

Electromagnetic Field Coupling to Large Antenna Structure

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Abstract—The study of electromagnetic field coupling to an electrically large structure is essential, in order to assess the degree of protection to be provided to harden the electronic or electrical system of interest, against electromagnetic fields. The electromagnetic field coupling study can be done by computational and experimental techniques. In this paper, we have studied the high altitude electromagnetic pulse (HEMP) electromagnetic field coupling to a large antenna structure using electromagnetic dimensional scale modeling approach, in the frequency range of 1 kHz to 100 MHz. This frequency range has been chosen because most of the energy of the HEMP lies in this frequency band [1].

1. INTRODUCTION

The antenna size becomes large as one moves down in the frequency range. At very low frequencies (VLF) the antenna size is from a few hundred meters to a few kilometers [2]. High amount of power is required to be fed to get the communication range. These VLF antennas have large wired structures, in different configurations (Spider web, Inverted cone, etc.) [2–4]. High altitude nuclear Electromagnetic Pulse (HEMP) is generated as the byproduct of the nuclear detonation. The gamma rays from the nuclear detonation interact with air molecules through Compton process which produces transient electromagnetic field under the effect of earth magnetic field. The unclassified HEMP is defined in the IEC 61000-2-9 standard [1], which has the rise time of 2.3 ± 0.5 ns and full width at half maximum (FWHM) width of 23 ± 5 ns and peak electric field of 50 kV/m. The time domain and frequency domain characteristics of HEMP are shown in Figures 1 and 2, respectively. These large wired structures (VLF antenna) can also be a good receptor of external electromagnetic energy, like HEMP. Therefore, it is essential that electromagnetic field coupling to this electrically large wired structure for HEMP frequencies shall be estimated, and the adverse effects on communication can be studied. Subsequently, measures can be taken to mitigate the conducted coupling effects due to HEMP.

In this study, first the electromagnetic dimensional scale modeling approach is described and validated on a arbitrary chosen monopole antenna, and then the HEMP coupling to a large VLF antenna is studied on scaled down model. The results of the scaled down model are experimentally validated on a scaled down physical model. After validation the results of the scaled down model are scaled up for getting the response for actual size of the antenna. In this study, we use the commercially available method of moment (MoM) code Altair FEKO 2017.2.

A typical MoM [7, 8] formulation solves the electrical field integral equation (EFIE) using the method of moments numerical technique, with piecewise linear basis functions. The derived linear system is then solved by matrix inversion, and the unknowns (segment currents) are computed. These currents are then propagated towards the load impedance to induce the voltage in it.

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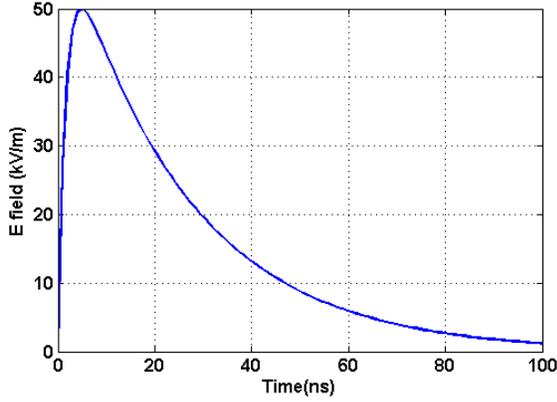


Figure 1. Time domain HEMP waveform.

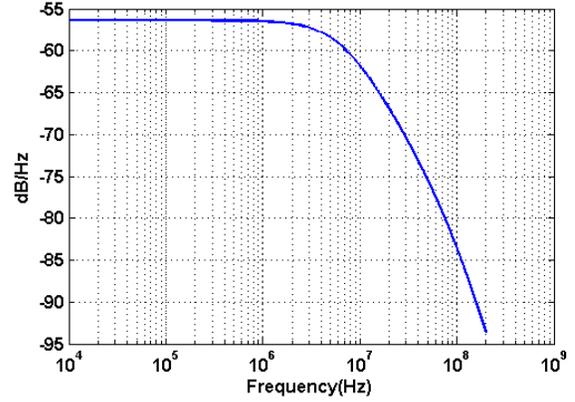


Figure 2. Frequency domain HEMP waveform.

2. ELECTROMAGNETIC DIMENSIONAL SCALING

The VLF antenna at HEMP frequencies becomes electrically large, computationally expensive and time consuming. Such large structure cannot be experimentally studied for HEMP coupling, because to accommodate VLF antenna inside HEMP simulator, a huge HEMP simulator with very high pulsed power sources is to be built, which will not be an economical solution. The electromagnetic dimensional scaling [5,6] is an effective approach to study the coupling of electromagnetic fields to large antenna structures, with less computation time and possibility of experimental verification. It is able to verify the computational results of scaled simulation model with the scaled physical model experimentally. According to this approach if we scale down a physical model by α times, then frequency will be multiplied by α ; time will be divided by α ; impedance will remain the same as both inductance and capacitance will be divided by α , and current will also be divided by α [5].

In order to verify the electromagnetic dimensional scaling, a two-step procedure has been followed. In the first step, an arbitrary monopole antenna of 500 m height and 5 mm diameter, on an infinite ground plane as shown in Figure 3, is simulated. The monopole is excited by a plane wave, and induced voltage in load impedance of 50Ω is recorded at 32 frequencies from 1 kHz to 200 MHz. In the second step, the monopole antenna, as shown in Figure 4, is scaled down by a factor of 250, and the simulation frequencies have been scaled up 250 times. The simulation results with and without scaled down model are shown in Figures 5 and 6. It can be seen from the results that the induced voltage is also scaled by the chosen scale factor of 250. Therefore, it can be concluded that this approach can be used for studying the electromagnetic field coupling to a large antenna, by scaling it down by a suitable factor which can be experimentally validated by the scaled physical model. Once the scale model is validated by measurement, the simulation results can be scaled up for getting the response of the original geometry.

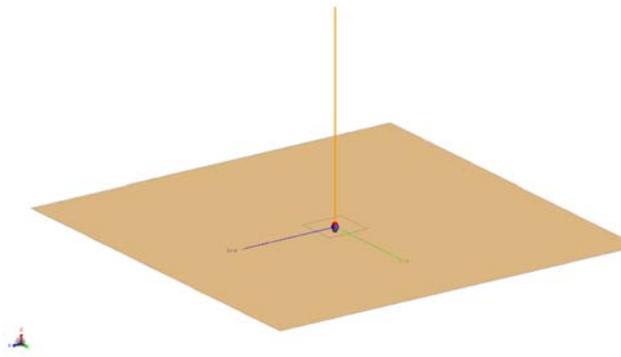


Figure 3. 500 m monopole antenna.

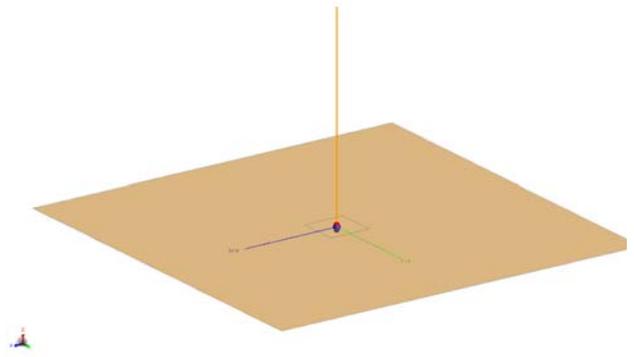


Figure 4. 2 m monopole antenna (scaled down).

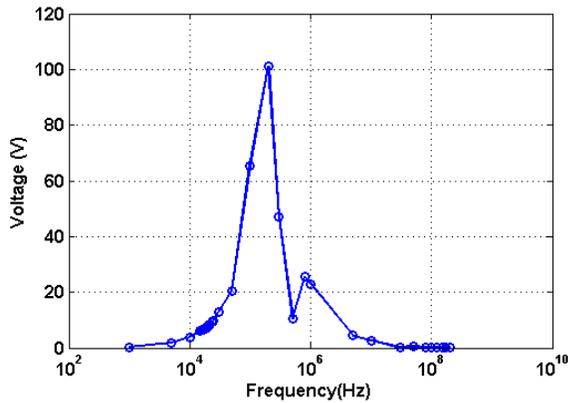


Figure 5. Induced voltage in 500 m monopole antenna.

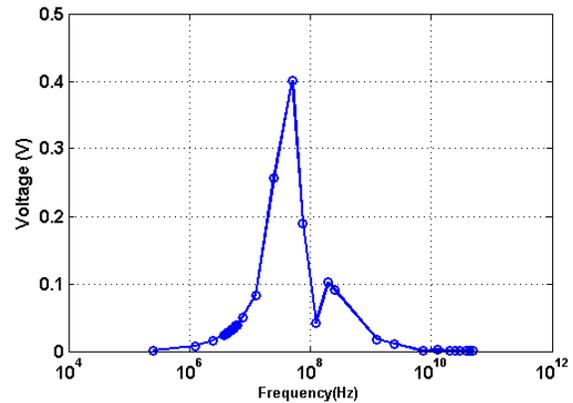


Figure 6. Induced voltage in 2 m monopole antenna (scaled down).

3. HEMP COUPLING TO SCALED VLF ANTENNA

The HEMP coupling to inverted cone type VLF antenna (as shown in Figure 7) has been studied. The antenna has 24 slant wires with the dimension of 585 m and located 85 m height from the ground. It is fed with 200 kV voltage at VLF frequencies with load impedance of $\approx 70 \Omega$. In order to study the HEMP coupling to such a large antenna scaling factor of 250 has been used. The antenna model is excited with vertically polarized 1 V/m plane wave at $\theta = 90 \text{ deg.}$ and $\phi = 0 \text{ deg.}$, to yield the impulse response in load impedance. The induced voltage in load impedance is shown in Figure 8 for different frequencies.

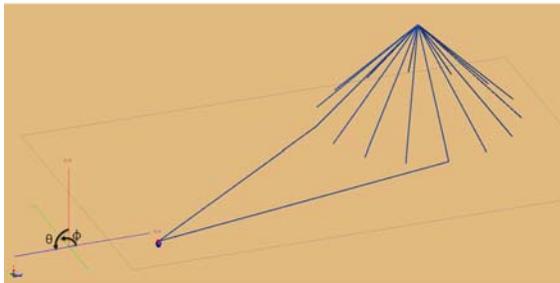


Figure 7. Scaled VLF antenna.

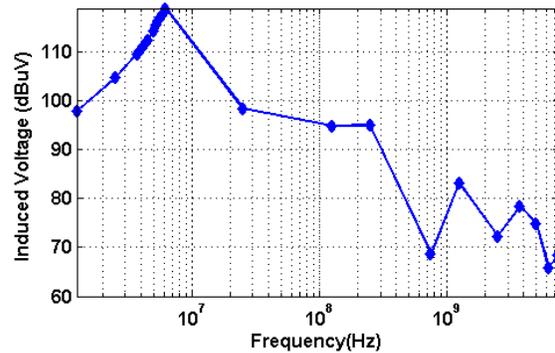


Figure 8. Simulation results of induced voltage in scaled down model.

3.1. Measurement Setup

The scaled VLF antenna model (1 : 250) is fabricated and shown in Figure 9. The experimental validation is done in a semi-anechoic chamber. The model is excited from a distance such that full model is illuminated with almost uniform field from $250 * 1 \text{ kHz}$ to $250 * 100 \text{ MHz}$ by using the signal generator, power amplifiers and field probes. The induced voltage is recorded with the help of spectrum analyser (Rohde & Schwarz FSV 30). The measured results are normalized to 1 V/m and shown in Figure 10, for comparison with the simulation results. It can be seen that there is a fairly good agreement between computed and measured results of electromagnetic field coupling to scaled model. It can also be seen that coupling takes place only at scaled up VLF frequencies of HEMP, and for the other higher

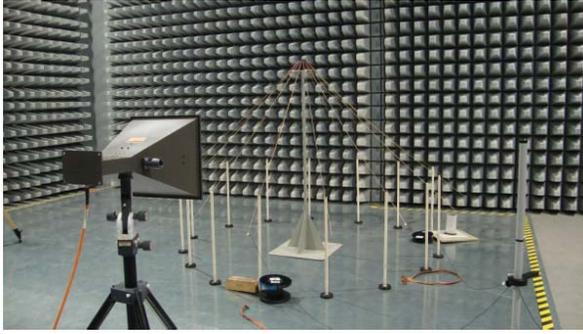


Figure 9. Experimental set up with scaled model.

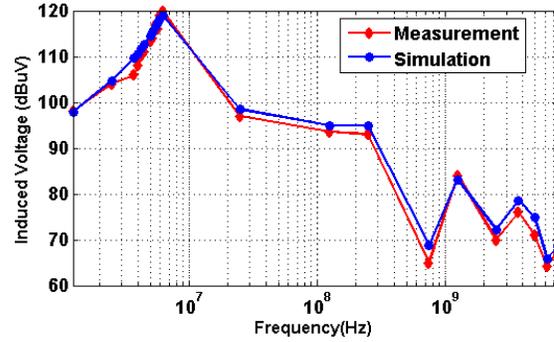


Figure 10. Comparison of measured and simulation results.

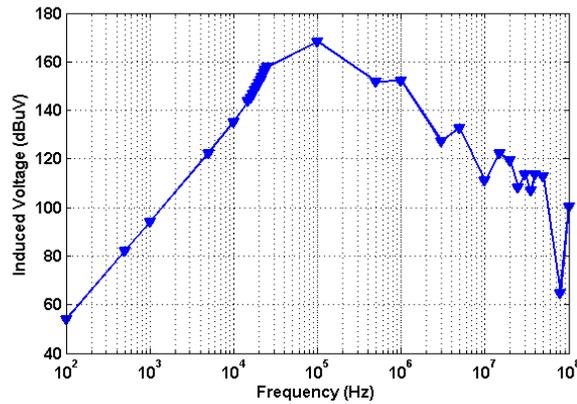


Figure 11. Induced voltage in full scale model.

frequencies poor coupling takes place. It is because the induced high frequency signals attenuate fast in an open wire structure. The full scale impulse response is obtained by scaling up the magnitude by 250 and scaling down the frequency with the same factor. The induced voltage for the full scale structure is shown in Figure 11.

3.2. Time Domain Results for Full Scale Model

The comparison between simulation and measurement results in frequency domain shows that the simulation results can be taken as upper bound for computing the time domain response of the full scale structure. The HEMP is a time domain phenomenon, and therefore, time domain response is desired. The time domain results of field coupling are computed by convolving the scaled HEMP pulse, as shown in Figure 12, with the impulse response obtained in Section 3.1 (Figure 8). In scaling of HEMP waveform, the rise time and FWHM width are reduced by 250 times, and amplitude is scaled up by the same factor. A compressed delay of 28 ns has been introduced in HEMP waveform in order to view the complete induced voltage waveform traveling through the structure. The computed time domain voltage in load impedance is shown in Figure 13.

3.3. Parametric Study

The aim of conducting the parametric study is to analyze from what direction the field will induce maximum voltage in load impedance. The study has been carried out for different incident angles for plane wave excitation. The variation of θ and ϕ has been kept from 0 deg. to 90 deg. and from 0 deg. to 100 deg., respectively. Figures 14 to 17 show the variation of induced voltage for different θ angles

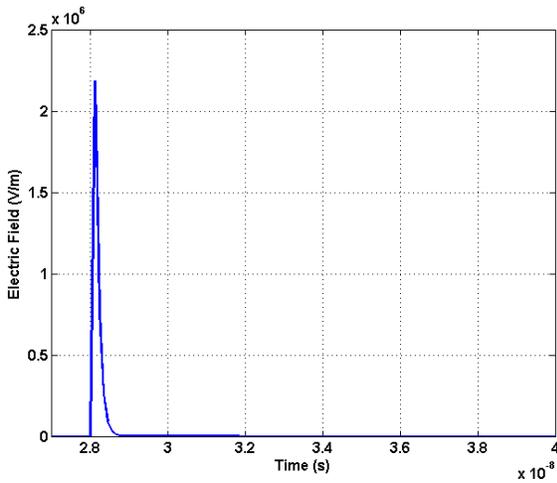


Figure 12. Scaled HEMP waveform.

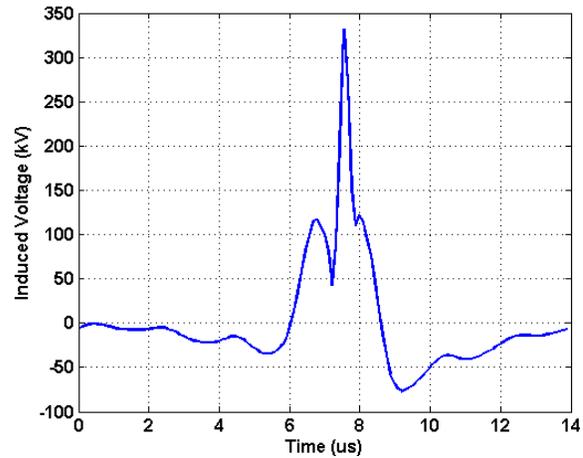


Figure 13. Time domain induced voltage in full scale structure.

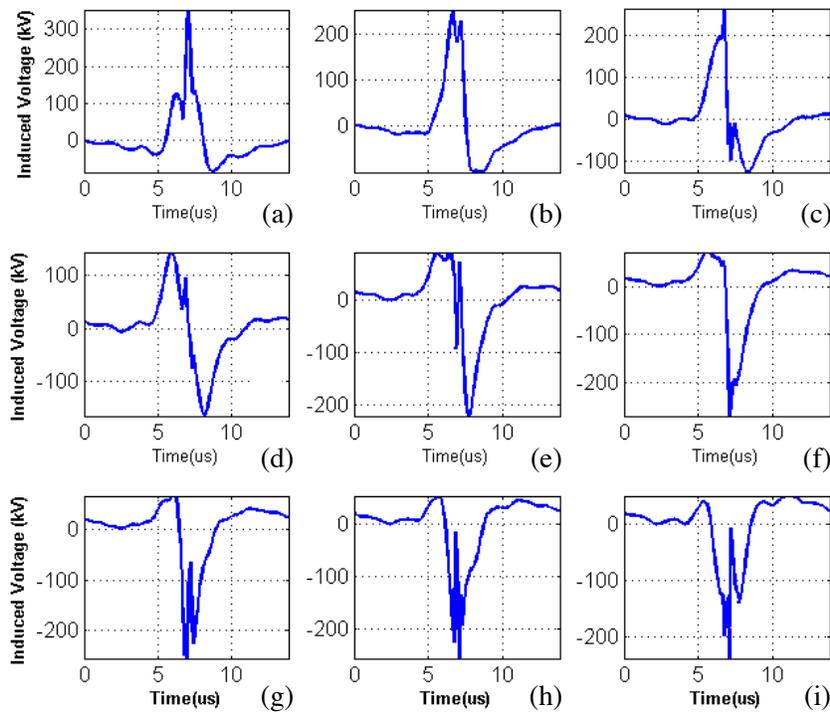


Figure 14. Induced voltage at $\phi = 0$, and at $\theta =$ (a) 0 deg., (b) 10 deg., (c) 20 deg., (d) 30 deg., (e) 40 deg., (f) 50 deg., (g) 60 deg., (h) 70 deg., (i) 90 deg.

at various ϕ angles. It can be seen from the responses that the maximum voltage (400 kV) is induced from $\theta = 10$ deg. and $\phi = 80$ deg., which is the opposite direction of feed to the antenna. The maximum voltage induced in the present structure depends upon the electric field polarization angle with respect to structure, and it will be maximum when field polarization matches with the structure. The high frequency content of the pulse dies out quickly, as it travels towards the load. This is also evident from all the time domain results, where rise time is becoming slower and pulse width getting widened.

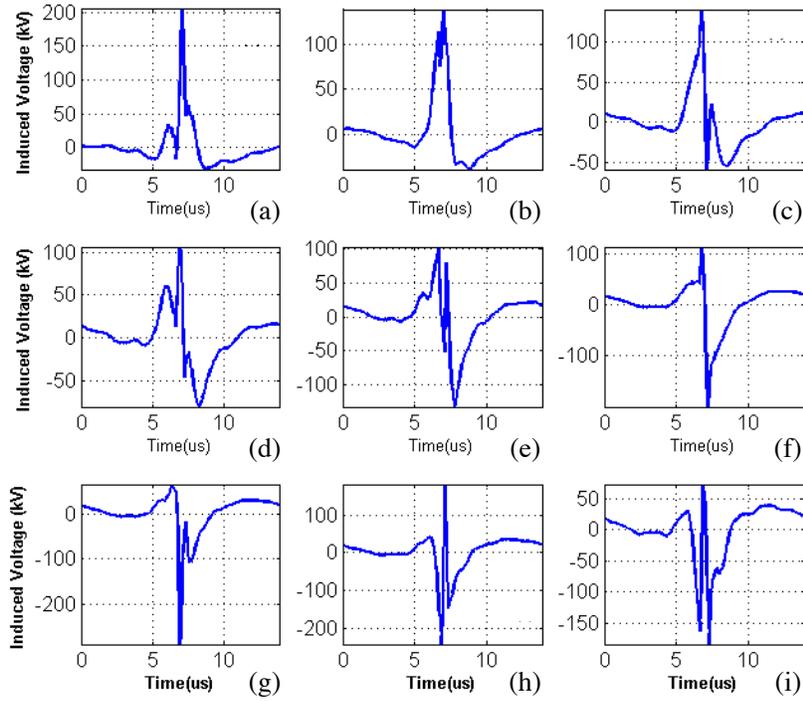


Figure 15. Induced voltage at $\phi = 20$, and at $\theta =$ (a) 0 deg., (b) 10 deg., (c) 20 deg., (d) 30 deg., (e) 40 deg., (f) 50 deg., (g) 60 deg., (h) 70 deg., (i) 90 deg.

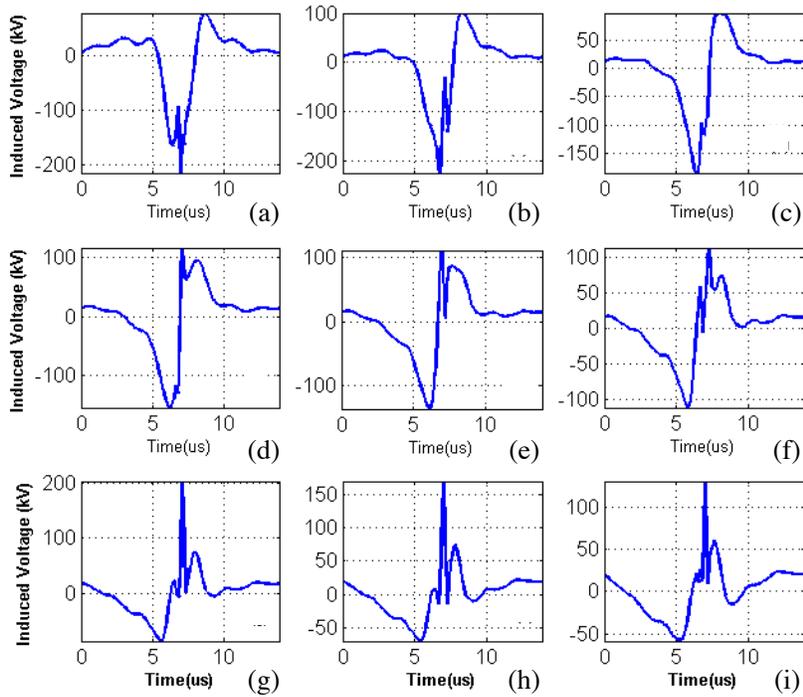


Figure 16. Induced voltage at $\phi = 60$, and at $\theta =$ (a) 0 deg., (b) 10 deg., (c) 20 deg., (d) 30 deg., (e) 40 deg., (f) 50 deg., (g) 60 deg., (h) 70 deg., (i) 90 deg.

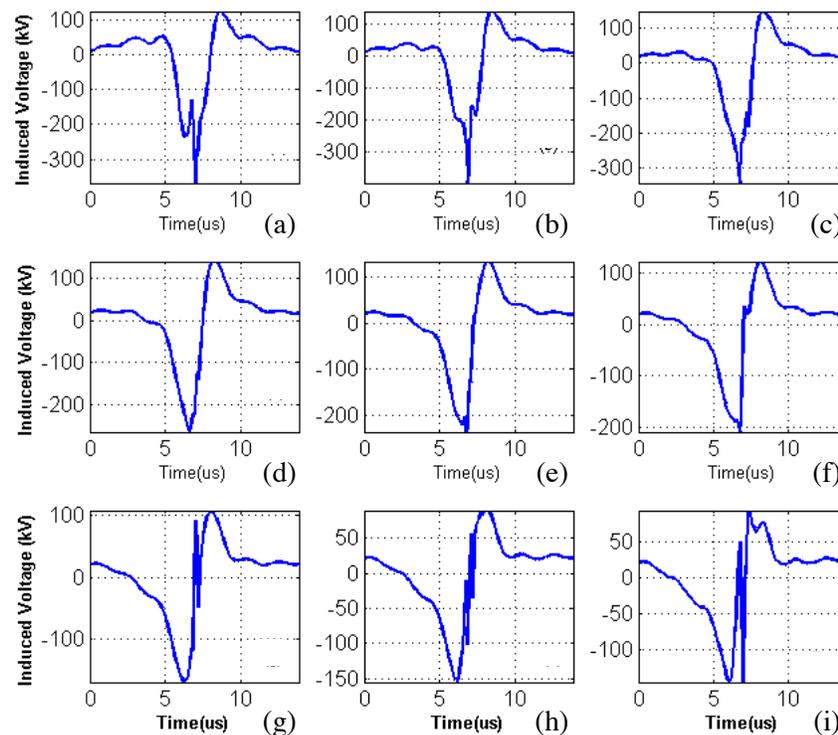


Figure 17. Induced voltage at $\phi = 80$, and at $\theta =$ (a) 0 deg., (b) 10 deg., (c) 20 deg., (d) 30 deg., (e) 40 deg., (f) 50 deg., (g) 60 deg., (h) 70 deg., (i) 90 deg.

4. CONCLUSION

In this paper, the HEMP coupling to a large antenna structure, like VLF antenna, has been studied using the electromagnetic dimensional scaling technique. The induced voltage is found varying with the field polarization and incident angle. The maximum time domain peak induced voltage in load impedance is found to be 400 kV, for the geometry discussed in this paper. Based on these results, the suitable HEMP filter/surge arrestors can be designed to suppress the induced transients voltages. However, the major limitation of this approach lies with fabrication capability and experimental setup availability at scaled up frequencies. Using this approach, an upper bound response of full structure can always be computed and experimentally validated. This upper bound response can be taken as the worst case response for the electromagnetic environment like HEMP, Lightning EMP, and based on this, the suitable protective measures can be adapted or designed.

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