LIGHTNING ELECTROMAGNETIC FIELDS INSIDE HIGH VOLTAGE SUBSTATIONS USING FDTD

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Abstract- High voltage substations are the main part in any power system utilities or municipalities. Proper design of lightning protection system should be done in the preliminary stage of the design process. In this paper, a typical high voltage substations of 500/220 kV is modeled by developing multi-scripts of Matlab m-files. To allocate and to simulate the whole carrying current conductors inside the substation and with 100 m length of input and output power lines. This is to calculate and to demonstrate the lightning electromagnetic fields inside the substations during lightning conditions using the Finite Difference Time Domain (FDTD) method with Maxwell's equations. The effects of the posts allocations, its heights and surge arrestors to secure optimum protection zones are investigated. The electromagnetic fields distribution around the posts and inside the entire area of the substation during lightning conditions are evaluated. The electromagnetic fields for lightning over the input/output power lines are depicted to stand precisely of how much of interference with the electronic devices inside the control room during the very small lightning interval. The obtained results while lightning strikes the masts or input/output lines show a reasonable deviation between the electromagnetic field values and the regulation standards.

1- INTRODUCTION

Design of electrical power substation involves more than installing apparatus, protective devices, and equipment. The significant monetary investment and required reliable continuous operation of the facility requires detailed attention to prevent surges (transients) from entering the substation facility [1, 2]. These surges can be switching surges, lightning surges on connected transmission lines, or direct strokes to the substation facility. Direct stroke shielding system for a substation or facility must contend with several elusive and mystery factors inherent in lightning phenomena. Moreover, the main reason is the unpredictable, probabilistic nature of lightning and the lack of data due to the infrequency of lightning strokes in substations [3-5]. Observations of lightning stroke phenomena throughout the power system utilities and the lightning surge intrusion at substations have been tackled in the design of the transmission and distribution systems [6-8]. The proposed shielding model [9] has been so far used as the direct lightning stroke current that is assumed for overvoltage analysis of lightning protection design. The finite difference time domain (FDTD) method is commonly used in high frequency electromagnetic fields. FDTD method can perform precisely the transient electromagnetic fields calculation [10,11]. Not only, it can be used to simulate the electromagnetic wave, but also the transient electromagnetic fields of the lightning. Based on the three-dimensional technique [12] a complete model of the substation is developed using Matlab software package to simulate the overall carrying current conductor inside the substation. On addition, the Masts and ground conductors are simulated with zero currents during the normal operation. During lightning condition, the lightning strikes any one of the masts and ground conductor with the value of lightning current while the power conductors carry the normal current values. There are two classical design methods that have been employed to protect substations from direct lightning strokes. The first method is the fixed angles while the second method is empirical curves. The two methods have generally provided acceptable protection zone. Based on the first method, the masts on both two sides of the substation are allocated with 65 m in between to provide save zone by integrating with input and output ground conductors [13,14]. The electromagnetic field values are calculated during the normal operation and lighting conditions. This paper uses FDTD method to simulate the distribution of the lightning transient electromagnetic fields inside typical Air Insulated Switchgear (AIS) high voltage substation of 500/220 kV during normal and lightning conditions. The different probable scenarios of striking positions are tackled. The effects of surge arrestors during lightning strikes the power line conductors of the input and output line on the electromagnetic fields distribution are considered.

2- LIGHTNING PARAMETERS AND SYSTEM CONFIGURATION

a) *LIGHTNING PARAMETERS*

Recent standards assume that the lightning current simulation for the first and subsequent return stroke is applied by the commonly formula [14] and the first stroke with its maximum value is considered through the simulation.

$$i = \frac{i_{max}}{k}\cdot\frac{\left(\frac{t}{\tau 1}\right)^{10}}{1+\left(\frac{t}{\tau 2}\right)^{10}}\cdot\left(e^{\frac{-t}{\tau 2}}\right) \qquad (1)$$

Where : i_{max} is the maximum current value (A)

K is the correction factor of the maximum current

$\tau 1$ and $\tau 2$ are the front and decay time, respectively.

Table 1: the main parameter values of the simulated lightning current.

Parameters	First stroke current			Subsequent stroke current		
	1st	2nd	3rd	1st	2nd	3rd
I (kA)	**200**	**150**	**100**	**50**	**37.5**	**25**
K	**0.93**	**0.93**	**0.93**	**0.99**	**0.99**	**0.99**
τ_1 (μS)	**19**	**19**	**19**	**0.45**	**0.45**	**0.45**
τ_2 (μS)	**485**	**485**	**485**	**143**	**143**	**143**

b) SYSTEM CONFIGURATION

The substation under consideration is Air Insulated Substation (AIS) of 500/220 kV substation as shown in Figure 1. There are 4 input lines of 500 kV single circuit with 2 ground conductors per each line. There 2 are output lines of 220 kV double circuits with 1 ground conductor per each line. The busbars are double bus bar configurations and there are 3 power transformers with 500/220/11 kV and 500 MVA. The area of the substation is 400x300 m^2. The masts are allocated around two sides of the substation and the ground conductors of the input and output lines are schematic in Figure 2. There 11 masts in each side with 65 m height and separated by 50 m apart and there are 8 ground conductors for input lines and 6 ground conductors for the output lines. Figure 3 illustrates the mast height and separation distance to protect equipment in the substation Based on the base of rolling ball [13], the different equipment are inside the protected area by the ground conductors and masts

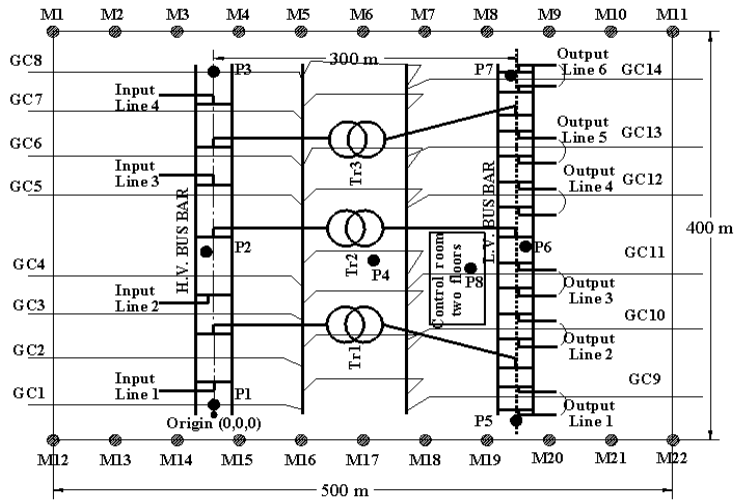

Figure. 1: the configuration of the substation layout with masts allocation and ground conductors with monitoring points.

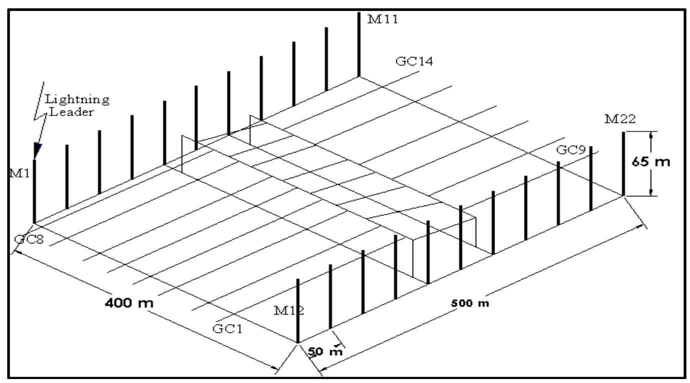

Figure 2: Schematic of the allocation of the masts and ground conductors to protect the entire area of the substation

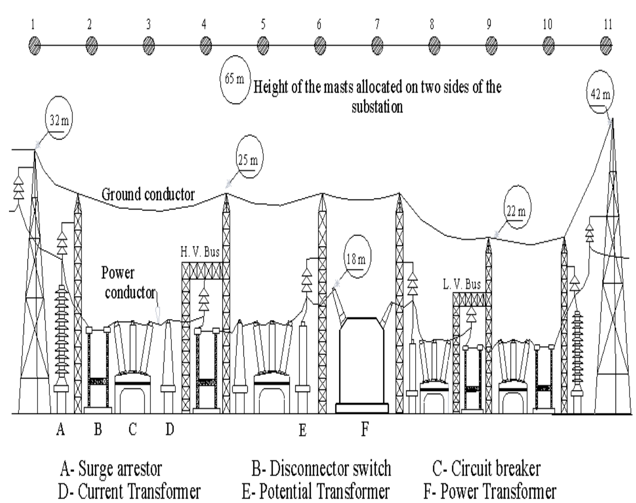

Figure 3: Schematic elevation view of the substation with mast and protected equipment

c) FDTD Electromagnetic Fields Calculation

Maxwell's equations can be presented in Equation 2. Expanding these two main equations over Yee cell in space with time domain [15] yields the main relations of electromagnetic fields in both space and time domain.

$$\left\{ \begin{aligned} \frac{\partial \vec{H}}{\partial t} &= -\frac{1}{\mu}\nabla \times \vec{E} - \frac{\sigma}{\mu}\vec{H} \\ \frac{\partial \vec{E}}{\partial t} + \frac{\sigma}{\varepsilon}\vec{E} &= \frac{1}{\varepsilon}\nabla \times \vec{H} \end{aligned} \right\} \quad (2)$$

Expanding E and H over the Yee cell in space as in Figure 4 and in time domain yields the main six sub-equations to build the standard FDTD algorithms. Two of theses six equations are presented in equation 3 and 4. Figure 5 presents the main steps used to develop the FDTD algorithm.

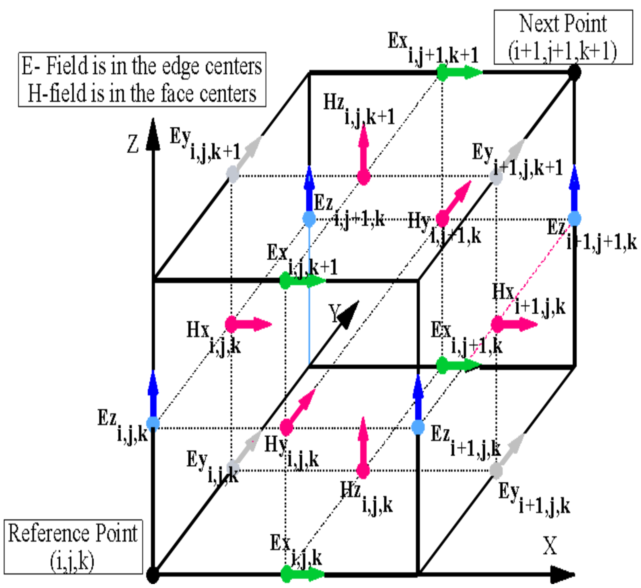

Figure4: Yee cell presentation in space for Maxwell's equations at n^{th} node

$$\left[\frac{H_y^{(n+1/2)}(i,j,k)-H_y^{(n-1/2)}(i,j,k)}{\Delta x}-\frac{H_x^{(n+1/2)}(i,j,k)-H_x^{(n-1/2)}(i,j,k)}{\Delta y}\right]= \quad (3)$$

$$\sigma(i,j,k)\left[\frac{E_z^{(n+1)}(i,j,k)+E_z^{(n)}(i,j,k)}{2}\right]+\varepsilon(i,j,k)\left[\frac{E_z^{(n+1)}(i,j,k)-E_z^{(n)}(i,j,k)}{\Delta t}\right]$$

$$\left[\frac{E_z^{(n+1/2)}(i,j,k)-E_z^{(n-1/2)}(i,j,k)}{\Delta y}-\frac{E_y^{(n+1/2)}(i,j,k)-E_y^{(n-1/2)}(i,j,k)}{\Delta x}\right]= \quad (4)$$

$$\sigma(i,j,k)\left[\frac{H_x^{(n+1)}(i,j,k)+H_x^{(n)}(i,j,k)}{2}\right]+\mu(i,j,k)\left[\frac{H_x^{(n+1)}(i,j,k)-H_x^{(n)}(i,j,k)}{\Delta t}\right]$$

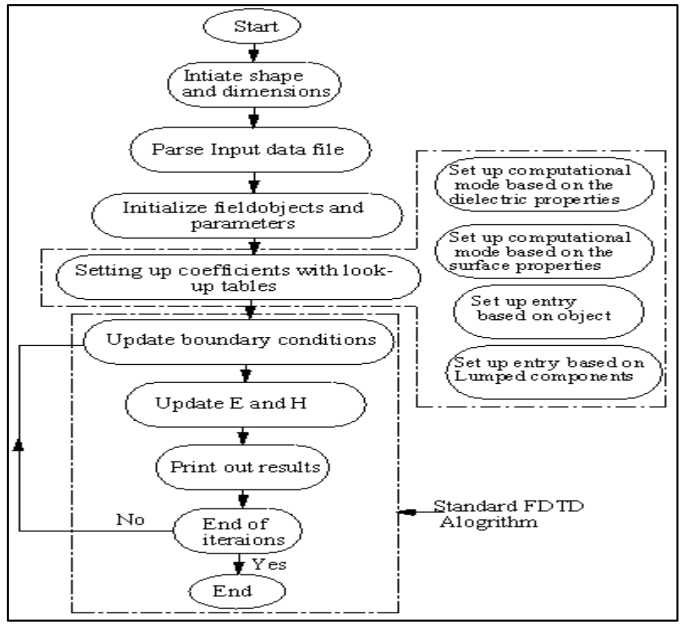

Figure 5: The main steps of the developed FDTD algorithm.

The FDTD computational region where the solution is sought, is divided into cells as Yee cell with the corresponding electric and magnetic fields being located on the edges and the faces. It assumed that all field values in the entire solution region are the maximum computed electric and magnetic fields. The computational region must be large enough to enclose whole conductors and the calculation points. In addition, suitable boundary conditions must be imposed to absorb outgoing waves to simulate the extension of the computational region to infinity. The discretization and time steps are accordingly adjusted. Around each calculation point a volume of 10 cm^3 is assumed. The discretization step is assumed to be $\Delta x = 10^{-12}$ m while the time step is assumed as:

$$\Delta t = \left(\frac{\Delta x}{2.c}\right) \quad \text{Sec.} \quad (5)$$

Where c: is the light speed = $3*10^8$ m/s

3- FIELDS UNDER NORMAL AND LIGHTNING CONDITIONS.

The output power lines of 220 kV are loaded with actual loads which are rated by 50 MW during the normal operation condition and consequently the currents are calculated distributed for each carrying current conductor segments over the whole substation. During the lightning strikes one phase of input or output power lines, the lightning current is over imposed on the normal operating current. The effects of the surge arrestors are considered to stop the lightning wave at the entrance/exit of the substation. For the masts, the current is assumed to be zero during the normal operation. Meanwhile, during lightning, the imposed lightning current over the mast is assumed to be downward to ground grids. Figure 6 presents the electromagnetic fields along the longitudinal direction of the higher voltage bus bar of 500 kV inside the substation during normal operation electric and magnetic fields profiles are aligned with the direction of the carrying current segments over the entire area of the substation. The maximum magnetic field value is about 64 A/m. Figure 7 presents the electromagnetic fields along the longitudinal direction of the higher voltage bus bar of 500 kV inside the substation during lightning strikes GC4 and GC 5. This scenario presents the worst scenario during lightning strikes masts or ground conductors of input or output power lines for time interval of 500 µS. This scenario exhibits the maximum electromagnetic fields induced at the different monitoring points. The distribution of the electric and magnetic fields profiles are aligned with the direction of the carrying current segments over the entire area of the substation. The maximum electric field value is about 43 kV/m while the maximum magnetic field value is about 113 A/m. For the different monitoring points under the higher and lover voltage busbars, and inside the control room , the electromagnetic field values are calculated during normal operation and at different lightning strikes point at masts and ground conductors. Also one phase of input and output power lines are considered with the effects of the surge arrestors. Different scenarios for lightning strike points are investigated. The most descriptive and effective scenarios are shown in Figures 8, 9 and 10. These figures present the maximum induced electromagnetic fields at the different monitoring points for normal operation and lightning condition while lightning strikes at GC4/GC5, Mast M1 and Phase A of input line L1, respectively.

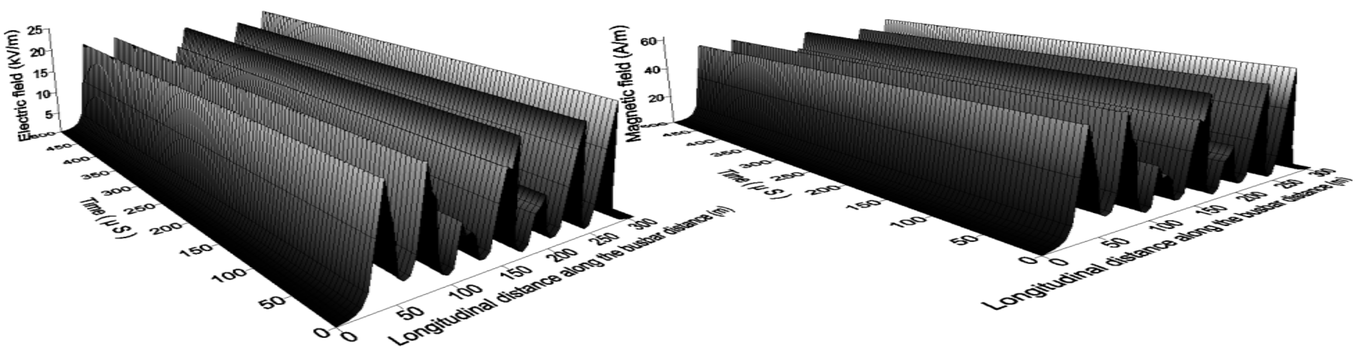

Figure 6: Electromagnetic fields along the longitudinal direction of 500 kV busbar inside the substation during normal operation

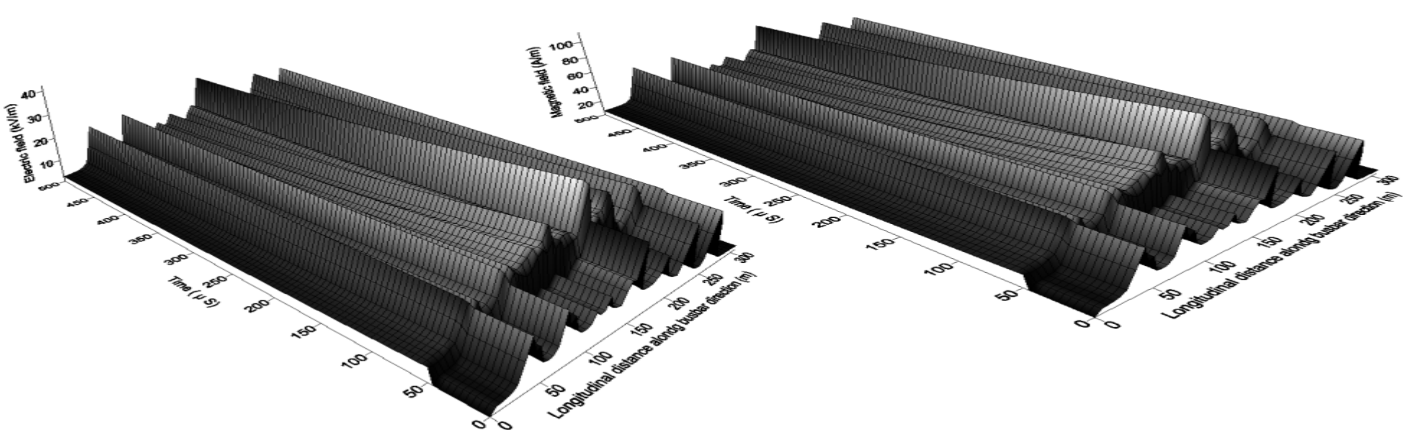

Figure 7: Electromagnetic fields along the longitudinal direction of 500 kV busbar inside the substation during lightning strikes the ground conductors GC4/GC5.

For lightning strikes at GC4/GC5 the maximum magnetic field is 140 A/m while the maximum electric field is 52 kV/m and this is obtained at point P4 at the middle of the substation. These values increased by about 45 % more than normal operation and these values decay to normal values within 200 µ S. For Lightning strikes at input line, the induced electromagnetic field values increase by 35 % at point P4 while in the control room it increase by 5 %. For Lightning strikes at output and line the induced electromagnetic field values increase by 35 % at point P4 while in the control room it increase by about 450 % due to nearby of the control room. Table 2 tabulated the statistical electromagnetic field values at the center point of the control room inside the substation for different strike points. The maximum worst scenarios are the cases of striking at GC4/GC5 and output line L1 (Phase A) because of the nearby of the ground conductors to the control room. Comparing these values with the different standards [16-17] gives minor deviation except in the control room, which contains the protection and control devices that should be carefully selected for electromagnetic compatibility. The effects of the surge arrestors limit the induced values of strikes at input/output phase conductors.

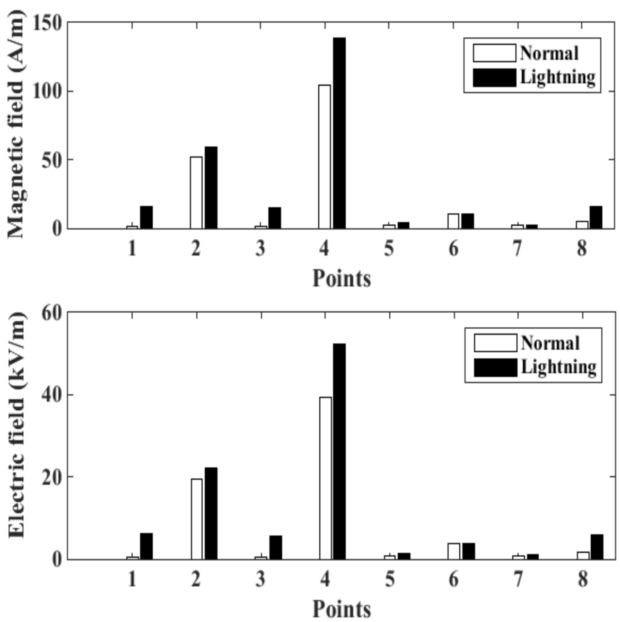

Figure 8: Electromagnetic fields induced inside the high voltage substation at different points for normal and lightning conditions at GC4/GC5.

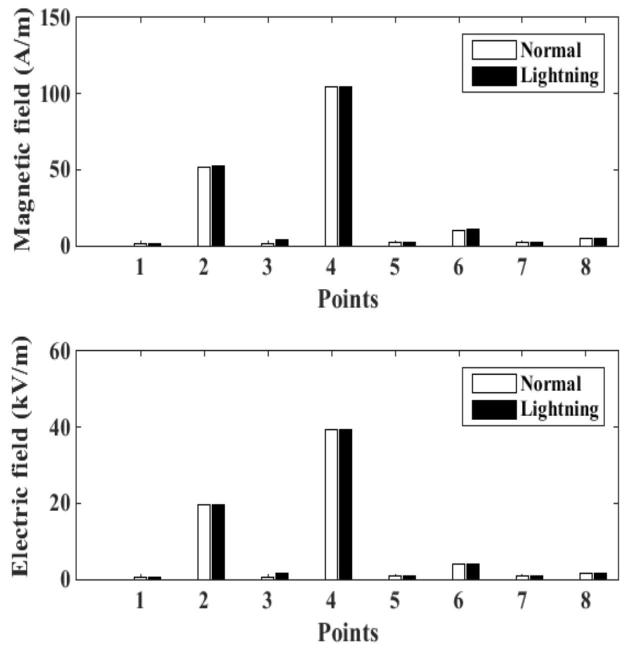

Figure 9: Electromagnetic fields induced inside the high voltage substation at different points for normal and lightning conditions at M1.

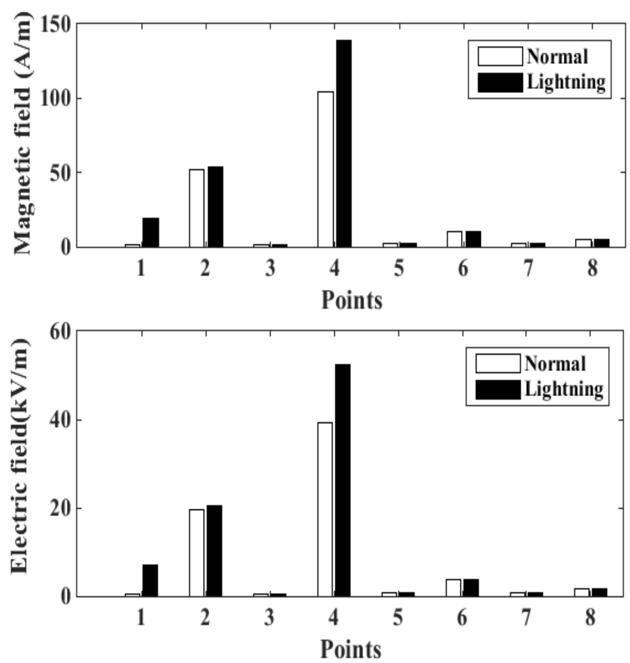

Figure 10: Electromagnetic fields induced inside the high voltage substation at different points for normal and lightning conditions at Phase A of input line 1.

Table 2: The statistical electromagnetic field values at the center point of the control room inside the substation for different strike points.

Strike point	M1		M6		M11	
	(A/m)	(V/m)	(A/m)	(V/m)	(A/m)	(V/m)
Max	4.58	1727.3	4.87	1834.1	4.68	1764.8
Min	4.57	1720.7	4.58	1727.3	4.58	1727.3
Mean	4.57	1721.8	4.69	1768.5	4.63	1745.8
STDV	0.005	1.87	0.08	28.61	0.03	9.60
Strike point	Input L1_Phase A		Output L1_Phase A		GC4/GC5	
	(A/m)	(V/m)	(A/m)	(V/m)	(A/m)	(V/m)
Max	4.58	1727.3	4.58	1727.3	15.82	5959.6
Min	4.31	1623.3	4.08	1538.3	4.58	1727.3
Mean	4.42	1665.7	4.28	1611.4	10.06	3789.6
STDV	0.07	26.63	0.13	48.64	2.99	1128.1

4- CONCLUSIONS

The FDTD technique and Matlab software package are used to model and simulate the lightning electromagnetic fields inside AIS of 500/220 kV substation. Simulation results show that lightning electromagnetic field at the selected points depends on the Masts position and the ground conductor's allocation over the entire area of the substation. The results of lightning electromagnetic fields could be used for electromagnetic compatibility studies of the equipment in the control room and insulation coordination in early design stage. The effects of the surge arrestors are considered for lightning strikes of power line conductors. Comparing the obtained results with different standards exhibits a great convenience with deviation in the control room position. For the considered worst scenario, the maximum electromagnetic field values during lightning condition is about 450% and remain for about 200 µS.

5- REFERENCES

[1] IEEE Std. 998-1996 (R2002), IEEE Working Group D5," Substations Committee. Guide for Direct Lightning Stroke Shielding of Substations".

[2] IEEE Std C62.22™-2009," IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems".

[3] S. Trabulus, E. Gokalp," Protection against lightning surges of electrical and industrial installations", Transmission and distribution Conference and Exposition, 2003 IEEE PES.

[4] Jun Takami, Shigemitsu Okabe and Eiichi Zaima ," Study of Lightning Surge Overvoltages at Substations Due to Direct Lightning Strokes to Phase Conductors", IEEE Transactions On Power Delivery, Vol. 25, No. 1, January 2010

[5] A. Ametani and T. Kawamura, "A method of a lightning surge analysis recommended in Japan using EMTP," IEEE Trans. Power Del., vol. 20, no. 2, pt. 1, pp. 867–875, Apr. 2005.

[6] T. Yamada, T. Narita, T. Shioda, S. Okabe, and E. Zaima, "Observation and analysis of lightning surges at substation connected with UHV designed transmission lines," IEEE Trans. Power Del., vol. 15, no. 2, pp. 675–683, Apr. 2000.

[7] J. Takami and S. Okabe, "Observational results of lightning current on transmission towers," IEEE Trans. Power Del., vol. 22, no. 1, pp. 547–556, Jan. 2007.

[8] J. Takami and S. Okabe, "Characteristics of direct lightning strokes to phase conductors of UHV transmission lines," IEEE Trans. Power Del., vol. 22, no. 1, pp. 537–546, Jan. 2007.

[9] H. R. Armstrong and E. R. Whitehead, "Field and analytical studies of transmission line shielding," IEEE Trans., Power App. Syst., vol. PAS-87, no. 1, pp. 270–281, Jan. 1968.

[10] K.L. Shlager and J. B. Sehneider, "A seleetive survey of the finitedifference time-domain 1iterature", IEEE Trans. Antennas Propagat. Mag., Vol. 137, No. 4, pp. 39-56, 1995.

[11] T. Noda and S. Yokoyama, "Development of Surge Simulation Code Based on Finite-Difference Time-Domain (FDTD) Approximation of Maxwell's Equations", Int'l. Conf. Power Systems Transients (IPST), pp.1-6, 2001.

[12] H. Anis, et al.," Computation of Power Line Magnetic Fields A Three Dimensional Approach", 9th International Symposium on High Voltage Engineering (ISH), paper 8333, Aug/Sept.1995.

[13] J. D. Mcdonald," Electric Power Substations Engineering", 3rd edition, ISBN 13: 978-1-4398-5639-0 (eBook - PDF)

[14] F. Heidler, et al," Parameters of the lightning current given IEC 62305- Background, Experience and outlook", 29th International Conference on Lightning protection, 23rd – 26th June 2008 – Uppsala, Sweden.

[15]. A. Taflove, Computational Electrodynamics, The Finite Difference Time Domain Approach, Third Ed., Artech House, Norwood, MA, 2005.

[16] IEEE Std. 998-1996 (R2002), IEEE Working Group D5, Substations Committee. Guide for Direct Lightning Stroke Shielding of Substations.

[17] IEEE Working Group, Estimating lightning performance of transmission lines. II. Updates to analytic models, IEEE Transactions on Power Delivery, 8(3), 1254–1267, July 1993.