Characteristics before and after Thermal Ageing of Main Insulating Materials for Pole Transformers”, KIEE Int. Trans. on EA., Vol. 12C, no. 1, pp. 24-32, 2002.



Eung-Bo Shim(Member, KIEE)
He received his B.S. degree in Electrical Engineering from Hanyang University, Seoul, Korea in 1982. He works for the Korea Electric Power Research Institute of KEPCO. His research interests include the analysis of power system overvoltage, insulation design and lightning observation



Sang-Ok Han(Member, KIEE)
He received his B.S. degree in Electrical Engineering from Chungnam National University in 1974, M.S. degree in Electrical Engineering from Dankuk University in 1978, and Ph.D. degree in Electrical Engineering from Inha University in 1986, Inchun, Korea. He was a Visiting Professor of Electrical Engineering at Nagoya University in 1989. Currently, he is a Professor in the Electrical Engineering Dept of Chungnam National University. His particular interest is insulation material of ultra high voltage.