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Investigation on Transient Response of Linear Dipole Antennas in the Presence of HEMP Based on Equivalent Circuit

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Abstract—Interfering electromagnetic energy could be a very powerful pulse which is generated and incident onto communication system such as linear wire antenna through direct radiation. In this paper, the transient responses of the linear wire antenna such as dipole antenna under the impact of the early-time (E1) high-altitude electromagnetic pulse (HEMP) are investigated using the equivalent circuit due to a primary element used in the modeling of systems for HEMP vulnerability is the linear wire antenna such as dipole antenna. Based on the equivalence concept of HEMP radiation source and linear wire antennas, the response at receiving antenna port is calculated efficiently with an uncomplicated circuit composed of pulse voltage source and lumped elements. Numerical results are presented to confirm the accuracy of the proposed method.

1. INTRODUCTION

Antennas are influential components of a communication system utilized to transmit or receive electromagnetic signal in free space. Among all types of antennas, linear wire antennas such as dipole antennas are commonly used in communication systems. Nowadays, linear wire antennas such as dipole antennas have been used in various types of communication systems such as TV antenna, FM broadcast receiving antennas, shortwave antenna, dipole towers, and Yagi-Uda antennas, due to their unique advantage. Furthermore, number of electromagnetic interference (EMI) sources is growing, and electromagnetic environment is becoming more complex. In fact, most of communication systems around us are very sensitive and susceptible to electromagnetic interference sources and especially to a purposeful electromagnetic interference [1]. Purposeful interfering electromagnetic energy could be a very powerful pulse which is unexpectedly generated and incident onto communication system such as linear wire antenna through direct radiation [2]. Therefore, incident high-altitude electromagnetic pulse (HEMP) could cause continual damage to the communication system [2].

A transient electromagnetic disturbance originated by high-altitude nuclear explosion commonly abbreviated as HEMP is the abrupt pulse of electromagnetic radiation resulting in large-power electromagnetic wave. The resulting quickly changing electromagnetic fields can couple with electrical and electronic devices through the receiving antenna and cable to produce damaging current and voltage surges. Therefore, under conditions of illuminating with HEMP radiation, their interior electrical or electronic systems may be susceptible to disturbance, upset, temporary or permanent damage. Electromagnetic coupling mechanism of the pulses at the port of the receiving antennas by theory, numerical computation or measure can be helpful for estimating the sensitivity of practical device and make guidance for electromagnetic protection from damage or harm.

The assessment of HEMP response was studied by many researchers. So far, various techniques are used for studying the effect of HEMP on dipole antenna. The responses of a dipole antenna under HEMP,

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high power microwave (HPM) and ultra-wideband (UWB) are computed using method of moment in [3]. For the useful time domain technique in solving wideband cases, the responses of linear wire antenna under HEMP are evaluated using time domain integral equation (TDIE), finite-difference time domain (spice-FDTD) method, or transmission line matrix method (TLM) in [4]. Though the computation has high exactness to some scope, modeling is hard to evaluate the real situation. In spite of the accuracy of those techniques, they use lots of time, need large amount of memory and are complex. For the sake of calculating the response of HEMP to linear wire antenna efficiently, this article concentrates on finding the strategy that evaluate the response of the dipole antenna in receiving mode under HEMP radiation based on a simple equivalent circuit.

For this purpose, an uncomplicated approach is presented based on the equivalence concept of HEMP radiation source and linear wire antennas, and the response at antenna port in receiving mode is calculated in an efficient manner with a straightforward circuit composed of pulse voltage source and lumped elements. The results obtained by presented technique are compared with the full wave simulator software such as CST microwave studio. The results show that it is more effective and easy; therefore it can be used in the circuit software packages.

2. THEORY

In the theory of antennas, antennas are usually investigated in the transmitting mode. An antenna in the transmitting mode can be modeled with a voltage source that is applied to the input ports of the antenna. The time-varying currents and charges radiate radio signals, which carry energy. An antenna in transmitting mode can then be assumed as a component that transforms energy from a generator to energy associated with an electromagnetic wave. On the other hand, an antenna in receiving mode takes out energy from an incident electromagnetic wave and delivers it to impedance as a load. By invoking reciprocity concept of an antenna in transmitting and receiving mode, it is possible to justify the following:

1) The equivalent source impedance of an antenna in the receiving mode is equal to the input impedance of the antenna in the transmitting mode.

2) The radiation pattern of an antenna for reception is identical to that for transmission.

For a receiving antenna weakly coupled to a transmitting source (generator), an approximate Thevenin's equivalent circuit at the receiving terminal can be used. A simple circuit for the calculation is shown in Figure 1, where V_g is the open-circuit voltage induced in the receiving antenna due to external radiation field, Z_g the equivalent generator internal impedance of the antenna in the receiving mode that is equal to its input impedance in the transmitting mode (antenna can be seen as an internal impedance of the source Z_g), and Z_L the load impedance (Note that the end circuit can be replaced by a load Z_L of any impedance). This model is suitable to use antenna equivalent circuit to solve this problem. For a dipole antenna with length l and radius a, the radiation resistance R_r can be written as following [5].

$$\begin{aligned} R_r \;=\; & \frac{\eta}{2\pi}\Bigg\{C+\ln(\beta l)-C_i(\beta l)+\frac{1}{2}\sin(\beta l)\left[S_i(2\beta l)-2S_i(\beta l)\right] \\ & +\frac{1}{2}\cos(\beta l)\left[C+\ln\left(\frac{\beta l}{2}\right)+C_i(2\beta l)-2C_i(\beta l)\right]\Bigg\} \end{aligned} \tag{1}$$

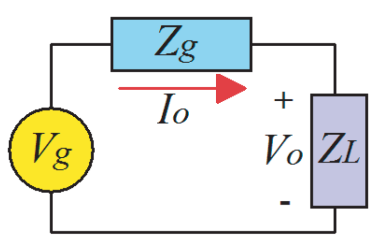

Figure 1. Antenna equivalent circuit in receiving mode.

Also, using the induced EMF technique, the imaginary part of the radiation impedance X_r, relative to the current maximum, can be written as [5].

$$X_r = \frac{\eta}{4\pi}\left\{2S_i(\beta l)+\cos(\beta l)\left[2S_i(\beta l)-S_i(2\beta l)\right]-\sin(\beta l)\left[2C_i(\beta l)-C_i(2\beta l)-C_i\left(\frac{2\beta a^2}{l}\right)\right]\right\} \tag{2}$$

where $C = 0.5772$ (Euler's constant) and $C_i(x)$ and $S_i(x)$ are the cosine and sine integrals. As a result, the radiation impedance (internal impedance of the antenna in the receiving mode) of a dipole antenna can be presented as $Z_g = R_r + jX_r$.

The electromagnetic environment generated by high altitude nuclear explosion is usually divided into three components: early time (E1 HEMP), intermediate time (E2 HEMP) and late time (E3 HEMP). Because of the short front time of E1 HEMP and its great field magnitude, it causes the strongest effects. Time variable radiates electric field of HEMP composed from double exponential function. The popular waveform of E1 HEMP is described as in the following equation.

$$E_i(t) = E_0 k_0 \left(e^{-\alpha t} - e^{-\beta t}\right) \tag{3}$$

where E_0 is the peak value of the incident radiated electric field of HEMP, k_0 the correction factor, and α and β are parameters that describe the rising edge features. According to IEC61000-2-9 published in 1996, $E_0 = 50\,\mathrm{kV/m}$, $k_0 = 1.3$, $\alpha = 4\times10^7\,\mathrm{s}^{-1}$, $\beta = 6\times10^8\,\mathrm{s}^{-1}$. Due to long distance between EMP source and receiving antenna, incident HEMP field to the dipole antenna can be assumed as plane wave (TEM Wave) that has a polarization angle ψ with the antenna extension direction.

The source field can be assumed as receiving electric potential at the forward terminal of the dipole antenna, and the receiving electric potential can be replaced by the voltage source V_g in the circuit shown in Figure 1. Usually, for real values of Z_L and Z_g, time variable receiving voltage can be indicated as

$$V_L(t) = \frac{Z_L}{Z_g + Z_L}\gamma L_e E_i(t) P(\theta,\phi) \tag{4}$$

where γ is a constant coefficient, $E_i(t)$ the time variable constituent of the incident electric field to the dipole antenna that parallel to the antenna extent direction, L_e the effective length of the dipole antenna that define later and $P(\theta,\phi)$ the normalized radiation pattern of the dipole antenna. As mentioned before, Z_g is the impedance of the dipole antenna which can be seen as internal impedance of the source in Figure 1, and Z_L is the load impedance of the receiving antenna. If both Z_L and Z_g are complex values, the circuit shown in Figure 1 can be solved with Laplace transform in frequency domain. Then, by taking the inverse Laplace transform, time variable receiving voltage $V_L(t)$ will be computed. Open-circuit voltage induced in the receiving antenna due to external radiation field $V_g(t)$ can be determined as

$$V_g(t) = \gamma L_e E_i(t) P(\theta,\phi) \tag{5}$$

For exact solution, effective length of dipole antenna must be calculated. For a thin linear wire antenna with a defined current distribution it is sometimes useful to describe a quantity called effective length, to which the far-zone field is proportional. By assuming a sinusoidal current distribution on a center-fed, thin, straight half-wave dipole, effective length can be written as

$$L_e(\theta) = \frac{2}{\beta}\left[\cos\left(\frac{\pi}{2}\cos(\theta)\right)/\sin(\theta)\right] \tag{6}$$

When the half-length of a dipole is greater than a quarter wavelength and approaches half wavelength, input current at the feed point of the dipole antenna would be progressively less than magnitude of current distribution, which would not occur at the feed point of antenna. This could make L_e much greater than antenna length. Thus equation of antenna effective length as given i above is relevant only for relatively short antennas that have a current maximum at the feed point. With these assumptions, equivalent circuit can hardly be solved because effective length is function of frequency, and all frequency components of HEMP must be considered. We know that an electromagnetic pulse is a short burst of electromagnetic energy. Its short duration means that it will be spread over a range of frequencies. To reach this goal, HEMP wave has to break it into single frequency signals by using even expansion of Fourier's series. By use of this technique, the final open-circuit voltage induced in the receiving antenna due to external radiation field can be calculated by adding the radiated electric field of each term of Fourier's series.

As noted above, the incident wave (HEMP signal) can be broken into single frequency signals by using expansion (in this paper even expansion is considered) of Fourier's series. By writing first 150 terms of Fourier's series, the incident HEMP field can be approximated accurately. As the spectrum of the double exponential function pulse is chiefly located at lower frequency band (it can be seen in Figure 2), the magnitude decreases with the increment of the frequency and reaches 0.01 of its maximum value at 300 MHz. So dipole antennas operating over this frequency range can nearly be considered as short dipoles. Therefore, for short dipole antennas situated along z-direction axis in spherical coordinates, their effective length is $l/2$, and the open-circuit voltage source can be written as

$$V_g(t) = E_i(t) l \cos(\psi) \sin(\theta) \tag{7}$$

By use of this assumption, equivalent circuit can be solved, and the final open-circuit voltage induced in the receiving antenna due to external radiation field can be calculated in a simple manner.

3. RESULTS AND DISCUSSION

Three examples with two cases are considered to verify the accuracy of the presented method. Geometric dimensions of the studied antenna, determined by Antenna Design Kit v2.1 package. In the first example, the length, radius and feed gap of assumed dipole antenna are 449.96 mm, 7.499 mm and 7.499 mm, respectively, and load impedance is 100 ohm. The resonant frequency of this antenna is considered about 0.3 GHz. In the second example, the length, radius and feed gap of assumed dipole antenna are 45 mm, 0.75 mm and 0.75 mm, respectively, and a load with 100 ohm resistance is connected to the dipole antenna. In this example, the resonant frequency of antenna is assumed about 3 GHz. In the third example, the length, radius and feed gap of the assumed antenna are 15 mm, 0.25 mm and 0.25 mm, respectively, and a load with 100 ohm resistance is connected to the dipole antenna. The resonant frequency of this antenna is considered about 9 GHz.

Two cases are supposed in all three examples. In the first case, the incident direction of HEMP is vertical. Also, electric field polarization direction is orthogonal to the antenna. In other words, incident and polarization angle are 90 deg, respectively. In the second case, the incident angle θ is 45°, and polarization angle ψ is 90°. Equation (7) is used to calculate the open-circuit voltage induced in the dipole antenna in receiving mode due to external radiation field (V_g) in time domain. In all three examples, the results obtained from Equations (1) and (2) are not accurate enough to calculate input impedance of dipole antenna. Therefore, instead of these equations and for increasing accuracy of response (V_L), antenna input impedance is obtained using simulation software. The time domain voltage signals $V_L(t)$ on the load for the three examples including the simulation results obtained by

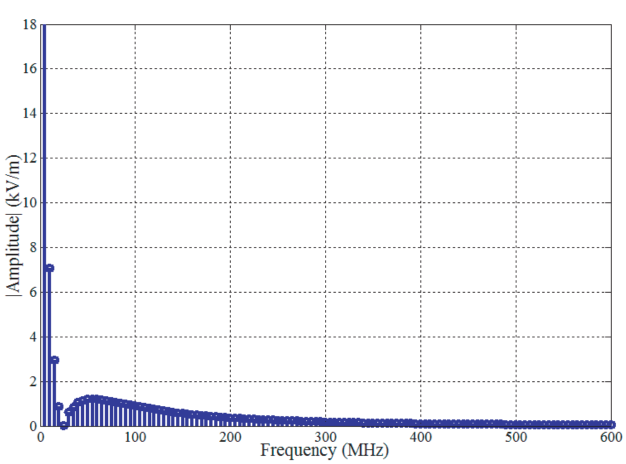

Figure 2. HEMP spectrum.

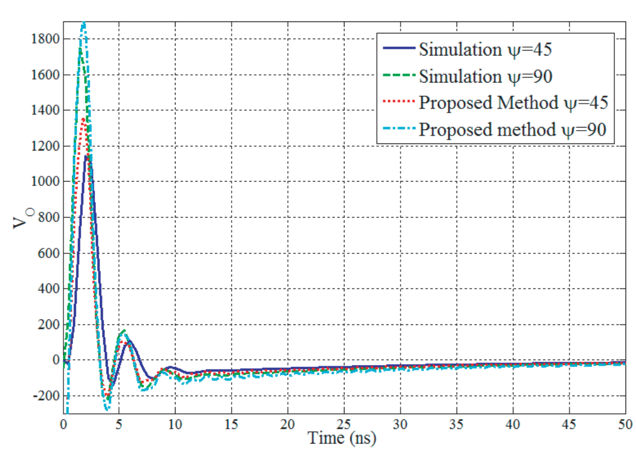

Figure 3. Results for antenna with l = 449.96 mm, radius = 7.499 mm, Gap = 7.499 mm.

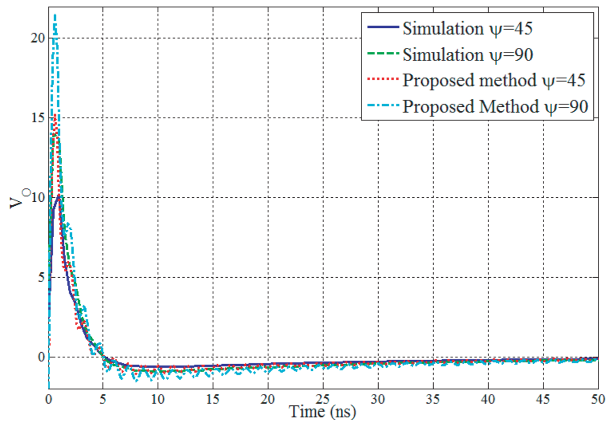

Figure 4. Results for antenna with l = 45 mm, radius = 0.75 mm, Gap = 0.75 mm.

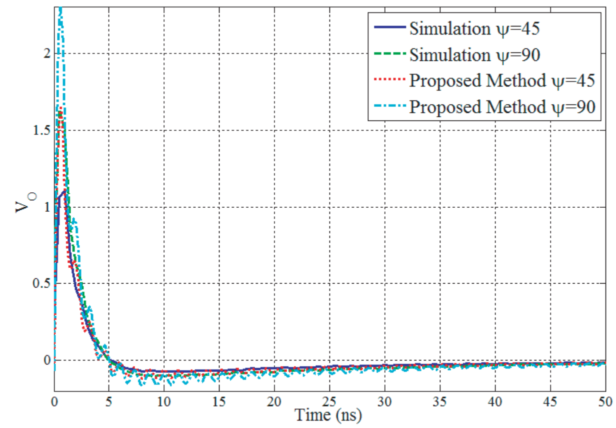

Figure 5. Results for antenna with l = 15 mm, radius = 0.25 mm, Gap = 0.25 mm.

CST Microwave Studio 2015 and the proposed method are plotted in Figure 3 to Figure 5. It can be seen from these figures that the equivalent circuit calculation results and full wave simulation ones match. Also, the proposed method is more efficient than the full wave simulation for designer because of the time needed to obtain the response is low. It can be seen that the proposed method has a good accuracy in wide frequency range.

4. CONCLUSION

Electromagnetic induction mechanism of the pulses at the port of the receiving antenna, cable, etc., which can influence surrounding equipment by theory, numerical calculation or measurement, can determine the sensitivity of the device and provide guidance for electromagnetic preservation. In this paper, the transient responses of the linear wire antenna, such as dipole antenna under the impact of the early-time (E1) high-altitude electromagnetic pulse (HEMP), are investigated using the equivalent circuit due to a primary element used in the modeling of systems for HEMP vulnerability is the linear wire antenna such as dipole antenna. Based on the equivalence concept of HEMP radiation source and linear wire antennas, the response at receiving antenna port is calculated efficiently with an uncomplicated circuit composed of pulse voltage source and lumped elements. The introduced method is more efficient than the full wave commercial simulator for designer because the time needed to obtain the response is low and has a good accuracy in wide frequency range. The results obtained by the suggested procedure are compared with that from the full wave commercial simulator such as CST microwave studio which confirms the accuracy of the introduced method in this work.

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