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A Review Paper: Electromagnetic Threats and the Protection

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ABSTRACT

A review is given for the different aspects of Electromagnetic threats. The threats include the nuclear electromagnetic pulse (NEMP) and the high power microwave weapons (HEMP) These waves produce a high intensity electromagnetic field in a time up to few microseconds with frequencies which may extend to several Giga Hertz. This concentrated energy is capable of destroying or causing different sorts of damage to any electronic component if it couples to it. Modes of penetration to the electronic systems take place by a direct penetration through the holes, high currents induced on cables and antennas. Results are presented for the transient response of NEMP and HEMP for dipole and microstrip antennas, emphasizing the mechanism of pulse coupling to the antenna. Protection methods from such threats are presented.

I. INTRODUCTION

High altitude nuclear explosions revealed the generation of strong electromagnetic pulse with electric field intensity reaching 50 kV/m and spectrum extending to 100MHz, which may propagate to distances reaching 2500 km, depending on the height of the explosion HEMP (high altitude electromagnetic pulse) [1]. Such pulse penetrates to electronic and electric systems through antennas, transmission lines and unshielded equipment [2-4]. Such pulse may cause damaging effects to sensitive front ends, temporary malfunction or disturbance of circuit function. Protective methods were introduced based on electromagnetic compatibility EMC rules of shielding, filtering, pulse suppression and grounding to avoid or reduce these effects [2-5].In this review, some simulation results for the transient response of dipole and microstrip antennas to high power electromagnetic pulses are presented, since the antennas are a main path of penetration of the electromagnetic pulses to electronic systems.

Following the discovery of the nuclear electromagnetic pulse, many researches and studies were performed on the subject, and hundreds of documentation were published in open literature in “Electromagnetic pulse notes” (EMP), edited and assembled by C. Baum. The different aspects of the subject are studied in the transactions of “electromagnetic compatibility”. The IEC (international electro technical committee) published more than 20 reports and standards covering the different aspects of electromagnetic pulses, including their characteristics, methods of protection , measurements and testing for immunity and for simulation of the pulses for disturbances induced by radiation and by conduction on conductors, within the scope of electromagnetic compatibility, e.g. [7-11].

2. HIGH POWER ELECTROMAGNETIC THREATS

High power electromagnetic threats include mainly nuclear electromagnetic pulse NEMP and electromagnetic weapons as HPMW.

2.1 NEMP Threat

2.1.1 Generation of High-Altitude Electromagnetic Pulse

The nuclear explosion emits Gamma rays within times of the order of nanoseconds [12, 1] . The gamma rays emitted by a high altitude detonation travel downward until they reach denser atmospheric layers at a height of 20 to 40 km, and in this pancake shaped zone , known as a deposition region the gamma rays strip current, which in turn produces a radially directed (and therefore propagating to the earth's surface) high altitude pulse of electromagnetic energy, Fig. (1) The pulse may attain a saturation value of about of 50 kV/m and its rise time is determined by a rise rate of the gamma flux, which is of the order of 10^{-8} sec.

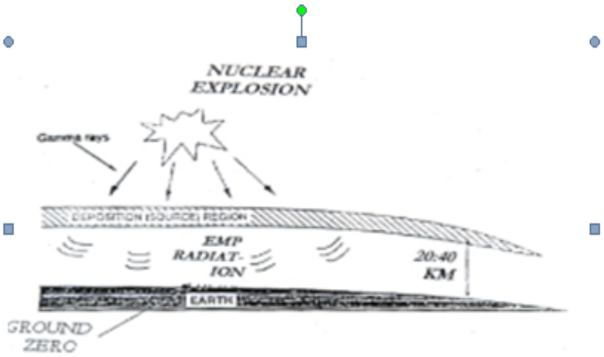

Fig. 1. NEMP Generation.

The early time incident pulse shape may be closely represented by a double exponential waveform as [1-4]

$$f(t) = E\left(e^{-\propto t} - e^{-\beta t}\right)$$

The typical pulse parameters are: $\propto = 6.10^{6} s^{-1}$, $\beta = 2.10^{8} s^{-1}$, $E_0 = 10^3 - 10^5$ KV/m.

β Corresponds approximately to the inverse of the rise time constant, and α corresponds approximately to the inverse of the decay time constant, and E_o equal approximately $5*10^5$ V/m for NEMP, Fig. 2.

The spectrum of NEMP is:

$$f(\omega) = E_0 \frac{(\alpha-\beta)}{(\alpha+j\omega)(\beta+j\omega)} \qquad (1)$$

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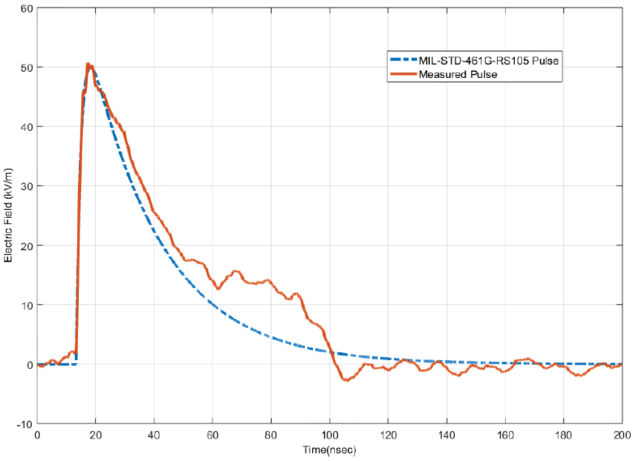

Fig. 2. The electromagnetic pulse.

2.1.2 NEMP Penetration Modes to Electronic Systems

The electromagnetic field induces currents and voltages in all sorts of conducting objects such as receiving antennas, transmission lines or through shields and the apertures there .Fig. 3. Coupling can take place through radar and broadcasting antennas, the resulting waveforms can take different amplitude, shapes, and durations [1-4].

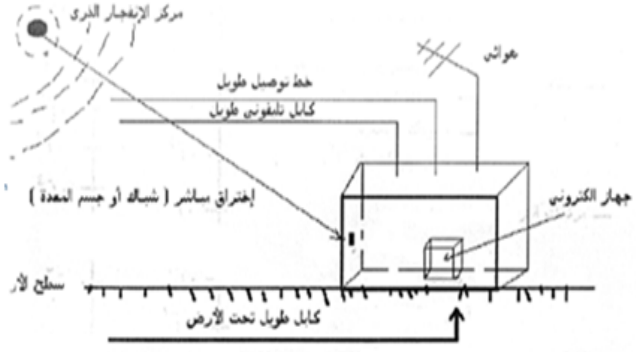

Fig. 3. Modes of EMP penetration.

2.1.3 Effects of NEMP on Electronic Systems

Effects of EMP on electronic systems vary in severity from circuit up set, latch up, to permanent damage.

a- Transient circuit upset

EMP transients, which are picked up by an electronic system and propagated into the electronics or electrical circuits, are generally short duration, damped sin wave with dominant frequencies, usually in the range of 100kHz to 100MHz. For example transients may trigger a flip-flop, counters can count, memory can be altered due to driving current or direct magnetic field effect resulting from transients, etc...Transient signal may also be amplified in electronic circuits and the amplified signals may be interpreted by the circuits as control signals. The sensitivity of digital circuits to upset for an arbitrary circuit can be estimated from the analysis of the circuit. The amount of energy required causing up set or cause erasure of the memory core is very small, in order of 10^{-9} to 10^{-8}.

b- Latch up

The latch-up is distinguished from upset since in latch up the circuit is not automatically restored, and the power into the circuit has to be removed for the restoration of the circuit. Latch up due to an NEMP–induced transient can occur when the transient flowing through the circuit causes a relay or a switch to latch up. A latch up can also occur within semiconductors.

C- Permanent damages

In addition to temporary circuit upsets and latch up, an electronic system can be affected almost permanently by NEMP coupled energy, particularly when such energy causes components burnout. There are various system components, which could be susceptible to burnout in an NEMP environment, the most sensitive of which are the semiconductors. NEMP–induced burnout can occur also for other circuit components, such as resistors, capacitors, inductors, transformers, relays, vacuum tubes, etc.

d- Protection against the nuclear electromagnetic pulse

Are inserted in parallel with the input TL, and when the strong NEMP signal appears they possess small resistance which diverts this signal to this low resistance path. These devices differ in their response time, power handling and stray capacitance, which limits Section 4 gives more details about protection.

2.2 Intentional Electromagnetic Environment (IEME)Threat

2.2.1 Classification of High Power Microwaves Threats

The high power microwave threats can be classified from different points of view. First they may be classified according to the source waveform bandwidth, namely narrow band and wide band waveforms [13]. A narrow band waveform is nearly a single frequency (typically a bandwidth of less than 1% of center frequency of power delivered over a fixed time frame (from 10 ns to microseconds)). Frequencies between 0.2 and 5 GHz seem to be the most concern. In terms of system vulnerabilities, the narrow band threat is usually one of very high power source, the electrical energy is delivered in a narrow frequency band. It's fairly easy to deliver fields on the order of thousands of Volts/meter at a single frequency.
The Wide band waveform is usually one in which a time domain pulse is delivered , often in a repetitive fashion .The term 'wide band' indicates that the energy in the waveform is produced over a substantial frequency range relative to the "center frequency" .The percentage bandwidth P_{bw} is defined as :

$$P_{bw} = \frac{f_{U}-f_{L}}{(f_{h}+f_{L})/2}\,100\ \%$$
(2)

f_l and f_h are the low and high frequency limits.

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A second type of classification is by type of effect [14. 15]. As discussed in relation to NEMP, the HPMW signal may penetrate to electronic systems through deliberate antennas that may be on the system, typical apertures, slots, holes and hatch openings having their resonances in the frequency range of 200MHz-5GHz, which are about a quarter to a full wavelength in this frequency range. At a frequency of ~1GHz, 10~100 of V/m of narrow band threat is required to cause an effect.

2.2.2 Technologies of High Power Microwave Sources

Different levels of technology exist; low, medium and high. Example of Low-tech generator systems is a microwave oven magnetron in the S-band (2.45GHz) with power rating of 800 to 1500 Watt of continuous microwave power. The peak electric field in the output wave guide is about 25kV/m.
Example of medium-tech generator system is a radar system modified to become a microwave weapon system.
High-tech generator systems require specialized and sophisticated technologies in their construction. An impulse radiating antenna IRA with a diameter of 23 cm is an example. which can be excited, e.g. with a commercially available pulsed voltage source (pulser) having a peak voltage amplitude of 2.5kV, rise time of 100ps, full width to half maximum pulse width of 2ns and a pulse repetition frequency of 500Hz [16].

2.2.3 Narrow Band HPM Sources

The source should be frequency stable (<1% bandwidth) and such sources tends to operate in the frequency range of (about 1GHz up to 3GHz) with high efficiency (>20%) [17]. Such HPM sources that meet these criteria are magnetrons, klystrons, and reltrons [18-20]. A relativistic magnetron source is good example, and it is commercially available with the following capabilities: Frequency: 1.1 GHz , Peak power : 1.8 GW (average power: 0.9 GW), Pulse width: 60ns
High power electromagnetic pulse generation techniques and high power microwave technology have matured to the point where practical electromagnetic bombs (E-bomb) are becoming feasible [21, 18]. Figure (4) shows the configuration of microwave bomb. The bomb produces very short (hundred of nanoseconds) but intense electromagnetic pulse, which propagates away from its radiating antenna with diminishing intensity. The pulse of energy produces a powerful electromagnetic field practically within the vicinity of the weapon burst. The field can be sufficiently strong to produce short transient voltage of thousands of voltage on exposed electrical conductors, which can result in irreversible damage to a wide range of electrical components.

2.2.4.1 The technology base for electromagnetic bomb

The technologies which are used in the design of electromagnetic bombs are diverse, and in many cases use explosively pumped Flux Compression Generators (FCG), explosive or propellant driven Magneto- Hydrodynamics (MHD) generators, excite a high power microwave device, the foremost of which is the virtual cathode oscillators or vircator. In the following, a description of these main two parts is given.

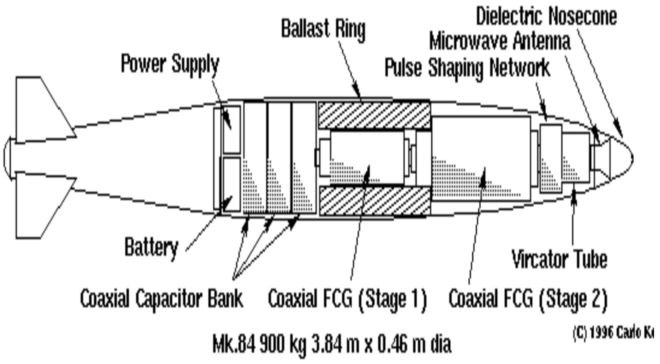

Fig. 4. Microwave bomb.

a. Explosively pumped flux compression generators

The explosively pumped FCG is the most mature technology applicable to bombs design [22] which generates a relatively long pulse to excite a microwave device (e.g. a vircator). A wide range of FCG configurations have been built and tested. The FCG is a device capable of producing electrical energies of tens of mega Joules in ten to hundreds of microseconds of time, in a relatively compact package. With peak level of order of Tera Watts, FCG may be used directly, or as one shot pulse power supplies for microwave tubes. The central idea behind the construction of FCG is that a fast explosive rapidly compresses a magnetic field, transferring much energy from the explosive into the magnetic field. The initial magnetic field in the FCG prior to explosive initiation is produced by a start current. The start current is supplied by an external source, such a high voltage capacitor bank (Marks bank). The basic principle of FCG operation may be illustrated on an idealized version of a plate generator, which will consist of a conducting rectangular box, with an input at the upper part, and a slab of high explosive on the upper plate. A current, usually supplied from capacitor bank, is passed through the input slot to develop an initial magnetic flux within the box. The explosive is detonated at such a time that it closes the input slot at a peak current, or a peak of magnetic flux within the box, and then continues to drive the top metal plate downward. A fundamental result from Maxwell's equation is that magnetic flux is conserved when bounded by a perfect conductor. As the top plate of the generator is driven downward, the area enclosing the flux is reduced, and thus, the average magnetic field must increase. A magnetic compressive pressure stress is established on the conductor. The magnetic pressure and the energy density of the magnetic field are both equal to $\frac{B^2}{2\mu}$ Pascals or $\frac{\text{Jouls}}{m^3}$.

b. The high power microwave source

Whilst FCG are potent technology base for the generation of large electrical power pulses, the output of the FCG is constrained to the frequency band below 1MHz. Many target

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sets will be difficult to attack even with very high power level at such frequencies, moreover focusing the energy output from such the device will be problematic. On the other hand, a high power microwave device output can be focused and it has a much better ability to couple energy into many target types. A wide range of high power microwave devices exist. Relativistic klystron, magnetron, slow wave devices and vircators are examples of the available technology base [18-20]. From the perspective of a bomb, the device of choice will be the vircator.

c-The Vircator

The Vircator is of interest because it is a one shot device capable of producing a very powerful single pulse of radiation, yet it is mechanically simple, small and robust, and can operate over a relatively broad band of microwave frequencies [18-20]. The fundamental idea behind the vircator is that of accelerating a high current beam against a mesh (a foil) anode, Fig. 4. Many electrons will pass through the anode forming a bubble. The space charge region will oscillate behind the anode, which under proper conditions, will oscillate at microwave frequencies. If space charge region is placed into a resonant cavity which is appropriately tuned, very high peak power may be achieved. Because the frequency of oscillation is dependent upon the electron beam parameters, the vircator may be tuned or chirped in frequency, where the microwave cavity will support appropriate mode. Power levels achieved in vircator experiments range from 170 kilowatts to 40 Giga watts over frequencies spanning the decimetric and centimetric bands. The most commonly described configuration for the vircator are axial vircator, Fig. 5, and the transverse vircator. The axial vircator is the simplest by design and has generally produced the best power output in the experiments.

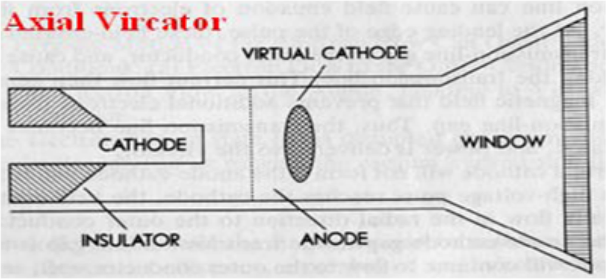

Fig. 5. Axial virtual cathode oscillator.

2.2.5 Common configuration of UWB antennas

The antenna is a main part of the high power microwave source. Antennas are required to be wide band [23].

2.2.5.1 Wide band dipole and derived configurations

A fat cylindrical dipole behaves like a wideband radiator because the capacitance between its arms is large and the inductance of its arms is small, thus the variation of its reactance with frequency is small and its transfer function becomes more flattened and the SWR is smaller. In addition to fat cylindrical dipoles, members of fat dipole family include bi-conical dipoles (which are very-wideband antennas), spherical antennas, triangular plates, V-conical antennas and bow-tie antennas.

2.2.5.2 TEM Horn

The TEM horn is one of the best known antennas for launching and receiving of UWB pulses. Figure (6) shows the basic TEM horn geometry. The TEM horn is a traveling-wave antenna and has no low frequency cutoff due to its TEM characteristics [24]. This antenna is characterized by nearly flat response and constant phase center. The transmitted signal of a TEM horn is nearly the first derivative of the input signal while the received signal is directly proportional to the shape of the incident pulse. TEM horn antenna has also directive properties where its maximum receiving is mainly focused along its axis. In order to suppress the reflection from the TEM horn edges, the antenna is commonly loaded with resistor or a conductive film .

The main disadvantages of TEM horn antenna are its large dimensions To reduce the size of the horn antenna, a dielectric wedge can be inserted between the plates of the antennas [25].

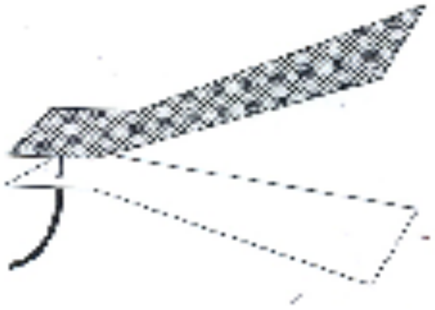

Fig. 6. TEM Horn Antenna.

2.2.5.3 Impulse Radiating Antenna

Impulse radiating antennas (IRAs) are a class of antennas that consist of a TEM feed section and either a lens or reflector to focus the aperture field [23]. They are widely used for radiating wideband HPM signals.

3. Results for electromagnetic pulse penetration to antennas.

3.1 used analysis

Resonant antennas are considered, namely the dipole antenna and the microstrip antenna. These antennas are widely used which have clear resonance frequencies, which enable the use of the singularity expansion method for studying their transient response in terms of their natural resonance frequencies [26].

3.1.1 Singularity expansion method (SEM)

The SEM has the advantage that once the antenna natural modes are obtained one can solve different excitation problems in a simple and fast way using a few numbers of natural modes [26]. Such transient problems include exciting the antenna with different waveforms (either as a transmitting antenna or a receiving one) and with different angles of incidence of a plane wave. The solution is particularly simple after the early time period when the incident wave has traversed the antenna**.**

In SEM method the transient excited current on an antenna can be obtained mainly in terms of the natural damped sinusoidal modes of the antenna, whose Laplace transform is expressed

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by simple poles, with additional polynomial and entire functions of s, whose contributions can be usually neglected. Such modes correspond to the resonant conditions of the antenna. The Laplace transform of the excited current contains mode coupling coefficients, expressed as an integral on the antenna surface of the dot product of the incident field and the mode current. If the incident wave is taken as a damped sinusoidal wave, the Laplace transform of the damped sinusoidal waveform is expressed by two poles, thus these forcing damped sinusoids appear in the time domain solution (obtained by inverse Laplace transform) together with the damped sinusoids of the natural modes of the antenna. The complex natural frequencies of least damping have real frequencies nearly equal to the resonance frequencies of the antenna in the frequency domain, with attenuation constants usually increasing for the modes with the higher resonance frequencies.

3.2 Transient response of dipole antenna using SEM method

Consider an incident plane wave with damped sinusoidal time dependence, given by

$$E(t) = 2E_0 \cos(w_K t) e^{-\sigma_k t}$$

(3)

where w_k is the radian frequency and σ_k is the damping constant of the incident wave. The Laplace transform of E(t) is (with $E_0=1$)

Where * denotes the complex conjugate and a = J w_k - σ_k

If the plane wave is obliquely incident on the dipole with an angle θ with the z- axis, the wave front arrives at a point z on the dipole after a time delay .

$$T = \frac{z\cos(\theta)}{c}$$

(4)

The damped sinusoidal wave can be used to represent a high power microwave signal and can be reduced to the EMP signal.

3.2.1 Dipole natural frequencies

The basic natural modes of the dipole having minimum damping, which are required for solving transient problems [27, 28], are obtained in a simple way by using the FDTD method. The modes are obtained by exciting the antenna with a transient plane wave containing a frequency spectrum concentrated near the frequency of the required mode and with a spatial field distribution similar to that of the required mode current. After the transient excitation has died out, the excited antenna oscillates in the intended mode with an exponentially damped sinusoidal waveform, which is used to find the mode complex frequency. By such proper choice of the temporal and spatial distribution of the exciting waveform, each of the resulting modes becomes highly pure, i.e. least contaminated by other modes.

3.2.2 Dipole response to an incident NEMP

An NEMP can be approximated by the double exponential waveform [29]

$$E = E_0\left(e^{-\alpha t} - e^{-\beta t}\right)$$

Where $\alpha =$ 1.6*10^{6} sec^{-1}, $\beta =$2.6*10^{8} sec^{-1}

The Laplace transform of E is

$$E(s)/E_0 = \frac{1}{s+\alpha} - \frac{1}{s+\beta}$$

A dipole loaded with 75 ohm is then considered. Fig (7a, b) shows the transient current for dipoles of different lengths resonating at different frequencies [30]. It can be seen that the dipole current decreases as its resonance frequency increases. At high dipole resonance frequencies, Fig.(7b), the weak forced excitation by the double exponential NEMP waveform begins to dominate the current natural oscillations. The decrease of the current may be attributed to both the decrease of the effective dipole length and the decay of EMP spectrum.

3.2.3 Incident damped sinusoidal plane wave

High power microwave weapons use few cycles of microwave frequency in order to penetrate devices operating at microwave frequencies. Here we use a damped sinusoidal incident plane wave to investigate such conditions. In order to investigate dipole response to an incident plane wave of short period (wide spectrum), we use a large damping constant σ_k=1.9*10^{10}, which equals the inverse of the damping time constant of the sinusoidal wave envelope. If the frequency of the sinusoid is low, the high damping constant makes the waveform to be nearly an impulse.

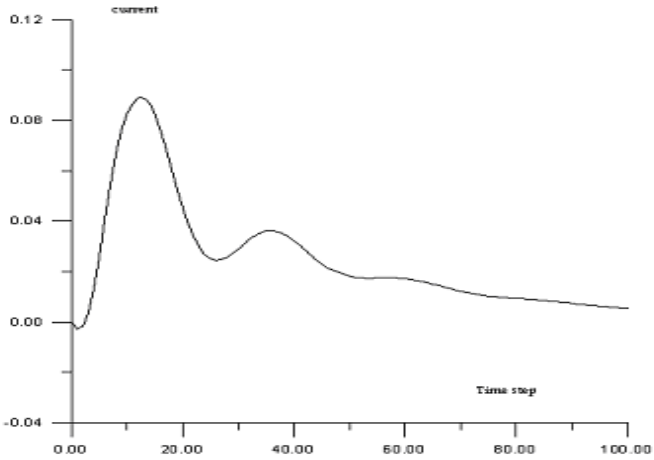

Fig. 7-a. Dipole of nominal resonance frequency of 500MHz

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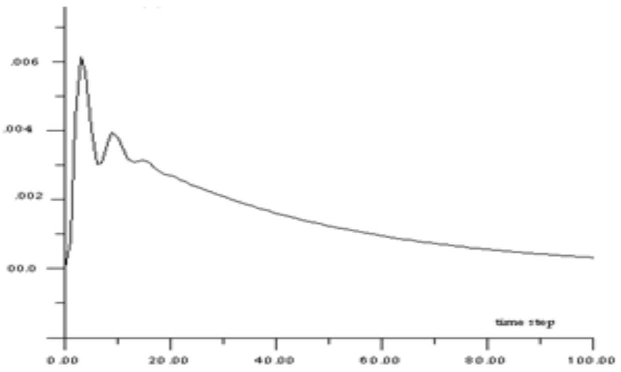

Fig. 7-b. Dipole of nominal resonance frequency of 2GHz.

A dipole of length 2.5 cm (nominally resonating near 6 GHz) is considered with incident plane waves of different frequencies (f_k=1GHz, 5GHz, 10GHz), normally incident on the dipole axis. Fig.(8) shows the dipole responses. In Figs.(8a,b), with f_k=1 and 5 GHz, the first natural mode of the dipole is excited. However, in Fig.(8b), the second and third peaks are higher than in Fig.(8a) since the frequency of the incident wave is near the dipole resonance frequency. In Fig. (8c), (f_k=10GHz), contributions of the third natural mode are noticed. It can be seen that the peak amplitude of the excited current varies slightly with changing the frequency of the incident wave. This can be attributed to the wide spectrum of the short period incident wave. The peak excited current in a dipole is thus expected to be mainly proportional to its length when a short high power microwave pulse (with wide spectrum) is incident on the dipole.

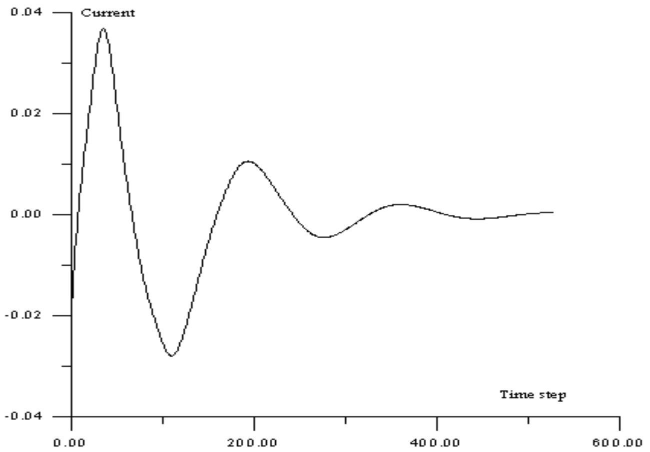

Fig. 8-a. Computed transient current (Amp) at the center of a dipole of length 2.5cm loaded with 75 Ohm due to a damped sinusoidal wave (E_0=1000V/m, Δt =1.2*10^{-12}sec.),f_k=1GHz.

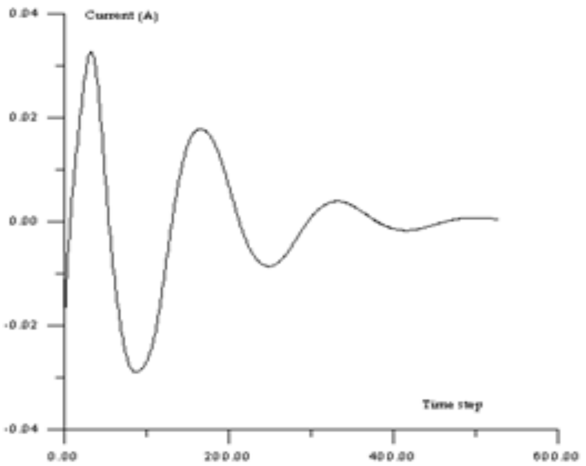

Fig.8-b. fk=5GHz.

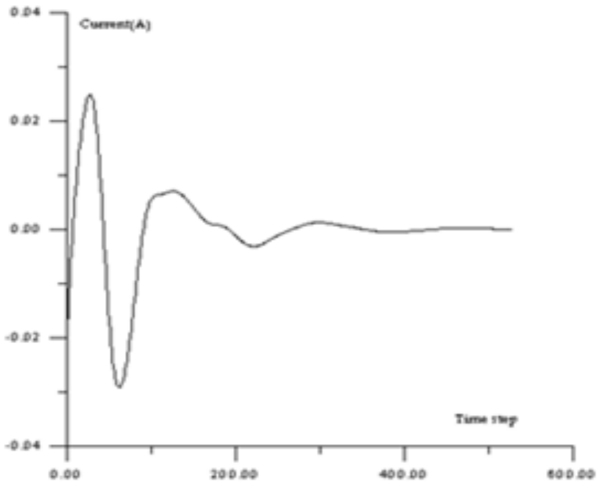

Fig. 8-c. f_k=10 GHz.

3.3 Transient Response of a Square Microstrip Patch Antenna to an Obliquely Incident Plane Wave Using T.L. Equations and Natural Modes

The transient response of a rectangular microstrip patch antenna was obtained by considering the patch antenna as a transmission line (TL) excited by a plane wave [31]. In Ref. 32, the analysis of [31] is extended to the case where the incident wave spectrum covers the resonance frequencies of some of the antenna modes. The time domain TL equations are solved using the complex natural modes of the microstrip patch antenna, where the Laplace transform is used in a way similar to that used in SEM method. The complex natural frequencies are obtained in a simple way as described for dipole antenna [30] using the FDTD method . For the lower order modes the antenna oscillates in nearly one mode, from which the natural frequency and damping factor are obtained. For higher order modes more than one mode become excited. The natural frequencies and damping factors are obtained using Prony's method which is used to decompose a transient wave into sinusoidal waves with exponential damping. Once the natural complex modes are obtained, the transient response can be obtained in a very short time for different excitation waveforms and angles of incidence.

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3.3.1 analysis of the microstrip patch antenna current for an obliquely incident plane wave with damped sinusoidal time dependence

Consider a square microstrip patch antenna on a grounded substrate of thickness 'h', Fig. (9). A transient plane wave is incident on the microstrip antenna where its electric field and plane of incident lie in the x-z plane and the direction of incidence makes an angle θ with the z- direction.

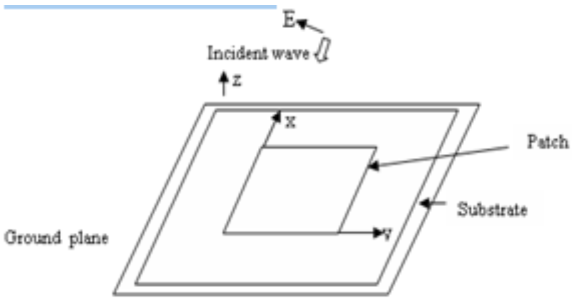

Fig. 9. Plane wave incident on a microstrip patch.

To consider certain mode, a plane wave is used to excite the patch antenna with approximate frequency and spatial distribution of field along the patch as the mode current required to be excited, having the form:

$$E_i = E_0 \sin(\omega_{n.} t)\sin(\frac{\omega_n t}{8})\sin[\frac{n\pi}{a}x]$$

In order to limit the period of the incident plane wave, a few cycles of the natural frequency ω_n are used, modulated by a half sine wave of a lower frequency (ω_n /8 in the equation), in order to make the field continuous with time, thus the spectrum of this wave becomes concentrated around ω_n, so the other natural modes are only negligibly excited. After the termination of this excitation, the current oscillates on the patch antenna mainly with the intended natural mode.

3.3.2 Microstrip patch antenna response to an incident damped sinusoidal plane wave

The microstrip patch antenna (with first mode frequency near 6 GHz) is considered with incident plane waves of different frequencies ω_k , with different angles of incidence on the microstrip patch antenna [33]. Figures (10, 11) show the total current responses at the center of the microstrip patch antenna (x=a/2) with f_k =5 GHz and angles of incidence of 0°, 45°. Figures 11, 12 show results at f_k = 10 GHz at the same angles of incidence A comparison is made in the figures between the solution obtained using the present method and the solution using the FDTD method, and reasonable agreement is found. The first natural mode of the patch antenna is clearly dominant at f_k = 5 GHz because the excitation frequencies are far from the frequencies of the higher order natural modes. For angle of incidence of 0° only odd modes are excited.

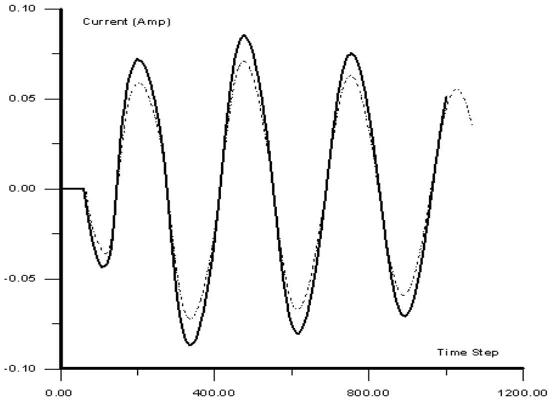

Fig. 10. Computed transient current (Amp) at the center of a patch antenna due to damped sinusoidal wave (E_0 =1000V/m, f_k=5GHz, Angle of incident θ = 0°) (dashed line: present method, heavy line: FDTD),(time step dt=5.8e-13 sec.)

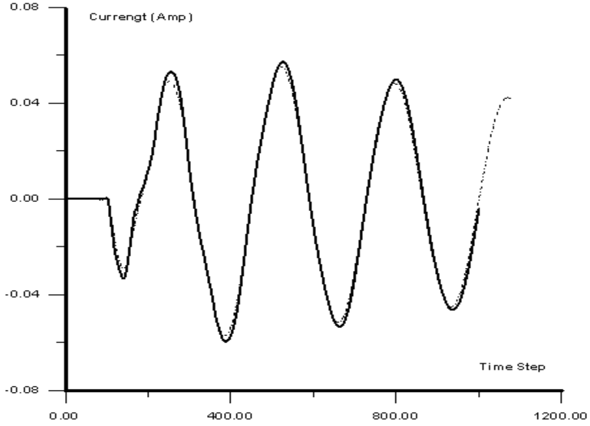

Fig. 11. f_k =5GHz, θ = 45°, other parameters as Fig. 10.

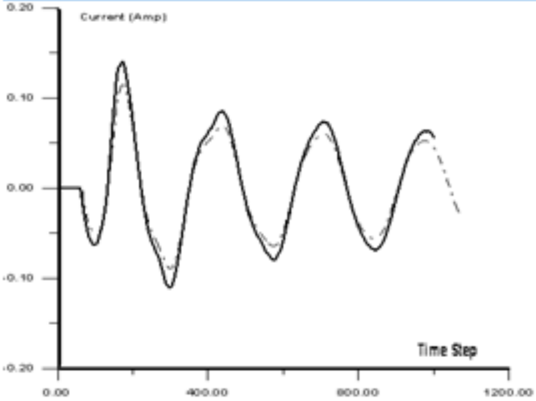

Fig.12. f_k = 10GHz, θ = 0°, other parameters as Fig. 10.

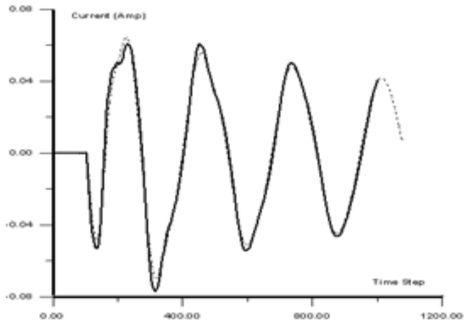

Fig. 13. f_k = 10 GHz, θ = 45°, other parameters as Fig. 10.

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4. Protection from UWB pulses

Protection methods include shielding, grounding, filtering and using suppressing nonlinear elements.

4.1 Shielding

An obvious method of denying the penetration of EMP energy into a system is to provide shielding by a continuous metallic enclosure .In an idealized shielding enclosure , the reduction of EMP field strength is determined primary by the reflection loss at the outer surface where the EMP field impinges on the enclosure, and the exponential attenuation of the field that occurs during its penetration through the shielding material due to skin effect. A metallic enclosure can provide protection to any arbitrary level, when appropriate thickness of the shielding material is provided. Shielding, therefore, could be an effective tool to minimize system vulnerability [3].

4.2 Grounding

The accepted purpose for grounding is to give a reference for external connections to the system [5] .An alternative definition for a ground is a low impedance path by which the current can return to the source .The most important EMC function of a ground system is to minimize interference voltages at critical points compared to the desired signal .To do this it must present a low impedance path at these critical locations.

4.3 nonlinear components suppressing UWB pulses

Nonlinear protection elements like spark gaps, varistors or Zener diodes are used to protect electronic systems against conducted transient natural or man-made electromagnetic interferences with high energies and amplitudes, like lightning electromagnetic pulse, nuclear electromagnetic pulse or electrostatic discharge pulses. The nonlinear device is connected between the feeding transmission line wires preceding the circuit to be protected. The nonlinear behavior of these elements is such that the device impedance is high with no strong applied signal, i.e. it behaves as an open circuit. Its impedance decreases with increasing the amplitude of the applied signal such that it short circuits the incident high level signal to protect the circuit.. This reduction of the impedance is either abrupt at certain signal level, as for the gas discharge tube or the Zener diode, or gradual as for the varistor. The response of such protection elements to ultra wide band (UWB) pulses with significant amplitudes and rise time in picoseconds were investigated to determine whether traditional protection concepts provide sufficient protection against such extremely fast pulses [34].

In general, it can be distinguished between the protection of power lines and transmission lines with high frequency signals. For protecting power lines and low frequency transmission lines, spark gaps, varistors and feed through capacitors are used. For protection of high frequency transmission lines, components with only small additional parasitic capacitance and inductance are used as Zener diodes and Band pass filters.

4.3.1 Protection of power lines

a. Spark gaps, gas arrestors

If we assume a typical UWB pulse with a rise time of 150 ps , a pulse duration of 2.5ns and a voltage amplitude of about 700 V this gives an energy of 16.6 J at a 50 Ohm resistance .The tested spark gaps (Epsos90, Citel 230) do not show any protection behavior against UWB pulses with the described characteristics**.** At much higher voltages above 10 kV a breakdown can be noticed, but there is no significant voltage reduction and only a pulse shorting.

b. Varistors

In general, there is a tradeoff between the energy absorption and capacitance of a varistor. The higher the energy capability of the varistor, the higher is the parasitic capacitance. In combination with transmission line inductivities, varistors show low pass behavior .Therefore, they are mainly used in low-frequency applications. At frequencies higher than 500 MHz there is nearly no attenuation of the pulse. The response times of varistors are typically in the nanosecond range. There is a significant reduction of overall energy content of the interfering pulse due to the varistor, but the rising edge of the pulse has not been influenced. The time response with reduced voltage amplitude of the UWB pulse shows very similar results and therefore the behavior of the varistor in not nonlinear in nature. Linear effects caused by the capacitance and lead inductivities of the varistor are causing the resulting time response.

4.4 Feed through capacitors

Feed-through capacitors have a low pass character. At high frequencies they start to short circuit the signal (cutoff frequency), so these elements can be used in applications with frequency up to several megahertz and especially for the protection of dc power lines .The capacitance has a voltage limiting effect on the UWB pulse. The capacitor with the largest capacitance has the lowest cutoff frequency and the best pulse suppression**.** This gives again the tradeoff between protection level and bandwidth.

4.5 Protection of high frequency transmission lines

4.5.1 Zener diodes

Zener diodes are used in traditional EMP protection circuits as fine protection in combination with spark gaps or varistors. When comparing protective components, Zener diodes have the fastest response, but they can withstand high voltage pulses only for a limited time. For shorter pulses diodes can be used as a single protection element. Two diodes can be used to suppress pulse of the two polarities.

4.5.2 Linear filtering

In recent years, linear filters found applications in form of EMP–suppressors in mobile telecommunications substations GSM 900 and GSM1800 band or Bluetooth and wireless in ISM band (industrial, scientific, medical). The main request on the filter is to suppress the interference as good as possible without changing the wanted signal. A bandpass filters can be

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used in high frequency applications against broadband interferences

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