STUDY OF THE TRANSIENT ELECTROMAGNETIC FIELDS INSIDE HIGH VOLTAGE SUBSTATIONS

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***Abstract*: Inside high voltage substations, the protective and control equipment are placed in the switchyard and control room as well as the main elements. Proper design for these equipment should include precise clarifications of the immunity levels to typical exposure of transient electromagnetic fields produced inside high voltage substations. Consequently, accurate calculation of very fast transient electromagnetic fields inside high voltage substations is essentially demanded early in the design stage. This paper presents full simulation of a typical high voltage substation of 500/220 kV to calculate the transient electromagnetic field during switching conditions based on Finite Difference Time Domain (FDTD). Very fast transient electromagnetic fields are calculated taking the effects of the complete configuration including all current carrying conductors inside high voltage substations. The effects of switching different lines are monitored at different accessible points and inside the control room. The obtained results show a good agreement with the previous studies and electromagnetic compatibility standards.**

Keywords: *High Voltage substations, very fast transient electromagnetic fields, Finite Difference Time Domain (FDTD).*

I. INTRODUCTION

Very fast transient electromagnetic fields have high and wide frequency range in power systems. The frequency range of transient electromagnetic field in high voltage substation spans from 100 kHz to 100 MHz according to the system configurations and positions of the switched devices [1,2]. These transient electromagnetic fields are originated within a gas-insulated substation (GIS). These fields appear any time there is an instantaneous change in currents. Generally, this occurs as a result of the opening or closing of any disconnect switch [3-5], but other events, such as the operation of a circuit breaker, the closing of a grounding switch, or the occurrence of a fault, can also cause very fast transient electromagnetic fields. In GIS the fast transient electromagnetic fields can appear due to internal or external sources. Internal sources can produce overvoltages between inner conductor and enclosure, meanwhile external transients can cause stress on secondary and adjacent equipment. The magnitude of internal transients is in range from 1.5 to 2 per unit of line-to-neutral voltage crest, but they can also reach values as high as 2.5 per unit. [6]. There are three main differences between Air-insulated substation (AIS) and GIS. The first difference is the electrical component sizes, in GIS which are much smaller than those in AIS so the frequencies of multiple reflections of traveling waves on the bus bars of GIS are at least 10 times higher than those in AIS. The second difference is the characteristic impedance of the high voltage bus bars in GIS is about 5 times smaller than that of AIS. The third difference is the coaxial conductors of the bus bars in GIS have higher specific capacitance to ground in rather than the AIS. Therefore, the capacitive currents of the off-loaded bus bars in GIS are larger than such capacitive currents in AIS [7]. Sophisticated models of the substation have been developed in power systems for transient electromagnetic fields calculation purposes [8-11]. Nonetheless, further investigations are implemented to determine the effects of different materials and structures on the transient field's values inside the substation [12]. Recently, new advanced techniques tackled new algorithms such as Finite Difference Time Domain (FDTD). These new algorithms have been used to calculate precisely very fast transient electromagnetic fields inside high voltage substation. The FDTD method can be used to simulate the above problem and predict electromagnetic fields effectively. For the computation of transient fields in a substation, the transient current propagating along the bus bars is needed. Instead of using the actual bus currents, a damped sinusoidal current with varying frequency, which are good representations for transient currents in substations, have been used to calculate the radiated fields [13]. Although, this implementation simplified the whole substation to be modeled as a bus section in a substation consisting of three parallel bus bars with 50 m long and located at 11 m above ground. In spite of its simplicity, it presents a preliminary step towards transient electromagnetic field calculation inside high voltage substation. The present work implements the FDTD techniques to evaluated the transient electromagnetic fields inside high voltage substation of 500/220 kV. Furthermore, it considers the whole construction of the substation (bus bars, ingoing and outgoing lines). The transient electromagnetic fields profiles inside the high voltage substation have been simulated analytically and numerically during the normal and switching conditions.

II. SYSTEM CONFIGURATIONS AND TRANSIENT FIELDS CALCULATION

A) System configurations

Mainly, the substation under study consists of 4 input lines with 500 kV, three phases power transformers of 500/220 kV (500 MVA each) and 6 output lines of 220 kV (double circuits). The geometry configuration of conductor system per each phase is allocated in space to develop M-script Matlab file for the whole coordination for each segment and in the meanwhile, a second M-script is developed in parallel to allocate the current values in each conductor segment shifting 120^0 between each phase. Figure 1 shows the simple layout of the substations main parameters, the selected points to monitor the electromagnetic fields inside the substation and the selected lines to be switched on.

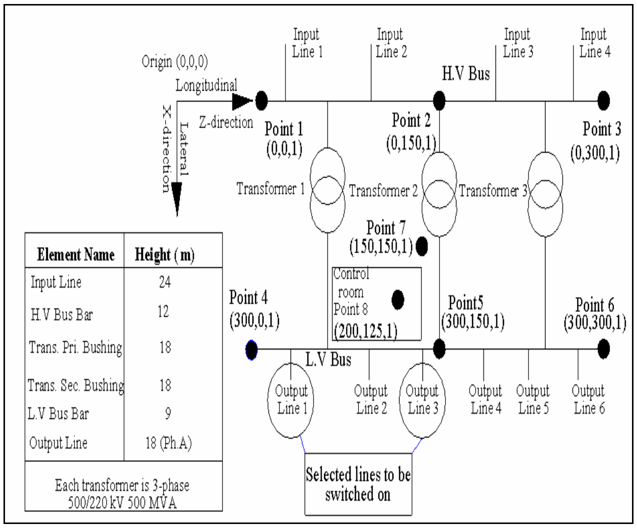


Fig.1. Simple layout of the substation 500/220 kV.

B) Transient electromagnetic field calculation

The transient electromagnetic field is a function of conductor current (magnitude and waveform) and conductor configuration system over the entire substation area as well. Consequently, two simultaneous steps have to be tackled to evaluate the transient electromagnetic field under switching conditions. The first step is to calculate the transient currents on the conductors due to switching conditions, the second step is to calculate the radiated electromagnetic field around the conductors due to the travelling current wave. The transient electromagnetic field can be evaluated numerically [14] or analytically [15] by assuming the line or conductor to be a cylinder with very small radius with respect to the wavelength. The whole conductor system inside the substation is divided into series of connected segments to closely fit the complete shape of the substation conductor per each phase shifted by 120^0 electrical angle. The conductor length to the closest inter-crossing of each segment is very short compared with the wavelength as the switching wave frequency spans a range from 100 kHz to 100 MHz, the wavelength ($\lambda=3*10^8/1*10^6$) is 300 m which is very long with respect to each segment length. For this reason, the reflection of the current waveform over the conductor inside the substation can be neglected [16]. This is because the effective reflection is usually proportional to the target electrical size coupled with the frequency. Frequency should be in microwave frequency range of greater than 100 MHz to considered effective reflection. Figure 2 shows a line segment of length L along z direction from the origin and P(x,y,z) is an arbitrary point in space around the conductor [13].

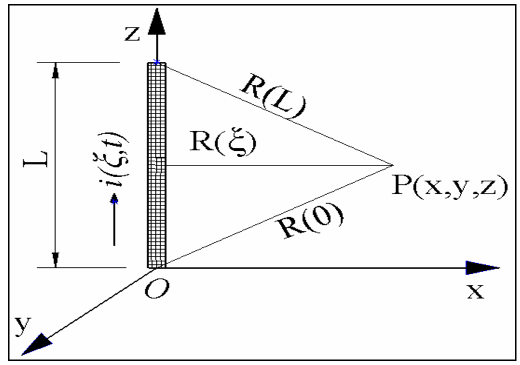


Fig. 2: Simple presentation of the current carrying conductor segment.

For the electromagnetic field potential vector $\vec{A}_z(t)$ for a filament along the z- axis is presented as shown in Figure 2 while the x and y components of the electromagnetic potential vector can be neglected [17]. The z component $A_z(t)$ created by current $i(\xi,t)$ flowing in the line at the point P can be expressed as:

$$A_z(t)=\frac{\mu_o}{4\pi}\int_0^L i(\xi,t-R(\xi)/c)/R(\xi)d\xi \tag{1}$$

$$i(\xi,t-\frac{R(\xi)}{c})=i_g(t-\frac{\xi+R(\xi)}{c})+i_f(t-\frac{-\xi+R(\xi)}{c}) \tag{2}$$

This yields to:

$$A_z(t)=\frac{\mu_o}{4\pi}\int_0^L\left[i_g(t-\frac{\xi+R(\xi)}{c})+i_f(t-\frac{-\xi+R(\xi)}{c})\right] \tag{3}$$

where:

ξ : arbitrary point on the conductors

C : speed of the light in free space (3x 10^8 m/s)

i_g : the current wave travelling in the forward direction

i_f : the current wave travelling in the backward direction

The electromagnetic field $\vec{H}(t)$ can be given by the curl of the electromagnetic potential vector $\vec{A}(t)$ as $\vec{H}(t)=$ curl ($\vec{A}(t)/\mu_o$). For simplicity purpose the $\vec{A}(t)=(0, 0, A_z(t))$. The three components of $\vec{H}(t)$ can be expressed by:

$$H_x(t)=\frac{1}{\mu_\circ}\frac{\partial A_z(t)}{\partial y};H_y(t)=-\frac{1}{\mu_\circ}\frac{\partial A_z(t)}{\partial x};H_z(t)=0 \tag{4}$$

Furthermore, $A_z(t)$ can be expressed into two terms as:

$$A_g(t)=\int_0^L\left[i_g(t-\frac{\xi+R(\xi)}{c})\frac{d\xi}{R(\xi)}\right] \tag{5}$$

$$A_f(t)=\int_0^L\left[i_f(t-\frac{-\xi+R(\xi)}{c})\frac{d\xi}{R(\xi)}\right] \tag{6}$$

By substituting the expression of A_g(t) and A_f (t) from equations (5) and (6) in equation (4);

$$H_x(t) = \frac{1}{4\pi}\frac{\partial}{\partial y}\left[A_g(t) + A_f(t)\right] \qquad (7)$$

$$H_y(t) = -\frac{1}{4\pi}\frac{\partial}{\partial x}\left[A_g(t) + A_f(t)\right] \qquad (8)$$

Then the analytical solution of the electromagnetic field components can be obtained as follows:

$$H_x(t) = \frac{-y}{4\pi}\left[I_0(t) + I_L(t)\right] \qquad (9)$$

$$H_y(t) = \frac{x}{4\pi}\left[I_0(t) + I_L(t)\right] \qquad (10)$$

where:

$I_0(t)$: current at lower end of the conductor
$I_L(t)$: current at upper end of the conductor
R(0) : distance from lower conductor end to point P
R(L) : distance from the upper conductor end to point P
R(ξ) : distance from center of the conductor segment to point P
C : speed of the light in free space (3x 10^8 m/s)

The current applied for switching on one of the output lines is assumed to be damped sinusoidal pulse shown in Figure 3. The equation describing the current is:

$$i(t) = I_m * e^{(-\alpha * t)} * \sin(2\pi f t) \qquad (11)$$

where:

I_m = 1kA, α = 500000 and f= 1MHz .

After determining the transient magnetic field, the transient electric field $\vec{E}(t)$ is calculated by integrating the curl of $\vec{H}(t)$ to get the three components of the electric field as follows:

$$E_x(t) = \frac{1}{\varepsilon_\circ}\int_0^t \frac{\partial H_y(t)}{\partial z}dt$$

$$E_y(t) = \frac{1}{\varepsilon_\circ}\int_0^t \frac{\partial H_x(t)}{\partial z}dt \qquad (12)$$

$$E_z(t) = \frac{1}{\varepsilon_\circ}\int_0^t \left[\frac{\partial H_y(t)}{\partial x} - \frac{\partial H_x(t)}{\partial y}\right]dt$$

Figure 3 shows the sample of the applied current at the lower end of the conductor (beginning of the current segment) with a frequency of 1 MHz. Equations (9) and (10) are solved using equation (11) to get the magnetic field components. In the area of the substation at 1 m above ground, the electromagnetic fields are solved numerically using the FDTD technique.

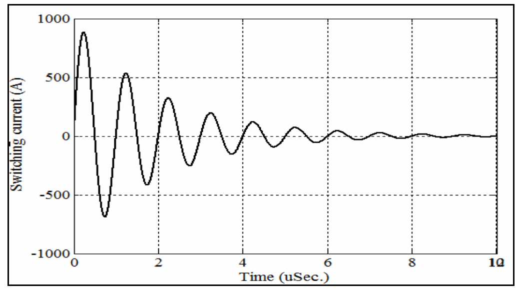


Fig.3: Transient sinusoidal switching current (A).

III. TRANSIENT ELECTROMAGNETIC FIELD RESULTS

A) *For Normal Operation*

The outgoing power lines of 220 kV are loaded by the actual loading conditions of the selected substation during a selected hour per day during summer time as demonstrated in Table 1.

Table 1:- Actual loading conditions of the substation.

Actual loads for 500/220 kV substation (Ampere)											
Line 1		Line 2		Line 3		Line 4		Line 5		Line 6	
C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
155	148	151	158	138	140	155	160	151	155	160	158

The considered model is solved analytically and numerically using FDTD to verify the validity of the model results during normal operation of the substation. Table 2 presents the maximum electromagnetic field values at different points (shown in Figure 1) during the normal operations with comparing the analytical and FDTD technique. The maximum deviation is found to be around 3%.

Table 2: Maximum electromagnetic field values using analytical and FDTD technique during normal operation.

Point No.	Maximum Magnetic field (μT)			Maximum Electric field (kV/m)		
	Analyt -ically	Numer -ically	% Error	Analyt -ically	Numer -ically	% Error
Point 1	3.8	3.82	2	13.46	13.47	1
Point 2	10.7	10.9	2	13.47	13.48	1
Point 3	3.85	3.88	3	13.31	13.33	2
Point 4	20.1	20.13	3	5.90	5.92	2
Point 5	29.04	29.06	2	5.91	5.92	1
Point 6	20.2	20.022	2	5.89	5.9	1
Point 7	10.43	10.45	2	4.15	4.16	1
Point 8	10.51	10.54	3	4.7	4.72	2

B) *For switching conditions*

For simulating the switching operation, the substation is loaded as actual loading conditions in Table 1 except line 3 is kept off. For simulating switching process, time period of 10 μs. is considered and line 3 is switched on at a time of 2.5 μs. The switching current waveform is considered the damped sinusoidal presented in equation (11). Table 3 shows the maximum electromagnetic field values at different points due to switching line 1 and 3 at 1 m above ground.

Table 3: The maximum electromagnetic field values at different selected points for switching line 1 and line 3 at 1 m above ground

Point No.	Max. magnetic field (uT)		Max. electric field (kV/m)	
	line 1	line 3	line 1	line 3
Point 1	355.1	92.2	38.1	25.1
Point 2	176.8	3670	21.5	93.2
Point 3	45	88.5	18.9	21.2
Point 4	890.7	154	78.6	36.1
Point 5	246.1	6125	75.9	97.5
Point 6	61.7	123	25.6	35.5
Point 7	310.2	5150	34.7	77.6
Point 8	201.4	1200	32.9	76.2
Overall max.	5213	6820	96.8	98.4

Figure 4 presents the transient magnetic field inside the substation along the lower voltage bus bar due to switching on line 3. The maximum value of the transient magnetic field is about 6 mT and it decays to about 0.5 mT within 7 µs. The peaks of transient magnetic field profile appear with a wide area around the switching element within 100 m.

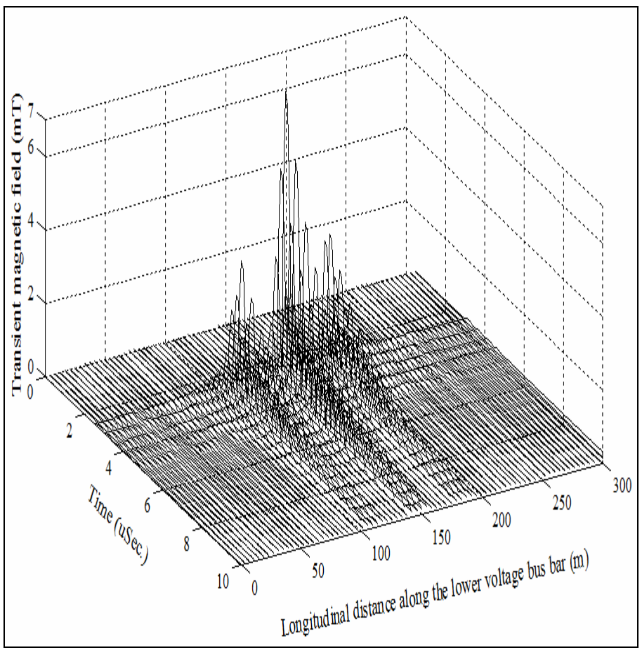


Fig.4. Varation of transient magnetic field (µT) along the lower voltage bus bar with switching line L3

Figure 5 presents the transient magnetic field inside the substation along the lower voltage bus bar due to switching line no.1. The maximum value of the transient magnetic field is about 5 mT and it decays to about 0.5 mT within 6 µs. The peaks of transient magnetic field profile appear with a wide area around the switching element less than 100 m.

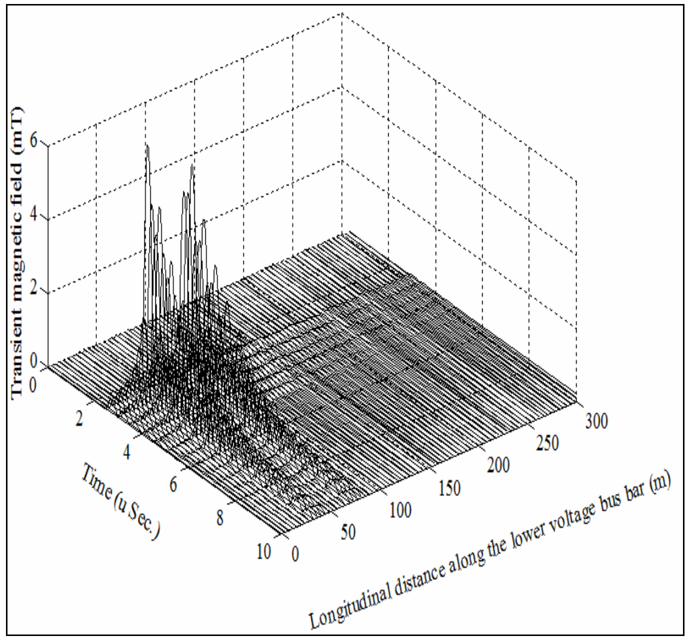
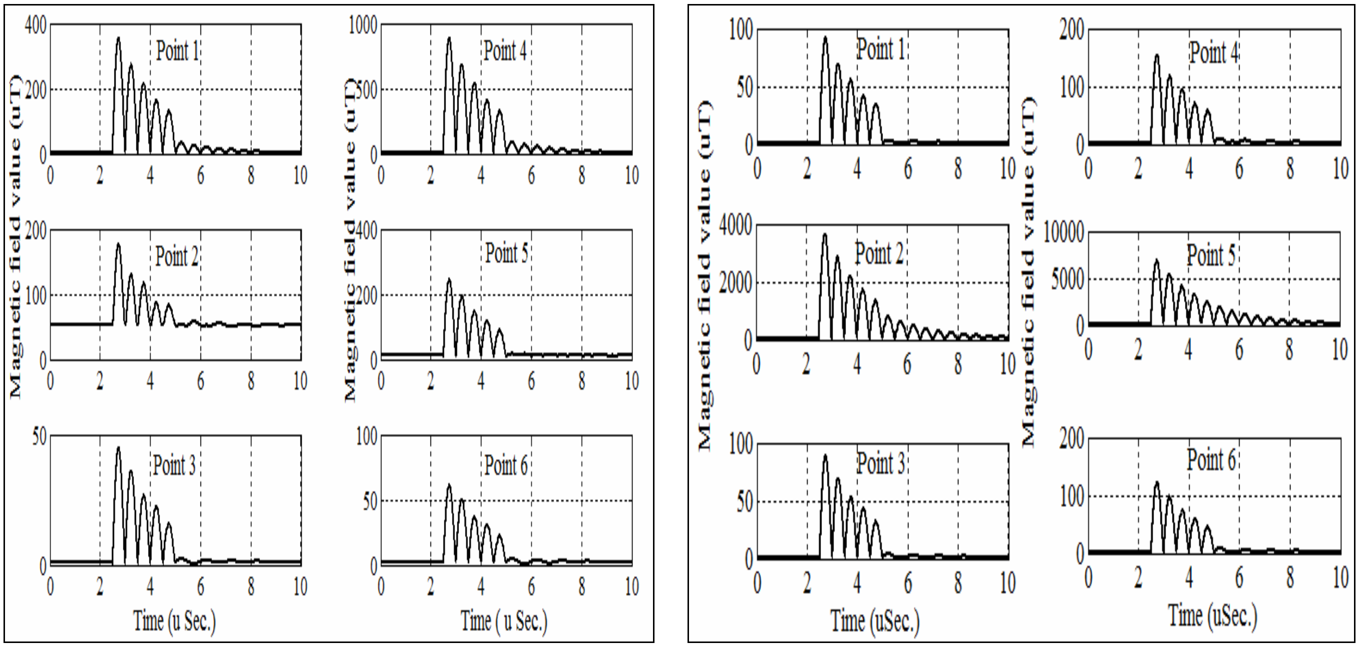


Fig.5. Varation of transient magnetic field (µT) along the lower voltage bus bar with switching line L1

Figure 6 shows the variation of the transient magnetic fields at different points under the higher and lower voltage bus bars in case of switching on both line 1 and line 3 at 2.5 µs. For switching line 1, point 4 acquires the highest transient magnetic field value as it is the closest point (of the selected points) to the switching element while point 3 acquires the lowest transient magnetic field value as it is the most remote point of the switching elements. For switching line 3, point 5 and point 7 acquire the higher transient magnetic field values as they are very close to the switching element while point 3 and point 6 acquire the lower transient magnetic field values as they are the most remote points of the switching elements. For switching line 3, point 1 and point 3 acquire almost the same transient electromagnetic field values and both of points 4 and 6 are almost as well this is due the symmetry design of the substation. Figure 7 shows the transient magnetic field statistical values for the case of switching on line 1 with frequency of 1 MHz on the different points over the area of the substation. The maximum transient magnetic field inside the control room is order of magnitude of 300µT for switching line 1 while it reaches about 5 mT for switching line 3 and these values remain for about 6 µs. As the control room contains almost all the electronic devices, the control room values should be evaluated early in the design stage to avoid any malfunction of the protection and control devices. Figure 8 presents the transient magnetic field statistical values for the case of switching on line 3 with frequency of 1 MHz on the different points over the area of the substation. The maximum transient magnetic field inside the control room is of magnitude of 5mT and remains for 6µs and these values are within the range of electromagnetic compatibility standard of the digital relaying system and control devices of the high voltage substation and with previous immunity studies [18,19].



(a) For switching line 1

(b) For switching line 3

Fig.6. Varation of transient electromagnetic field (μT) at different considered points for 10 μs. When line 1&3 are switched on individually.

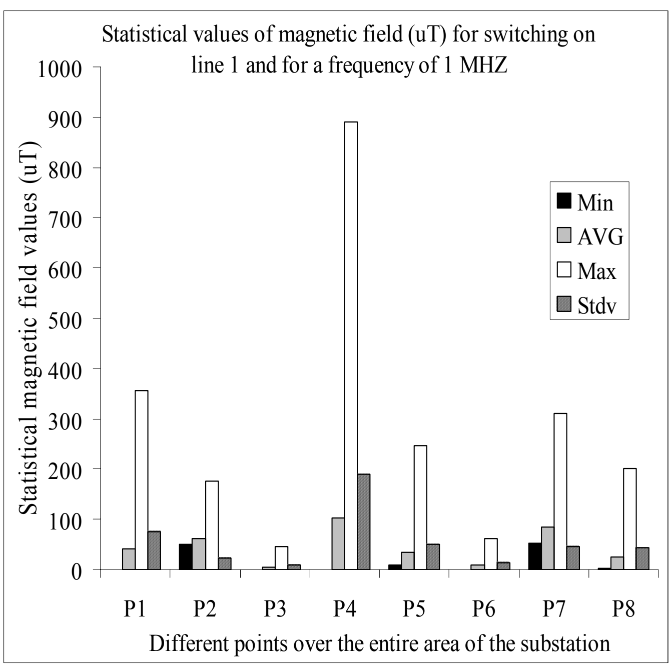


Fig. 7. Statistical transient magnetic field values (μT) at different points for switching on line 1 with frequency of 1 MHz.

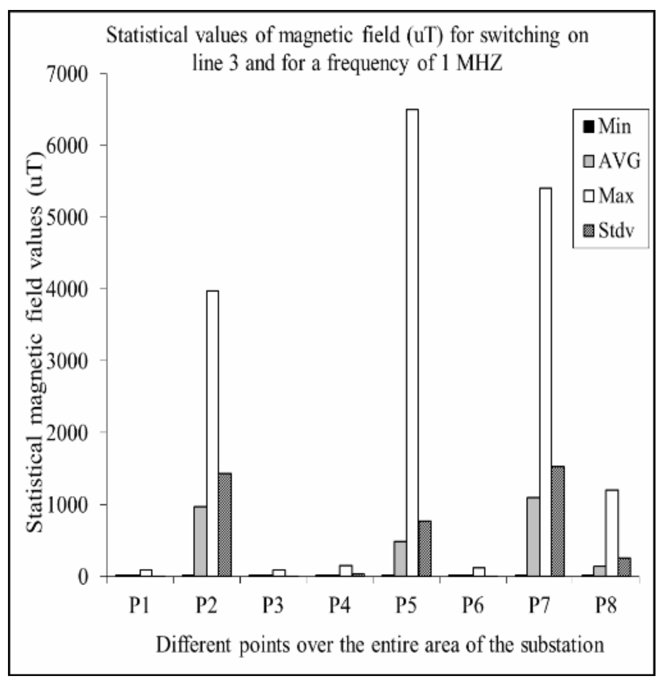


Fig. 8. Statistical of transient magnetic field values (μT) at different points for switching on line 3 with frequency of 1 MHz.

Figure 9 shows the transient electric field inside the substation along the lower voltage bus bar due to switching on line 3. The maximum value of the transient electric field value is about100 kV/m and it decays to about 15 kV/m within 7 µs. The peaks of transient electric field profile appear with a wide area around the switched element within 100 m.

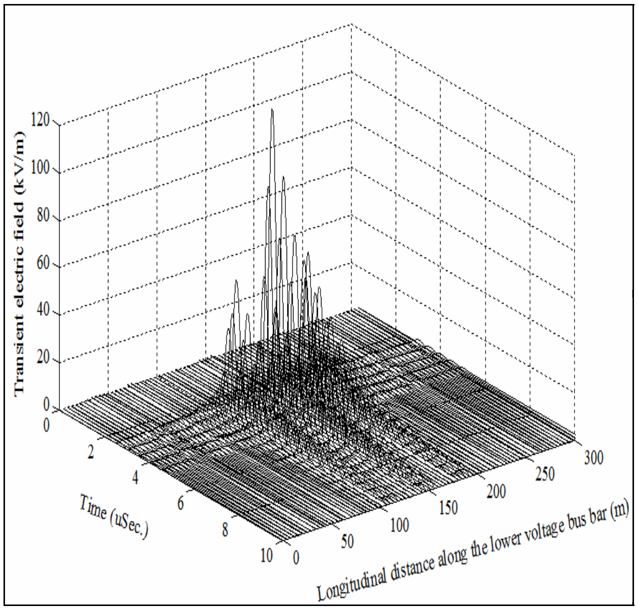


Fig.9. Varation of transient electric field (kV/m) along the lower voltage bus bar with switching line L3

Figure 10 shows the transient electric field inside the substation along the lower voltage bus bar due to switching line 1. The maximum value of the transient electric field value is about 85 kV/m and it decays to about 15 kV/m within 7 µs. The peaks of transient electric field profile appear with a wide area around the switching element within 100 m.

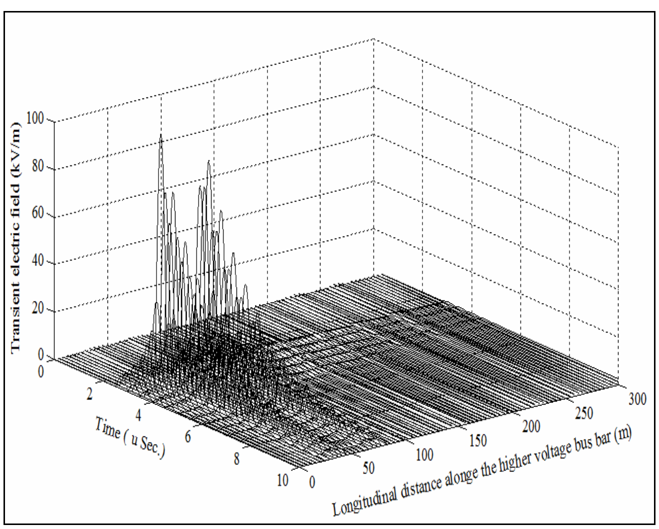


Fig.10. Varation of transient electric field (kV/m) along the lower voltage bus bar with switching line 1.

Figure 11 shows the variation of the transient electric fields at different points under the higher voltage bus bars in case of switching the line 3 at 2.5 µs.

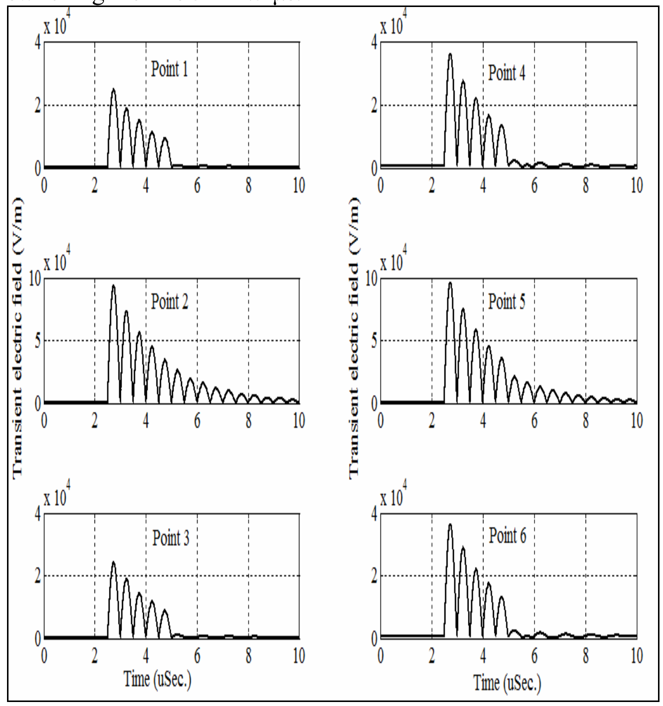


Fig.11. Varation of transient electric field (V/m) at different considered points for 10 µs. with switched on lines 3.

Figure 12 presents the transient electric field statistical values for the case of switching on line no. 3 with frequency of 1 MHz on the different points over the area of the substation. The maximum of 100 kV/m appears on the point 5 as it is the closest point to the switched element.

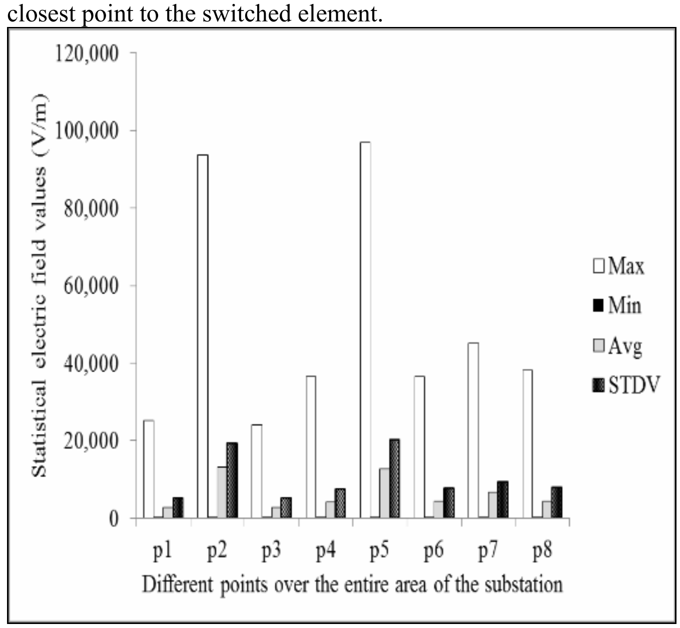


Fig. 12. Statistical of transient electric field values (V/m) at different points for switching on line 3 with frequency of 1 MHZ.

IV. CONCULSION

The obtained results indicate that the FDTD can be used to model and simulate the whole air-insulated substation conductors to calculate the transient electromagnetic fields. Comparing the results obtained from the FDTD model and analytical solutions shows that a small deviation no more than 3%. Simulation results show that transient electromagnetic field at the selected points depends mainly on the relative position to the switching element besides the switching current waveform. The resultant transient electromagnetic fields could be used for electromagnetic compatibility studies and incorporated into the early design stage of the substation and planning process. The maximum value of the transient electromagnetic field is order of magnitude of 7 mT and it remains for 6 μs for the studied switching cases while the maximum electric field value is about 100 kV/m and decays to normal value within 5 μs. The effects of electromagnetic field due to switching appear within distance of 100 m around the switched element.

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