ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 2, Issue 5, September 2013

Application of Finite Difference Time Domain Method to High Voltage Substations: Switching Transient Fields

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Abstract*— Operation of switchgear equipment in high voltage substations results in the propagation of transient currents in bus bars. The bus bars temporarily act as antennae, producing transient electromagnetic fields within the substations. With the introduction of new technology (microelectronics) into the substations for measurement and control purposes, there is renewed interest in the assessment of the electromagnetic environment of substations to ensure electromagnetic compatibility. This assessment is gaining increased importance as new equipment could be located very close to the switch being operated, potentially making the electronic equipment more vulnerable to disturbance. This paper discusses the prediction of transient electromagnetic field emissions due to switching operations in a typical 400kV air insulated substation using the Finite Difference Time Domain (FDTD) method. Electromagnetic fields radiated by bus bars due to transient currents during switching were evaluated at various positions within the substation. The effects of adjacent substation equipment and of ground conditions on the radiated fields were also investigated. Finally the dominant frequency components of the radiated fields were identified and were found to be in general agreement with measured values.

***Index Terms*— Field emissions; finite difference time domain; switching transients; HV substations.**

I. INTRODUCTION

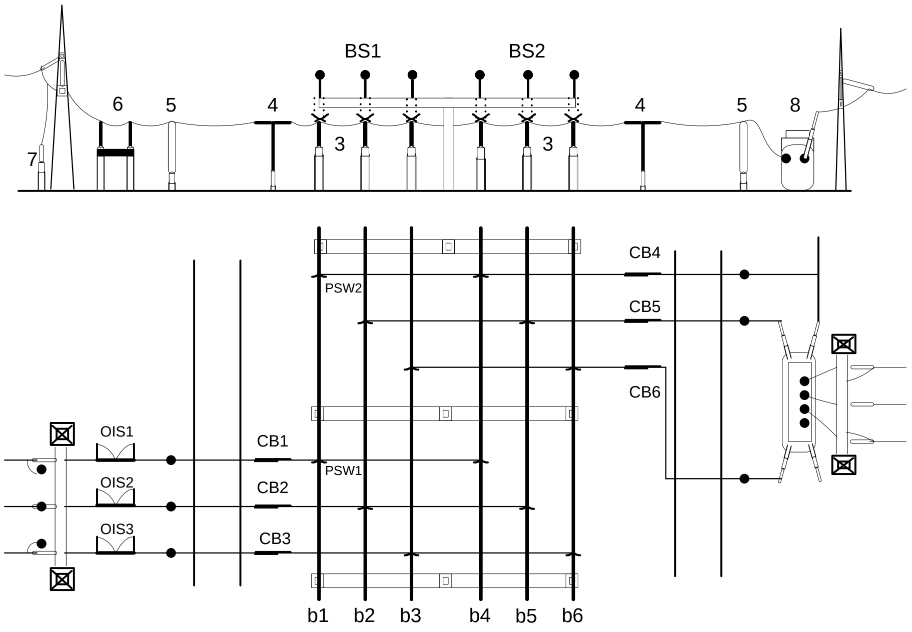
Characterisation of substation electromagnetic environment due to switching can be achieved by either measurement or computation. Measurement of the transient electromagnetic fields involves complex and expensive equipment and may require arrangement for system outages. A more convenient alternative is to develop models to predict the electromagnetic emissions [1].

A number of substation models have been developed since the introduction of automation and control in power systems and substations [2, 3, 4, 5]. For most of these models, the emphasis of the transient field predictions was mainly on how the radiated field affected electronic equipment located in the control rooms. However, equipment used in the substations have changed greatly and maybe highly sophisticated. Moreover, some of the new electronic equipment introduced into substations are not necessarily housed in the control rooms. Instead, it may be located close to the switching devices or other sources of disturbance such as circuit breakers and disconnect switches in the switchyard. The location of electronics in the switchyard is referred to as “distributed electronics” [6]. For the successful introduction and operation of new equipment in the substations, it must have adequate immunity to the disturbances present in these harsh environments. Hence, the electromagnetic compatibility of such equipment in the substation environment must be taken into consideration at the design stage. In addition, there is a need to evaluate the transient electromagnetic emissions in the switchyard, especially at positions close to the switching devices which requires the consideration of near field coupling.

Transient fields may be calculated using analytical as well as numerical methods. Only simple cases can be computed using analytical methods. When the radiating structures are complex, such as those found in a substation environment, the problem is best tackled by numerical approaches. For example, the finite difference time domain (FDTD) method can be used to model the above scenario and the simulation results used to predict the electromagnetic fields effectively [7]. A custom code based on the FDTD method has been developed for this purpose [8]. The capability of the code for performing field calculations using damped sinusoidal current source has been established and which was used to validate the code. In addition, the applicability of the code for prediction of radiated electromagnetic field emissions in high voltage substations has been demonstrated for a very simple case. This was done by calculations using sinusoidal current source with varying frequency in a representative substation containing three parallel bus bars. It was shown that the code was flexible in that any type of current wave shape can be used as the input source. In this paper, a model was developed for a 400 kV air-insulated substation incorporating equipment that may be found in a typical high voltage substation and the custom code was applied to predict the emissions. Electromagnetic fields are computed and analyzed at positions close to the operated switch and the ground using the validated code. The peak magnitudes and the highest frequencies of the transient fields generated were predicted for different substation layout. Considerations for the location (and subsequent safe operation) of electronic equipment are made based on the magnitude and frequencies of the radiated fields.

II. BUS BAR TRANSIENT CURRENTS

The transient currents in a substation have different peak magnitudes and frequency content depending on the factors involved. Among these factors are the substation layout, the switching configurations and the point of observation of the current. Bus bar transient currents can reach peaks of 2.7 kA and frequency components up to 50 MHz [10]. Fig.2 shows the wave shape of the transient current propagating on the bus bar b1 due to switching operation of isolator OIS1 in the layout of fig. 1. This current was computed at the position of switch PSW1 [10]. This current wave shape is used as the input to the FDTD program in the following section to calculate the radiated electromagnetic fields within the substation.



Legend

BS1: Busbar system I; BS2: Busbar system II; 3: Busbar isolating switches; 4: Circuit breakers;

5: Current transformers; 6: Outgoing feeder isolating switches;7: Capacitve voltage transformers;

8: Power transformer

Fig 1. Substation model used for analysis, based on the layout of a 400kV outdoor substation outlined in the reference [9].

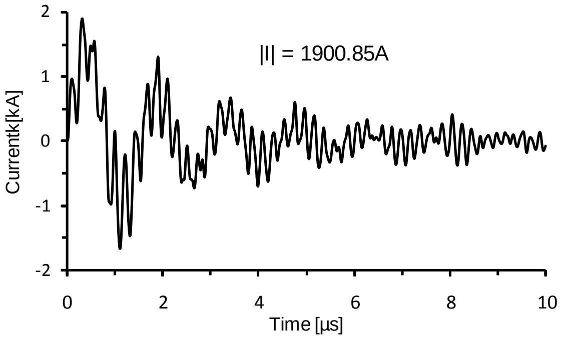


Fig 2. Transient current due to switching operation of isolator OIS1

III. COMPUTATION OF TRANSIENT FIELDS

Once the transient current on the bus bars was obtained either by computational methods or by measurements, the transient electromagnetic fields radiated by the bus bars can be calculated using the current as the source. The calculation can be made in two ways: numerical or analytical techniques. In any case, the substation bus bars, which are the main radiators, are modelled as radiating antennae. In the FDTD technique, the bus bars can be modelled by simply specifying their constitutive parameters within the computational grid once the length, radius and position above ground are known. The source location representing the transient current can then be specified to compute the transient fields. For the purpose of this analysis, the layout in fig.1 is modelled in the FDTD computation space. This is achieved by specifying the equivalent dielectric and conductive properties of each component given in Table 1. The following parameters were specified for the computation:

(a) The volume of the computational space was set as: $N_x = 87$ m, $N_y = 27$ m and $N_z = 65$ m. N_x, N_y and N_z are the dimensions in the x, y, and z directions respectively.

(b) All materials are assumed to have relative permeability (μ_r) of unity.

(c) The spatial increments are chosen as $\Delta x = \Delta y = \Delta z = 0.5$ m

(d) The discrete time step was set at 95 % of the Courant condition giving [7]

$$\Delta t = 9.141 \times 10^{-10}.$$

(e) Bus bars are represented as thin wire structures [11, 12].

(f) 10-cell thick perfectly matched layer (PML) absorbing boundary condition is applied to the artificial boundaries to absorb outgoing waves [13].

It should be noted that bus bar b1 is considered as the radiating antenna and the radiated electromagnetic fields are computed at different positions within the substation. The current wave shape shown in figure 2 calculated for this substation layout is assumed to propagate along the bus bar located 14 m above the ground. Figure 7 shows the end-view arrangements of the bus bars presented in figure 1, in the x-y plane and the positions at which radiated fields are computed.

Table 1. Equivalent dielectric and metallic representation of substation components for transient field computations [14]

Structure	Representations	Properties	
		ε_r	σ
Power transformer	Metallic Cuboid	1	∞
Power transformer bushing	Dielectric Cylinders	3	0
Current transformer and bushing	Dielectric Cylinders	3	0
Current transformer Supports	Metallic Cuboids	1	∞
Capacitive voltage divider	Dielectric Cylinders	3	0
Cap. voltage divider bushing	Dielectric Cylinders	3	0
Cap. voltage divider support	Metallic Cylinders	1	∞
Circuit breakers and bushing	Dielectric Cylinders	3	0
Circuit breakers support	Metallic Cylinders	1	∞
Isolators and supports	Metallic Cylinders	1	∞
Isolator Insulators	Dielectric Cylinders	3	0
Bus bars	Thin wires R=0.05m	1	∞
Bus bar supports	Metallic Cuboids	1	∞
Bus bar Insulators	Dielectric Cylinders	3	0
Ground	Dielectric Cuboids	10	0.01
Conductors	Thin wires R=0.025m	1	∞

A. Time variation of electromagnetic field in the vertical direction in the presence of different substation components

In this case, electromagnetic fields are computed at 2 m, 7 m and 13 m (1 m above ground) below the bus bars as shown in figure 3(a) with the presence of the following components in the substation space: (a) the six bus bars only, (b) the six bus bars together with their support structures and (c) all equipment included.

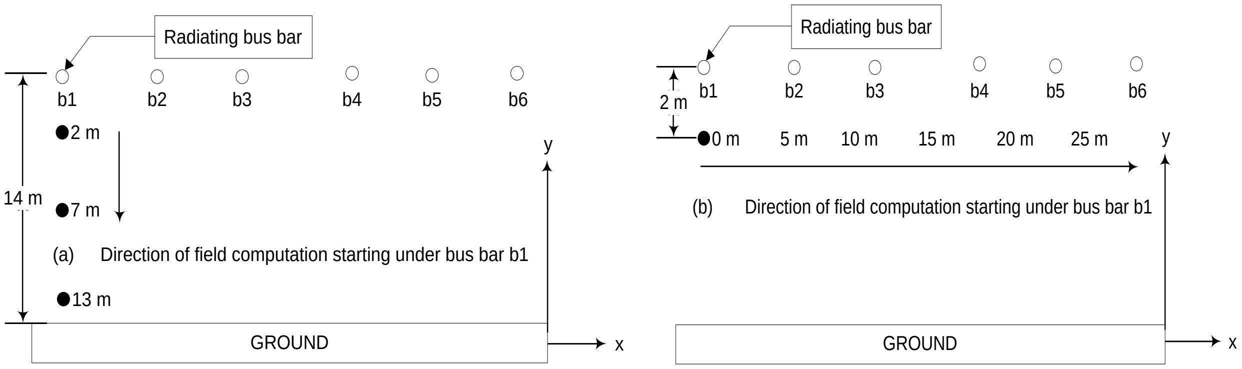
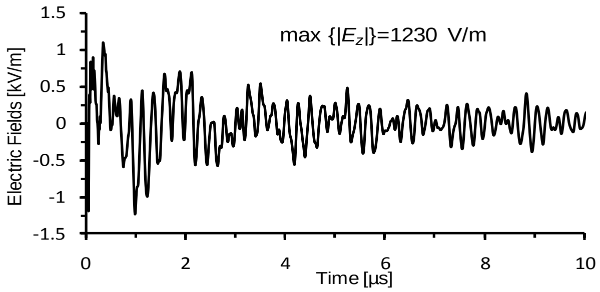
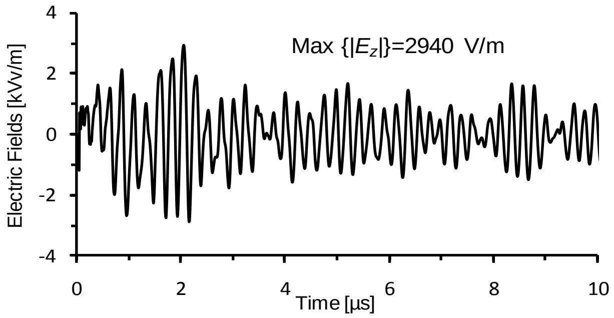


Fig 3. Arrangement of bus bars and points where electromagnetic fields are computed. (a) Vertical direction (b) Horizontal direction

At 2 m from the source, E_y is the dominant component and it is higher when the bus bar structures are not physically supported compared to that when supporting and other structures were present. This may be due to the location which is in the middle of two bus bar support structures. The bus bar supports are represented as metals. Reflections from these structures tend to oppose each other thereby resulting in a reduction of the total field. At 7 m from the bus bar, which is midway between the bus bar and ground, E_z is now dominant and there is an increase in the field magnitude. This is expected as this point is closer to the metallic support structures. Further down 13 m from the bus bars, which is just 1 m above the ground, E_z is the dominant field. The magnitudes and wave shapes for the three different situations are shown in figure 4. The field variation is almost the same as that obtained at 7 m. However, the effect due to the ground is more pronounced in the presence of the bus bar structures at this point. When all other structures are included, the field tends to decrease slightly and this may be attributed to the aggregate effect of these structures. In the case of magnetic fields, H_x is the dominant field at all points regardless of the type of structure within the environment. The behaviour of the magnetic fields is also similar to the electric fields at all points. In general, the magnitudes of the fields are influenced by the location, the presence and type of structures in the environment.



(a) Bus bars only



(b) Bus bars and support structures

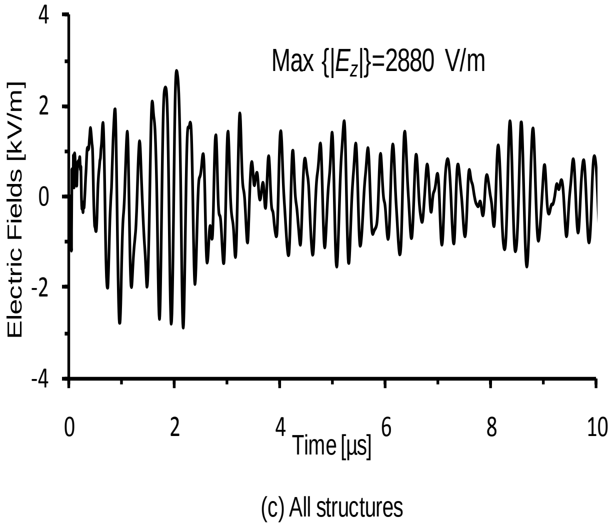
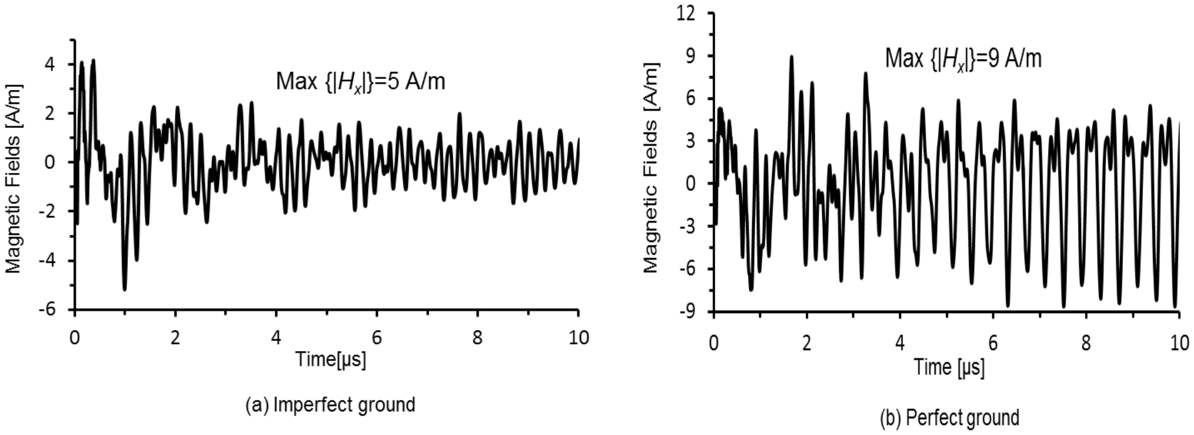


Fig 4. E_z component of electric fields computed at 1 m above ground for substation environment containing different structures

B. Variation of electromagnetic field in the vertical direction in the presence of imperfect and perfect ground conditions

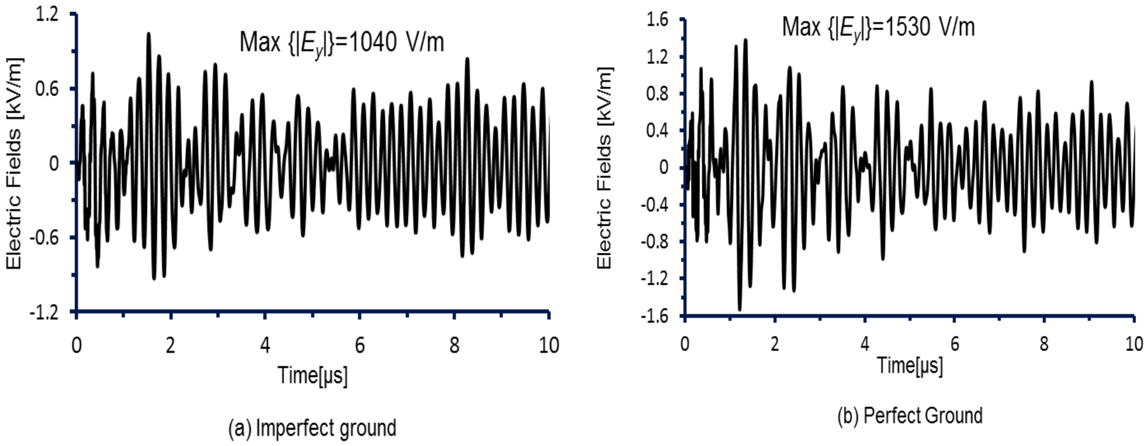
In this case, fields are computed at the same positions (2 m, 7 m and 13 m) and with all structures included in the computational space. Fig.5 shows the H_x component of the magnetic field at 1 m above the ground for imperfect and perfect ground conditions. It can be seen that the field in the presence of the perfect ground has almost doubled compared to that with imperfect ground. E_y component of the electric fields at this point is shown in figure 6. The electric field in the presence of perfect ground has higher magnitudes compared to that with imperfect ground. However, the enhancement is lower compared to the magnetic field.



(a) Imperfect ground

(b) Perfect ground

Fig 5. H_x component of magnetic fields computed at 1 m above ground for imperfect and perfect ground conditions



(a) Imperfect ground

(b) Perfect Ground

Fig 6. E_y component of electric fields computed at 1 m above ground for imperfect and perfect ground conditions

Shown in Table 2 and 3 are the rest of the fields for the two ground conditions. At 2 m below the bus bars, electric fields are the same for both imperfect and perfect ground conditions. This also applies to the magnetic fields. However at 7 m below the bus bars, electric fields are higher with perfect ground than with imperfect ground conditions except E_z. All the three components of the magnetic field are higher in magnitude with perfect ground. At 13 m below, E_y is higher with perfect ground than with imperfect ground. All magnetic fields are higher with perfect ground than with imperfect ground except H_y.

In general, electromagnetic fields decrease in the vertical direction as one moves away from the source. Perfect ground conditions enhance both electric and magnetic fields. The enhancements of magnetic fields are more pronounced than electric fields. Electric field as high as 24 ksV/m are possible near the source and the field reduces by a factor of about 10 at 10 m away. Magnetic fields can reach 36 A/m near the source and falls by a factor of about 3 at 10 m away.

Table 2. Electromagnetic fields at different points below bus for imperfect ground conditions

Distance[m]	Electric Fields[V/m]			Magnetic Fields[A/m]		
	E_x	E_y	E_z	H_x	H_y	H_z
2	5680	20600	11700	34	11	2
7	563	2890	4900	8	5	2
13	417	1040	2880	5	1	3

Table 3. Electromagnetic fields at different points below bus for perfect ground conditions

Distance[m]	Electric Fields[V/m]			Magnetic Fields[A/m]		
	E_x	E_y	E_z	H_x	H_y	H_z
2	5680	20600	11700	34	11	2
7	582	4000	4780	10	7	4
13	312	1530	1280	9	1	6

C. Variation of electromagnetic field in the horizontal direction

For the third situation, starting directly under the radiating bus bar b1, fields are computed horizontally to the right in steps of 5 m. Figure 3(b) shows the bus bars, the direction and positions where the fields are computed. Imperfect ground conditions are assumed and all structures are included in the computation space.

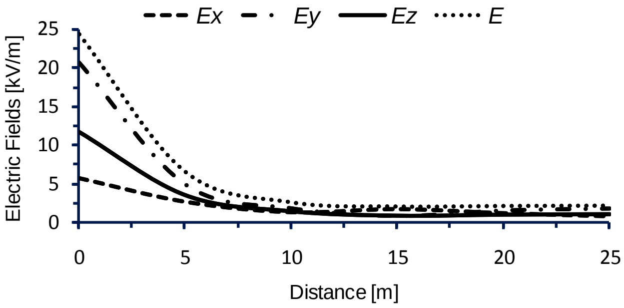
The respective peak magnitudes of the electromagnetic fields are also computed using the following equations

$$E = \sqrt{E_x^2 + E_y^2 + E_z^2} \; ; \qquad\qquad H = \sqrt{H_x^2 + H_y^2 + H_z^2}$$

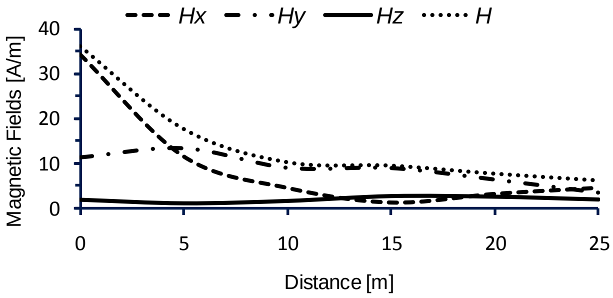
Fig.7 shows how the electromagnetic fields vary with distance in the horizontal direction. It can be seen that there is a rapid fall in both electric and magnetic fields within the first 5 m from the source. To show how fast the electromagnetic fields attenuate from the source, Table 4 shows the peak magnitudes at different distance and the factors of the fields. The factor for the electric fields is defined as E_D / E_o in which E_o is the electric field directly under the bus bar and E_D is the electric field at a distance D from the bus bar. Likewise for the magnetic fields, the factor is defined as H_D / H_o. At 5 m from the source, the electric fields are reduced to 0.27 of the initial value and magnetic fields to 0.5 of the initial value. At 25 m from the source, the electric fields have decreased to 0.09 and magnetic fields to 0.17. These results show that bus bars are poor radiators of energy as suggested by Pretorius and others [15].

Table 4. Electromagnetic fields at different points from bus in horizontal direction

Distance[m]	Electric Fields[V/m]		Magnetic Fields[A/m]	
	E [V/m]	Factor	*H* [A/m]	Factor
0	24362	1.00	36	1.00
5	6477	0.27	18	0.50
10	2506	0.10	10	0.28
15	1961	0.08	10	0.28
20	2028	0.08	8	0.22
25	2073	0.09	6	0.17



(a) Electric fields

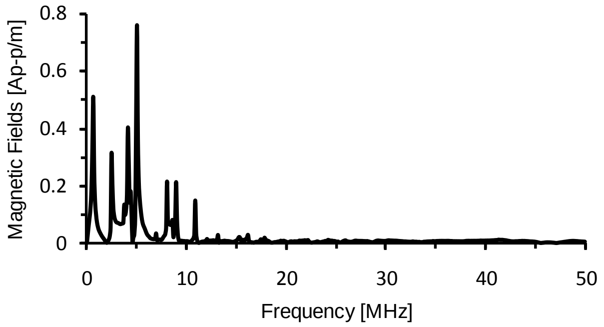


(b) Magnetic fields

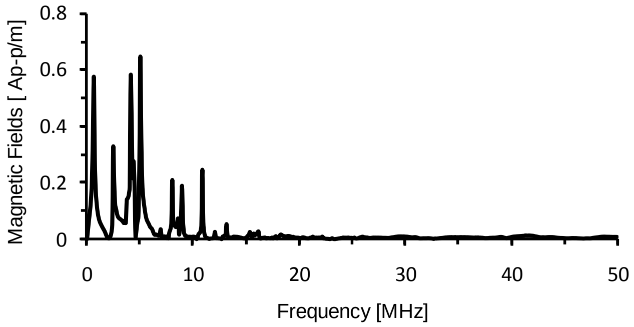
Fig 7. Variation of electromagnetic fields with distance in the horizontal direction

D. Frequency domain analysis

Fig.8 shows the frequency components of the magnetic fields at 1m above the ground for an environment containing various structures. It can be seen that magnetic fields are associated with high frequency components up to 20 MHz for all the three cases. With reference to fig. 8(a), the environment containing only bus bar structures produces frequencies with higher magnitudes than the other two configurations. This could be due to the presence of more metallic and insulating structures in the other two cases and the aggregate effects of the reflections tend to have a cancellation effect.

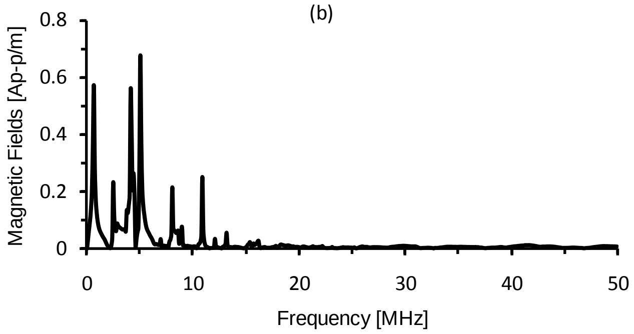


(a) Bus bars only



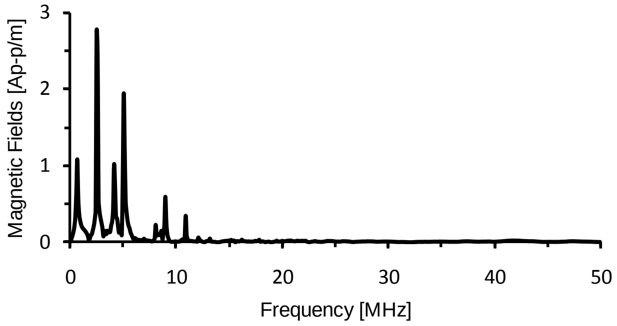
(b) Bus bars and support strucrures

(b)

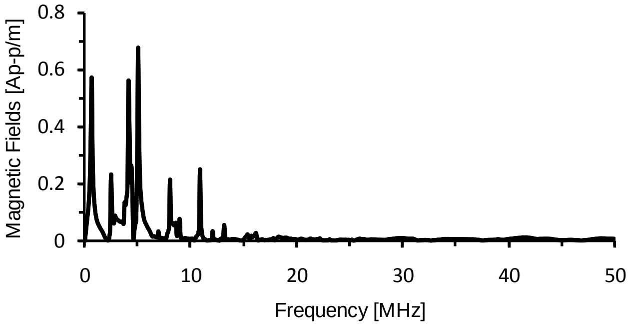


(c) All structures

Fig 8. Frequency spectrum of magnetic fields at 1 m above ground for substation environment containing different structures



(a) Perfect ground



(b) Imperfect ground

Fig 9. Frequency spectrum of magnetic fields at 1 m above ground for perfect and imperfect ground conditions

Fig.9 shows the frequency components of the magnetic fields at 1 m above ground for perfect and imperfect ground conditions. At this observation point, frequency component with high amplitudes were observed at 5 MHz and below for the imperfect ground and for the perfect ground conditions. However, perfect ground produces frequency with higher amplitudes than the imperfect ground. This is in order since reflections from the perfect ground are expected to be higher than the imperfect ground and therefore has the possibility of enhancing the magnetic fields. The predicted results are not significantly different from measured results and show that the simulation code generated is suitable for the prediction of emission due to a switching operation within a substation [6]. This is an important capability because software modelling and simulation is much less costly when compared to site assessment of the electromagnetic environment when switching takes place.

IV. CONCLUSION

The application of the FDTD method for the computation of transient electromagnetic fields due to switching within a high voltage substation has been demonstrated in this paper. The effects of different substation components and ground conditions on the radiated fields have been studied. It was observed that the presence of adjacent materials within the substation will affect the electromagnetic fields at various observation points differently. Reflections from perfect ground tends to enhance electromagnetic values compared to imperfect ground conditions. In addition, variations of electromagnetic fields in the vertical and horizontal directions from the bus bars have been analyzed. Transient electromagnetic fields with the highest peak values are found to occur at positions close to the bus bars and decrease with distance. There is a rapid fall in electromagnetic field values within the first few meters from the bus bars. At about 25 m away from the operated switch in the horizontal direction, the fields have decreased to 10% or less of the peak values. This suggests that the bus bars are poor radiators and radiated electromagnetic fields may not be a serious threat to electronic equipment at such distances. Radiated fields can contain frequency components of up to 20 MHz with dominant frequencies at around 5 MHz. The most important benefit is that the software code is suitable for predicting electromagnetic emissions due to switching within high voltage substations and consequently is crucial in substation design in order to satisfy the electromagnetic compatibility requirement of a large electrical installation.

ACKNOWLEDGEMENT

This work was supported in part by the Petroleum Technology Development Fund (PTDF), Nigeria.

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Martin D. Judd (M’2002–SM’2004) was born in Salford, England, in 1963. He graduated from the University of Hull in 1985 with a BSc (Hons) degree in Electronic Engineering after which he gained 8 years of industrial experience with Marconi Electronic Devices Ltd and EEV Ltd. Martin received his PhD from the University of Strathclyde in 1996 for research into the excitation of UHF signals by partial discharges in gas insulated switchgear. He is now a Professor in the Dept. of Electronic and Electrical Engineering at Strathclyde, where he runs the High Voltage Technologies Research Laboratory. His fields of interest include sensors, generation and measurement of fast transients, partial discharges and energy harvesting.