System Design and Assessment Notes

Note 28

1984

Hardening of Telecommunication Networks against Electromagnetic Pulses

MANUEL W. WIK
DEFENSE MATERIEL ADMINISTRATION
ELECTRONICS DIRECTORATE
S 11588 STOCKHOLM
SWEDEN

ABSTRACT

Nuclear explosions at high altitudes generate strong electromagnetic pulses (EMP), which can induce large currents and voltages, for example in power and telecommunication networks over a whole continent simultaneously.
The author describes the increasing EMP threat and why it concerns telecommunications administrations and the electronics industry. He also describes the generation mechanisms and pulse waveform. The EMP impact on telecommunication facilities is discussed, together with hardening and testing methods.

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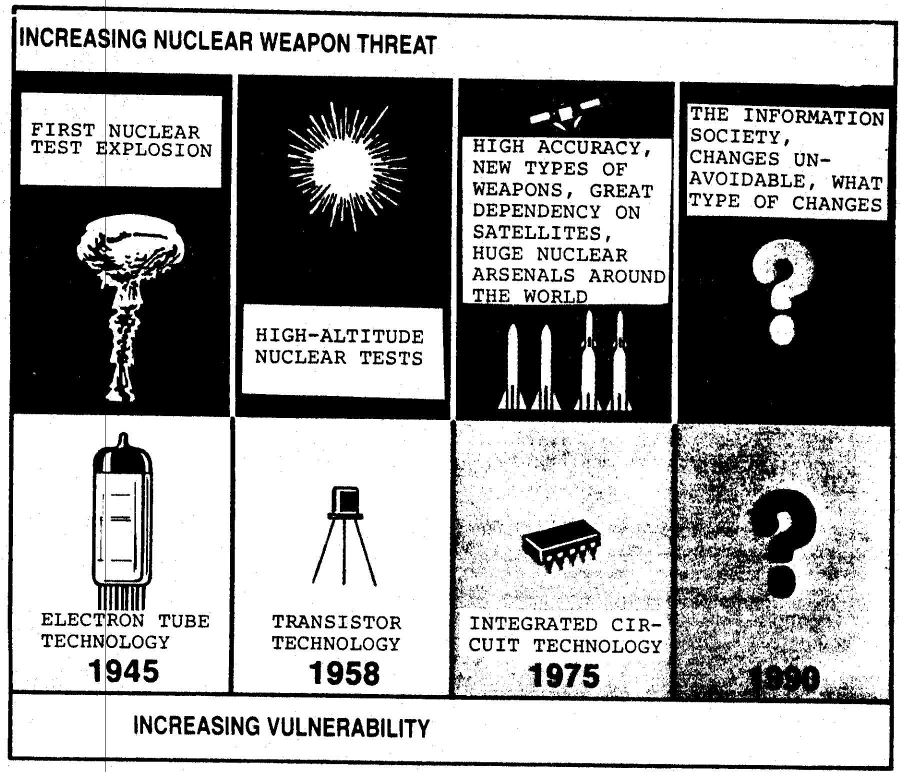
MANUEL W. WIK
The Defence Materiel Administration of Sweden
Electronics Directorate
Stockholm

Fig. 1
Diagram showing the increasing EMP threat posed by the development of nuclear weapons technology and electronics



Nuclear explosions can generate very strong electromagnetic pulses (EMP, or nuclear EMP = NEMP). Such pulses can in certain cases dominate over other more well-known effects, such as nuclear and thermal radiation, blast and shock. For high altitude explosions (above 30 km) EMP is practically the only effect apparent at ground level, and the following description is mainly concerned with this case.

A nuclear EMP can roughly be compared to the electromagnetic field very close to a lightning stroke, but the field can extend much further and cover whole countries. It also has a broader frequency spectrum covering the whole radio frequency communication band. Currents and voltages are induced in metallic objects. Large aerial or buried power and telecommunication networks can absorb considerable amounts of energy and be damaged, but even short radio antennas and other lines can be sufficient to cause serious damage to the connected equipment. Consequently telecommunications administrations and electronics designers – civil as well as military – have every reason to consider the problems posed by EMP.

The threat

The continuous development of nuclear technology over the years has resulted in new generations of nuclear devices and weapon systems. Outer space has become increasingly important as satellites having important tasks in communication and surveillance have been launched. Intercontinental ballistic missiles (ICBM) with nuclear warheads have been programmed for high trajectories, and so have other weapons intended to combat ICBMs. All in all the probability of nuclear explosions at high altitudes (tens to hundreds of km) has increased considerably.

In 1963 the limited test ban treaty came into force, which prohibits atmospheric nuclear test explosions. Before that time both the US and the Soviet Union had started to carry out test explosions at high altitudes. It was then discovered that the nuclear EMP effect, which was already known from explosions closer to the ground, occurred with great intensity over enormous areas at ground level. The information was classified as secret, and after the test ban agreement the superpowers were confined to theoretical calculations and simulations. However, some information leaked out, such as the following newspaper report about a US high-altitude test over the Johnston Island in the Pacific Ocean in 1962:

– The quiet predawn in Honolulu was shattered by the simultaneous pealing of hundreds of burglar alarms. At the same time circuit-breakers on the power lines started blowing like popcorn. Not a cloud in the sky, so lightning could not be blamed. The power company failed to trace any gigantic electrical surge able to blow out virtually the entire systems simultaneously. The mystery was solved later – then promptly sealed under a "top secret" stamp. The culprit: A high altitude nuclear test burst more than 500 miles away.

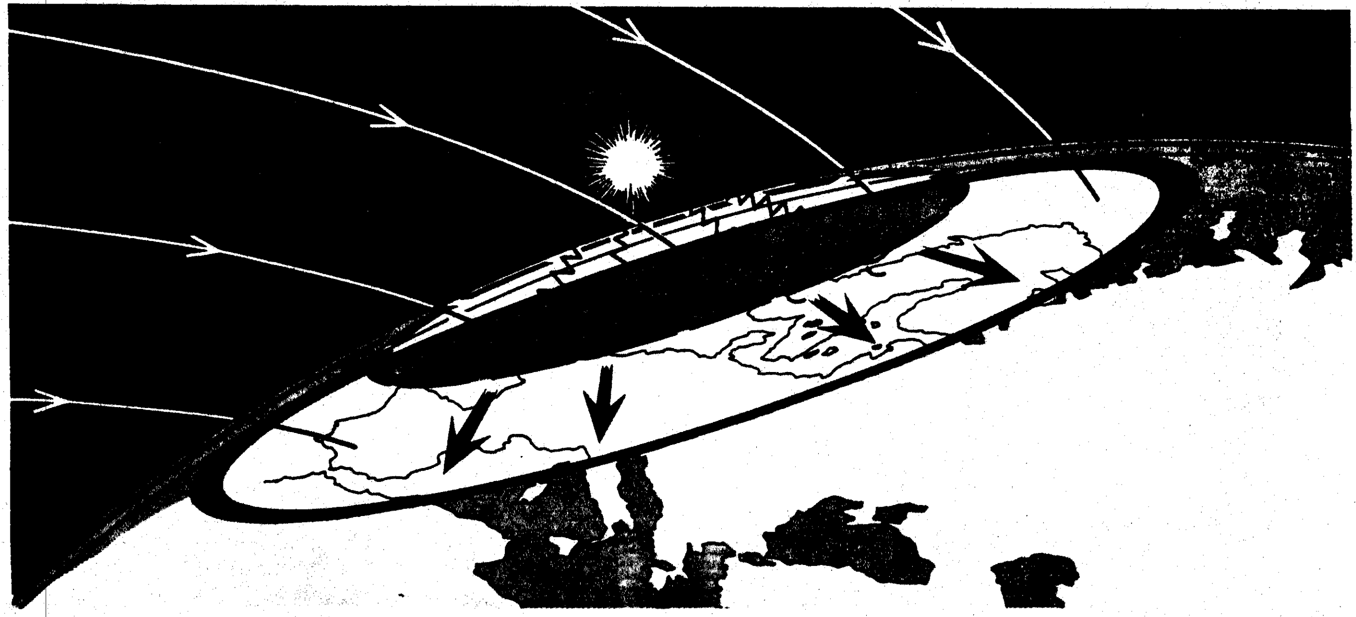
More than twenty years have passed since then, and society has developed and changed in such a way that the nuclear EMP threat has grown. The development in electronics has gradually led from transistors to large and very large-scale integrated circuits (LSI, VLSI) that work with low signal and power levels in the range 10^{-3} to 10^{-8} W per transistor. Susceptibility thresholds are increasing and the pulses and energy surges need not be very high in order to cause damage (junction burnout), only of the order of 10^{-3} to 10^{-6} J.

At the same time society has become much more dependent on electronics. For example, telecommunication networks, high-voltage power supply networks, railway networks, air traffic, water supplies and process industries are all controlled and regulated by equipment which usually contains susceptible semiconductor components. The increasing anxiety about nuclear EMP has recently been mirrored in the increase in newspaper articles and TV reports on the subject.

The greater vulnerability makes EMP attacks more attractive. It is quite possible that special EMP weapons already exist. An attacker could find it profitable to start military operations with an EMP attack. This would create such chaos that subsequent measures would be more effective and counter-offensives made more difficult. A high-altitude explosion can be triggered at a large distance from the borders of the country to be attacked and still have a great impact on that country. The country attacked might not even realize that a nuclear explosion had occurred, let alone who set it off. With a high-altitude explosion (at above 30 km) effects other than EMP could be negligible at ground level, and perhaps be impossible to detect without special equipment.

Large sums have been invested in EMP protection. Ten years ago the US was spending over 250 M US$ a year on EMP protection and testing. In October 1981 president Reagan stated that the US defense project with the highest priority was not the MX system or the B1 bombers but "to strengthen and rebuild our communications and control systems –

Fig. 2
An example of the impact area of EMP from a high-altitude nuclear explosion over Europe



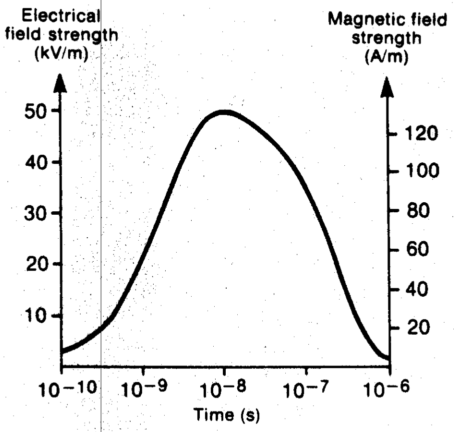


Fig. 3
The electrical and magnetic EMP field from a high-altitude explosion, plane wave and horizontal polarization. The time dependency is generalized

a much neglected factor in our strategic deterrent". 20 billion (10^9) US$ was earmarked for this project, a large part of which is intended for EMP hardening. In the Soviet Union EMP protection has even been provided for facilities of less than top priority for about 20 years.

Telecommunication networks that still function after high-altitude explosions are vital if diplomatic and political communication between nations is to be possible so as to avoid the military escalation of a limited nuclear confrontation into a total nuclear war. In the case of a nuclear war elsewhere a country needs a working telecommunication network, partly in order to be able to collect and process weather and nuclear radiation reports. It must be possible to inform the population of the country about the situation if chaos and exposure to nuclear radiation are to be limited. This could save many lives. Without a secure telecommunication network it would also be very difficult to rebuild and reconnect the country's electric power system before chaos arises and spreads. Disruption of electric power would seriously affect pumping of water and fuel supplies, and many other vital functions.

The generation of nuclear EMP

From a nuclear explosion an intense gamma radiation pulse propagates at the speed of light. The gamma radiation consists of photons (radiation quanta) which collide with air molecules or other matter and release free electrons. The so-called Compton electrons leave positively-charged ions behind and move on in the direction of propagation. They are slowed down by collisions, and each Compton electron thereby generates tens of thousands of secondary electron-ion pairs. The charge separation causes a strong electric field and the charging movements produce a current.

For explosions close to the ground, conditions are strongly asymmetrical. There is a net electron current with a strong upward component from ground zero. Electrons travelling outward in the air from the burst return toward the burst point through higher-conductivity ground and ionized air paths. The current loops generate very large azimuthal magnetic fields. For exo-atmospheric explosions Compton electrons are not generated until the gamma rays that travel downward reach the denser atmospheric layers, at a height of 20 to 40 km above ground. This is known as the deposition layer. The electrons encounter the earth's magnetic field and are deflected, producing a transverse electric current. This results in electromagnetic radiation which is directed radially out from the explosion point, adding in phase. This EMP has a tremendous coverage. In the case of large explosion yield, the higher frequency part of EMP extends to the horizon. The lower frequencies will follow along a duct between the earth and the bottom of the ionosphere as well as along the surface of the earth far behind the horizon. For example, with a height of burst of 100 km, large parts of Europe could be covered (impact radius approximately 1200 km along the surface of the earth; 400 km altitude would give a radius of approximately 2200 km). The EMP effect would be noticeable even outside this area.

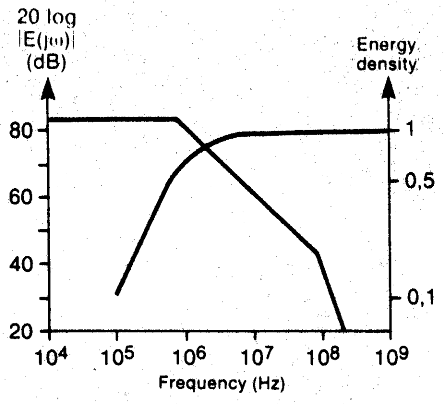


Fig. 4
The spectrum of the electrical field and the corresponding normalized cumulative energy density of EMP from a high-altitude explosion

Magnitude of the EMP

The EMP from a high-altitude explosion consists of a plane wave (E/H=377 ohms), which is propagated along the line of sight from the explosion point. The E and H fields are perpendicular to each other and to the direction of propagation. A part of the pulse is reflected by the ground, and the rest is propagated into the ground and is gradually attenuated. The strength and polarization of the field vary within the impact area due to various factors. Vulnerability and

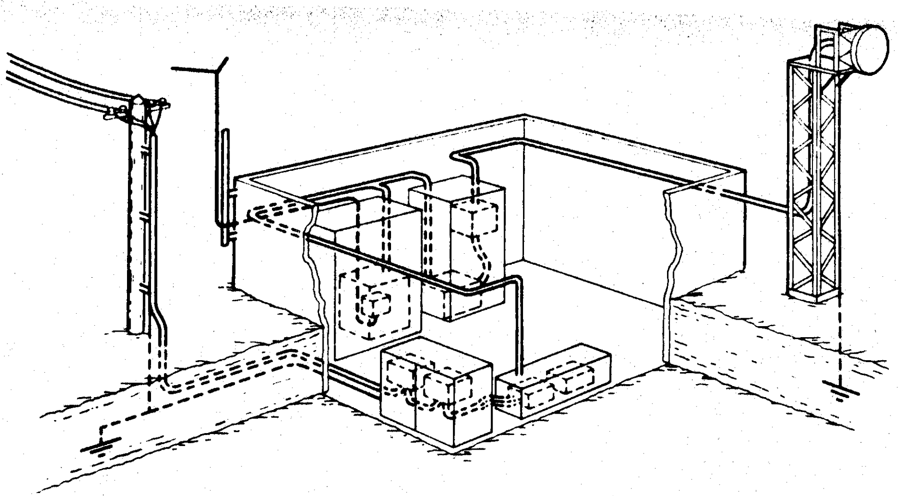


Fig. 5
Simplified picture of a communication installation with internal and external cabling

hardening calculations are often based on an electromagnetic field in free space before reflection, in accordance with fig. 3. The high amplitude (50 kV/m) and the short rise time (5 ns) are of particular importance for the effects. For comparison purposes it may be mentioned that a field amplitude of approximately 200 V/m is obtained near radar stations and approximately 0.01 – 0.1 V/m in urban areas. A generalized, time-dependent E field is often given as

$$E(t)=5.25\times10^4\times(e^{-4\times10^6 t}-e^{-4.76\times10^8 t})$$

Fig. 4 shows the frequency spectrum of the pulse. The energy density in this case is 0.9 J/m², and 99.9 % of the total energy lies below 100 MHz.

The effect on telecommunication facilities

Generally speaking the electromagnetic field induces currents and voltages in all sorts of conducting objects, which act as antennas, intentionally or unintentionally. The induced energy can find its way to connected objects where it is dissipated as heat, in some cases in combination with flash-overs. In a widespread network, pulses will be able to destroy or interfere with connected devices almost simultaneously in a number of places. The conductors can be compared to magnifying glasses which gather solar energy and focus it on points where heat is concentrated to such an extent that it is destructive. EMP energy is transmitted primarily by means of electromagnetic coupling (radiated field) and secondarily through galvanic coupling, inductive coupling ($u = M \times di/dt$) and capacitive coupling ($i = C \times du/dt$). In view of the circumstances all paths must be considered as risks. The current and voltage rise rates are considerable.

In order to give a more detailed picture of the EMP effects a communication facility with a microwave radio tower, fig. 5, is used as an example. This model is not necessarily typical, but is used to make the description more concrete.

The large external conductors are the power mains, telephone cables, antenna cables, waveguides and antennas. In addition there are large metal structures such as microwave radio towers, grounding conductors, fences, reinforcing netting in concrete walls, as well as air conditioning, water and sewage installations in the building. The building also contains internal cabling with electric power and telephone lines and cable ducts, racks and power and telecommunication equipment.

This model can be represented by a topological diagram as shown in fig. 6. The external environment includes air and ground.

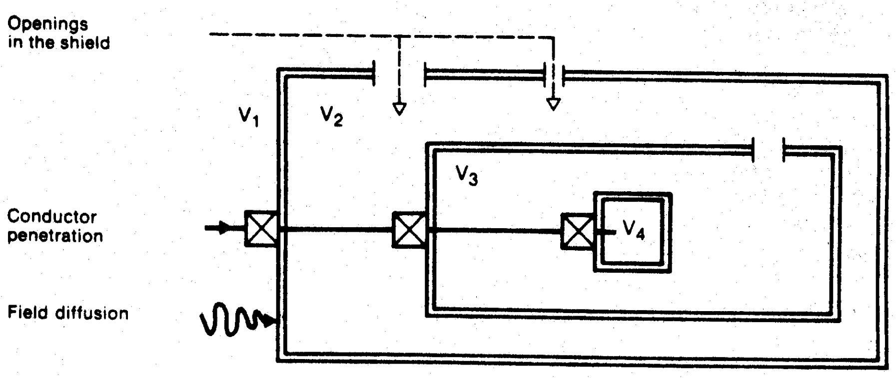
Fig. 6
A topological diagram

Volume	External boundary	Attenuation	Total
V_1	Air	0	0
V_2	Concrete	20 dB	20 dB
V_3	Shielded cabinet	20 dB	40 dB
V_4	Shielded unit	20 dB	60 dB

-⊠- **Transient protection**

‖ **Shielding boundary**

— **Penetrating conductor**



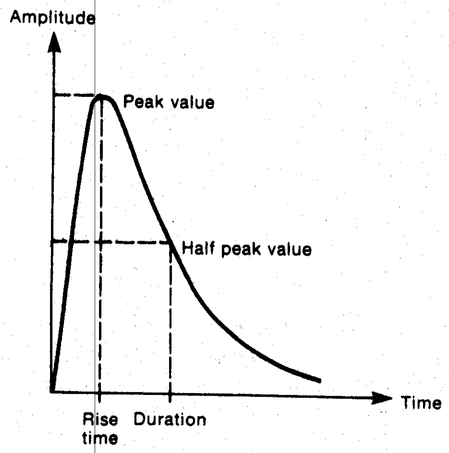
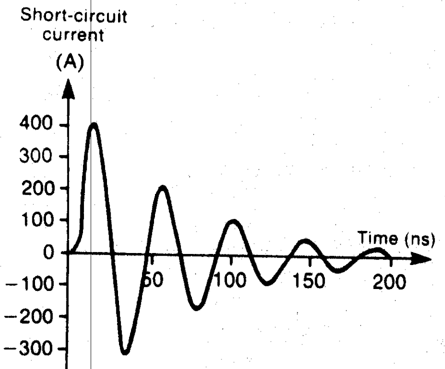


Fig. 7
Double exponential pulse waveform from induced currents in aerial and buried cables caused by EMP from a high-altitude explosion. If the lines are long, the pulses can have long decay (not included in the table below)

		Aerial line	Buried cable
Peak current	kA	5	1.5
Rise time	µs	0.1	0.1–0.5
Time to half value	µs	1	1–5
Rate of rise	kA/µs	50	15

Fig. 8
Short-circuit current for a 3 m long monopole antenna excited by an EMP field in accordance with fig. 3



Overhead power lines and telephone cables are severely exposed to EMP. The voltage to ground can be between 10 and 1000 kV and is limited primarily by the insulation resistance. The current is limited by the characteristic impedance of the conductors, which can be a few hundred ohms. At discontinuities, for example a transition from an overhead to a buried cable or to a transformer connection, strong pulse reflections occur. Buried cables obtain a certain amount of protection from the ground and cable sheath, and the induction is therefore less than for overhead lines. Fig. 7 gives some examples of EMP values for overhead and buried cables. The pulses have a double exponential waveform. Antennas and other short conductors that are exposed to EMP respond with an oscillating current and voltage, determined by the natural resonant frequency of the antenna or conductor. The oscillation has an exponential decay. Fig. 8 shows an example of a 3 m monopole antenna. Fig. 9 gives the voltage, current and energy as a function of the resonant frequency for excitation of conductors that can be considered as monopole antennas. The microwave radio tower in fig. 5 also acts as a large antenna, and peak currents of the same magnitude as for overhead lines can be induced. The long overhead lines and the microwave radio tower thus give rise to the largest induced currents, and buried lines to somewhat lower currents.

The conductors carrying the induced currents penetrate the building. The EMP field can also penetrate the building, through openings and, with some attenuation through the roof and walls. This field causes induction in the internal cabling. Concrete walls can attenuate the field by between 5 and 35 dB depending on their construction, the size of the building, frequency etc. If the building is equipped with a Faraday cage made of steel sheet the field attenuation can be some 50 to 100 dB. The higher frequencies are attenuated more than the lower, which makes the internal pulse rise time longer. However, the resultant attenuation is strongly dependent on how the shield penetrations are implemented.

The residual field can induce currents of the order of 1 to 20 A on internal cabling. But large currents entering via a lead-through can induce higher values in other cables which run parallel. The currents in the internal cabling can be a damped oscillation of between 1 and 10 MHz and with a time constant of between 1 and 10 µs, cf. fig. 8.

Reduction of induced pulses on conductors largely depends on whether the conductors have been equipped with some form of transient protection (surge arrester, gas tube spark gap, filter etc.), and on the design of the potential equalization. Special power conversion equipment (e.g. rectifiers and d.c./d.c. converters with accumulators) can in favourable cases provide attenuation of some 35 to 70 dB. Specially screened isolating transformers, in combination with filters, can provide even higher attenuation. If good protection is to be ensured, power supply lines must be shielded or at least installed at a considerable distance from other installations. It must also be ensured that other conductors do not form loops that can be closed by flash-overs.

The internal cabling terminates in various kinds of equipment cabinets. At best these can provide electromagnetic shielding, but whether the shielding is effective depends to a great extent on the cabling and how it is terminated. Inside the cabinet there is the equipment wiring, which leads to printed board assemblies and similar modules. In the best designs these are screened and the wires are terminated satisfactorily from an electromagnetic point of view, but often this is not a rigorous requirement. The equipment power supply can in favourable cases provide good supplementary attenuation of external transients. Finally the wiring on the printed board assemblies, in its turn, is terminated in components. However if the latter consist of integrated circuits there is a still lower level of wiring and components.

Knowledge of the threshold levels of the equipments and components for functional damage and operational interference is necessary in order to be able to assess the possible effects of EMP. The induced EMP energy must be compared with the energy threshold failure level of each component in order to esti-

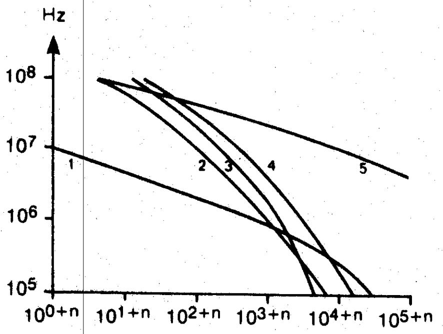


Fig. 9
Estimated voltage, current and energy as a function of the resonant frequency ($f = c/4l$, where c is the speed of light and l is the line length) when conductors that can be considered as monopole antennas are excited (field in accordance with fig. 3)

Curve		Abscissa, n =
1	EMP energy dissipated in a 50-ohm load (J)	0
2	Short-circuit current (A, peak value)	1
3	Open-circuit voltage (V, peak value)	3
4	Voltage across a 50-ohm load (V, peak value)	2
5	EMP energy dissipated in a 50-ohm load (J)	− 4

For example, for a conductor with a resonant frequency of 100 MHz:

- **the peak short-circuit current is 50 A**
- **the peak open-circuit voltage is 15 kV**
- **the peak voltage across a 50-ohm load is 2 kV**
- **the EMP energy dissipation in a 50-ohm load is 0.5 mJ**

The fraction of this energy that reaches sensitive semiconductor components in the connected equipment can be sufficient to cause damage.

mate the probability of damage. The charge or voltage can also be the limiting factor for thin oxide layers in semiconductors and electrolytes. In addition EMP energy can trigger dissipation of the system's own energy in inadmissible places, thus causing serious secondary damage. For short pulse widths, failure usually depends on the energy content of the pulse. Table 10 gives typical minimum threshold energy levels causing permanent damage. In semiconductor devices failure modes are typically junction burnout, oxide punchthrough and metallization burnout. With short pulses (less than approximately 1 to 0.1 µs) breakdown occurs in the semiconductor at a constant pulse energy regardless of the pulse duration, because the energy does not have time to disperse. Local melting occurs, particularly at any manufacturing defects. Such defects may be due to poor quality, which has not been detected during routine production control. Good quality and good control can give at least a tenfold improvement of the threshold energy compared with the values for low-quality circuits.

Although semiconductor components are particularly susceptible to transients, damage must also be expected in other components such as resistors (particularly metal oxide), capacitors (particularly tantalum electrolytic), relays, and indicator instruments. During the first nuclear tests in the middle of the 1940s many measuring instruments suffered EMP damage. Since then EMP simulations in communication facilities have resulted in false alarms, subscriber services outages, program interruptions in computers and certain permanent damage to the systems. However, it is difficult to make EMP simulations correctly on such large objects as communication installations so as to simulate high-altitude explosions correctly.

Among the conclusions from EMP simulations are:

- Permanent damage or impaired performance may be caused, particularly for active components (especially high-frequency transistors, integrated circuits and microwave diodes), passive components (particularly those with very low power or voltage ratings or precision components), semiconductor diodes and silicon controlled rectifiers (especially in power supply units connected to the mains) and insulated high-frequency and power cables (especially if they operate close to their maximum power and voltage levels, or are exposed to humidity or abrasion).
- Functional interference and status faults may be caused in low power or high speed digital processing systems, in memory units, control and alarm systems and in subsystems employing long integration or recycling times for synchronization, data acquisition or signal processing.

Hardening methods

A system that has to survive in an EMP environment must not undergo such disturbances or permanent damage as lead to functional failure. In order to reduce the effects of EMP on a system it will generally be necessary, either to limit EMP exposure or to increase the EMP susceptibility threshold. This can be achieved in various ways, most of which are well known and well proven e.g.:

- Electromagnetic shielding
- Potential equalization
- Isolation
- System delimiting (topological and/or functional)
- Well-designed cabling and wiring
- Transient protection
- Filters
- Availability of repair facilities and spares
- Use of more robust electrical components
- Use of non-electrical functions (e.g. mechanical, pneumatic, hydraulic, optical, acoustic, thermal)
- Disconnection of cables that are for the moment not absolutely necessary
- Redundancy.

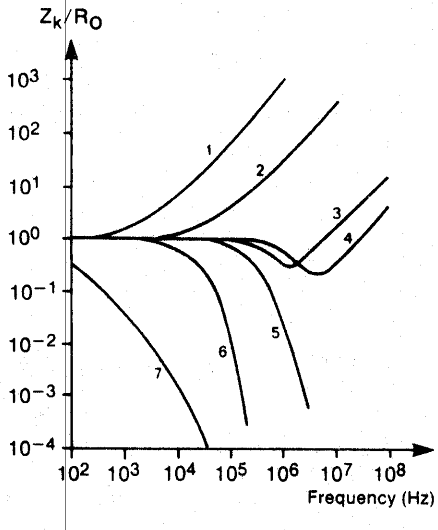
Several of the measures derive from methods of protection against lightning, static electricity, network transients and high frequency interference, as used in electromagnetic compatibility (EMC) technology. Hardening must be effective both for radiation and for

Component	Typical threshold energy levels (mJ)
Microwave diodes	$10^{-4}-10^{-2}$
Digital IC circuit	$10^{-3}-1$
Low power transistors	$10^{-2}-1$
Switch diodes	$10^{-2}-1$
Electroexplosive devices	$10^{-2}-1$
Tantalum electrolytic capacitors	$5 \cdot 10^{-2}-$
Metal oxide resistors	$10^{-1}-10$
High power transistors	$10^{-1}-10$
Silicon-controlled rectifiers	$10^{-1}-10$
Zener diodes	$10^{-1}-10^{2}$
Rectifier diodes	$10^{-1}-10^{2}$
Metal film restistors	$5 \cdot 10^{-1}-10$
Carbon film resistors	$5 \cdot 10^{-1}-50$
Electron tubes	$1 - 10^{4}$
Fuel-air mixture	3
Relays	$10 - 10^{3}$
Carbon composition resistors	50 –
Wire-wound resistors	10^{3} –

Table 10
Typical minimum threshold energy levels (mJ) to cause permanent damage for pulse durations $\leq 1\,\mu s$. Threshold energies for temporary functional interference are 10 to 100 times smaller than the values for permanent damage

Fig. 11
Relative transfer impedance as a function of frequency for different cables. The d.c. resistance of the sheath, R_0, is often 1–10 mohm/m

1 Aluminium tape wound with a helix angle of 25°
2 Power cable EKFR (10 x 1.5)
3 Braided coaxial cable RG 11
4 Mains cables (EKLR or FKLR)
5 1.4 mm thick homogeneous lead pipe
6 1 mm thick homogeneous aluminium pipe
7 Steel tape between two homogeneous aluminium pipes



conduction effects. Good EMC practice can be regarded as a step towards EMP hardening, but many methods must be applied more rigorously and systematically than is otherwise customary.

The principles of protection are quite simple. The problems arise in applying them without incurring excessive costs. Since it is difficult to predict, calculate and verify the effects of EMP exactly, it is often easier to choose better protection than may be absolutely necessary. Detailed analyses and simulations can turn out considerably more costly. A compromise consisting of a combination of a reasonable number of analyses, tests and protective measures is usually to be recommended.

The protection level should be related to the required probability of survival. For example, a survival probability of 99% for the worst possible EMP case for a large complex system would require an enormous investment. With more reasonable probability requirements and with protection planning included right from the start of the planning of a new system, the protection costs can be reasonable and quite acceptable. However, when modernizing old systems the costs can be unrealistic unless the measures are limited primarily to protecting certain parts, or raising the survival probability to a more moderate level.

EMP protection methods can be exemplified with the aid of the communication installation described above. The choice of action for a given overall result must be based on an assessment of the cost effectiveness of the various measures in relation to each other. The hardening alternative chosen must be documented in a project plan which gives instructions in the greatest possible detail, based on a topological decription of the object to be hardened, figs. 5 and 6. This work has to be systematic and disciplined. There is a much wider choice of action if the communication site and the associated telecommunication network are in the early planning stage. It might then even be possible to choose non-metallic optical fibre cables and microwave radio connections that work in high frequency bands. Aerial lines should be avoided if possible.

We face a rapid changeover to optical fibre cables in the telecommunication networks during the next few years. This provides a unique opportunity for planning an exclusive network with EMP protection, superposed on the ordinary network. The cables can be equipped with extra fibre pairs (single mode), which are run to subscribers of major importance for the administration and maintenance of the country. The optical-electrical conversion should take place as close to the exchanges, telephones, computers, video terminals etc. as possible. All such associated electrical functions must be equipped with EMP protection. The power supplies for cable repeaters, exchanges and subscriber terminals must be separate and protected. If the suggested EMP-protected network is to be implemented in a reasonable way it must be included in the planning for the optical fibre expansion right from the start. A new EMP-protected network for top priority subscribers will then be obtained at a relatively marginal cost as the ordinary telecommunication network is extended. The new protected network can be commercialized and justified for top priority subscribers for a number of reasons, such as very low congestion in crises and conflicts, very high capacity and flexibility as regards transmission of different types of information (including wideband services), and good protection against listening-in and disturbances (lightning, power failures etc.).

The power distribution lines connected to the EMP-protected network must be equipped with large primary surge arresters at the point where transition is made to buried cable. This point should be remote from the communication facilities, and the connecting cable should be shielded if possible. The external power line system should be isolated from the installation by means of, say, rectifiers, accumulators and d.c.-d.c. converters connected up for maximum transient attenuation, or by motor-generator transmission on an insulating shaft. The installation should be equipped with a standby power generator which starts up automatically if a mains failure occurs. The electrical installation must be carried out with great care, since external transients must be attenuated as much as possible by surge arresters, filters and other devices before they can reach standby power systems and finally internal loads.

The building could perhaps be constructed so that it provides electromagnetic shielding. This can be done by using small-mesh reinforcement and ensuring that the bars are in contact with each other wherever possible (may give 20 to 30 dB), or by supplementing the basic structure with metal sheets which are all welded or permanently joined in any other way (may give 50 to 80 dB).

The layout of external and internal wiring can also be modified during the planning stage. External power lines and telecommunication cables and grounding conductors can then be planned so that they are all run into the building at the same point. At this common entry point, cable shields and grounding conductors should be connected to the outside of a common inlet plate, which in its turn would be connected to the metal framework of the building. This arrangement diverts some of the currents induced in the lines to the outside of the installation, and only a minor part would penetrate inside.

At the inlet plate, transient protectors for the power and telecommunication lines should be installed with the shortest possible connections to the plate. The protective effect of even top quality overvoltage protectors is ruined if their connections are not as short as possible. The length of the connecting lead gives an additional voltage $u = L \times di/dt$, which can be of the order of 1 kV/cm. The transient protectors give potential equalization between different conductors and between the power and telecommunication networks, and thus reduce the risk of flash-overs in the internal installation.

If possible, cables should be shielded or run in shielded ducts or conduits. In some countries cables are run in iron conduits with threaded joints. A measure of the shielding effectiveness is the so-called transfer impedance. It is defined as the voltage drop, per unit length along the cable, along the inside of the cable shield in relation to the current on the outside of the shield. Fig. 11 shows typical values as a function of the frequency. Braided or in other ways transparent shields give considerably less protection against rapid transients which contain high frequencies than homogeneous (solid-walled) shields. Special sheath designs have been developed for EMP-hardened telecommunication cables. As regards the internal cabling it may be easier to run the cables together in special shielded cable ducts. However, such common cable runs must not include any conductors that can bring in large EMP currents from outside into the installation. Neither should the cabling be run near openings in the building shield, for example doors.

In shielded facilities the feed-through for air, light, fuel, water and sewage should be arranged with special care, e.g. by using waveguids. These are often sectioned and given a honeycomb structure, which makes them short and makes the overall attenuation the same as the attenuation of each individual cell.

The grounding or potential equalization in a telecommunication installation must be designed in accordance with

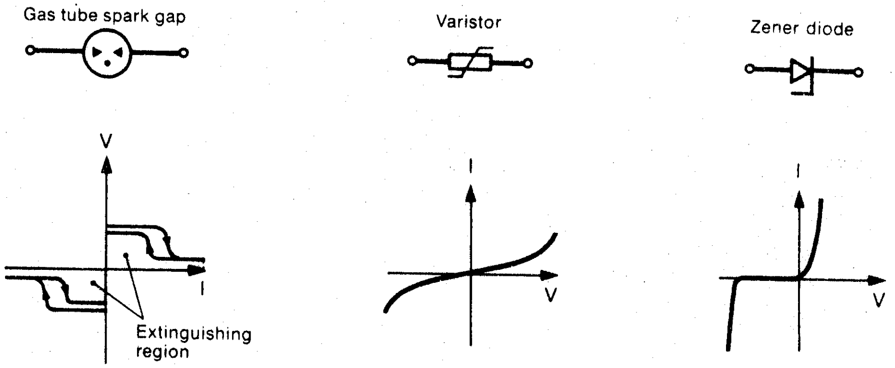


Fig. 12
Common components for transient protection

electrical safety regulations, and also in such a way that the grounding does not become a source of disturbances to the electronic equipment, or a conductor of EMP and lightning transients to susceptible points. In order to avoid damage from lightning or from earth faults in the power system the Swedish Telecommunications Administration now designs its installations so that external power and telecommunication cables are brought in as close to each other as possible. The power and telecommunication terminal grounding strips are joined together at the point of entry, either direct or via gas-type arresters, and the cables are equipped with overvoltage protection. If possible the internal cabling is arranged so that the power and telecommunication cables cannot form loops.

The protective measures are repeated at each new topological barrier, fig. 6. Some type of transient protection is usually required at equipment cabinets, and sometimes also at internal modules. The protective measures must be coordinated, which can be difficult. The type of transient protection varies from the outer barrier (primary protection) to the subsequent barriers (secondary protection), but the connection principles are the same. The final protectors must be placed as close as possible to the devices they are to protect. Protection components, such as gas-type arresters, varistors, zener diodes and filters, are often combined. Resistor fuses and protection diodes are sometimes used on printed boards. Fig. 12 shows some protections against transients. Circuits with differential coupling can suppress EMP induction by the order of 100 times (40 dB) as compared with circuits which are sensitive to common mode voltages.

The protection levels of the transient protectors and of the shielding barriers must be effective both for conducted and for radiated effects. It might be more economical to arrange protection in several topological steps of approximately 20 to 30 dB each. However good an electromagnetic shield is, its protective ability is largely lost if a cable is led through it without special protection being arranged at the point of entry.

The amplitude limiting given by overvoltage protectors is a function of time, whereas that given by filters is a function of frequency. Transient protectors can consist of one of these types or a combination of both. Power filters become larger and more expensive with increased power level. It is therefore more economical to use filtered power only for very sensitive equipment, and to connect units with lower sensitivity or priority to less well-protected power lines. This implies that conductors having different protection levels must be run in such a way that the mutual induction is negligible.

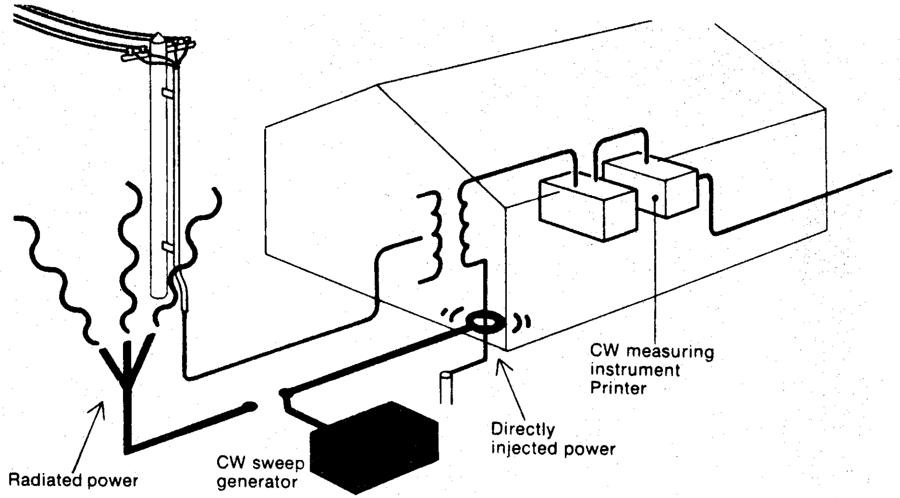
If a transmission equipment only uses a relatively narrow frequency band, it may be economical to install filters that attenuate the signal outside the operating range. At high frequencies, where a quarter wave corresponds to a reasonable length, a quarter-wave shunt can be used. It consists of a short-circuited transmission line connected in parallel with the ordinary transmission line. The

Table for fig. 12
Comparison chart of common transient protection devices. These are typical values; deviations can occur

		Gas tube spark gap	Varistor	Zener diode
Ability to withstand energy with 1 ms pulse	J	10^2-10^3	$1-10^3$	$10^{-2}-10^1$
Ability to withstand current with 1 ms pulse	A	10^4	10^2-10^3	1–500
Leakage current	A	$10^{-9}-10^{-12}$	10^{-3}	$5\cdot10^{-3}-10^{-8}$
Response time	s	$10^{-9}-10^{-6}$	10^{-9}	10^{-9}
Capacitance	F	$10^{-11}-10^{-12}$	$10^{-10}-10^{-8}$	$10^{-10}-10^{-8}$
Voltage range	V	$75-3\times10^4$	20–1 500	2–300
Polarity		bipolar	bipolar	unipolar
Failure mode		open or short-circuit	degradation and short-circuit	short-circuit
Operation mode		short-circuit	voltage clamping	voltage clamping
Ability to extinguish		*)	yes	yes

*) Can require combination with a non-linear resistor

Fig 13
A telephone exchange can be tested by means of low-level simulation with continuous wave (CW)



short circuit acts as an open circuit for frequencies corresponding to an odd number of quarter wavelengths. For other and lower frequencies it acts as a shunt.

In order to simplify the introduction of EMP hardening, detailed requirement specifications are needed to form the basis for a standardized range of protective devices. It will then also be easier to plan and estimate the cost of hardening plant or systems. Although a multitude of protective devices are now available, there is a lack of requirement specifications which could lead to homogeneous and standardized protection systems. This important omission must be remedied soon if EMP protection is to be more widely undertaken.

An EMP protection standard for radiated and conducted effects is being prepared. The proposal is similar to the current military EMC standard specifications. A number of different classes of radiated EMP environments, starting at 50 kV/m and divided into steps of 20 dB, are defined in the proposal. Cable-associated EMP environment is defined for a number of classes of double exponential and damped sinusoidal currents respectively. Test procedures for the various classes are also being prepared.

Most protection methods described here also provide protection against lightning. The handbook "Practical Methods for Electromagnetic Interference Control" published by Ericsson's Networks Department contains detailed instructions for protection against lightning strokes and EMP.[7]

Hardening verification

It must be possible to verify the hardening level in connection with installation and commissioning, and later periodically during service life. Protectors can deteriorate with time for environmental reasons (e.g. wear or corrosion of contacts) as well as maintenance and modification reasons (e.g. installation of new cables, which are run straight through a Faraday screen without any protection at the entrance).

The operating staff must be trained and have access to instructions and spare parts in case the EMP threat becomes a reality. The protective arrangements must be simple, clear and readily accessible. Training is also needed in order that the personnel should not incapacitate any protection by improper action. Test equipment needed for routine tests could be built into the equipment. The shielding effectiveness can, for example, be tested regularly with the aid of permanent measuring loops around the main body of the building. Surge devices can be used to test the transient protection. Fig. 13 shows one way of testing a communication installation at the time of commissioning.

The nuclear power nations, particularly the US, have extensive programs for EMP testing and simulations. Much work is also being carried out in Europe, for example in the UK, France and West Germany. A number of nations that do not have nuclear weapons also have EMP hardening programs, for example Sweden and Switzerland. Practical measurements are supplemented by theoretical calculations. A number of computer programs have been developed to aid complicated calculations of EMP environments, propagation penetration, induction response in different structures from macro (e.g. countrywide networks) to micro (e.g. amplifier stages, integrated circuits, simple components), and for respective threshold levels for interference of function and permanent damage (for final comparisons). Statistics programs have also been developed for determining the accuracy and reliability etc. of the data.

The classes of EMP tests include:

- low-level mapping of currents induced in subsystems that have not been activated
- high-level current injection
- high-level exposure of operational subsystems to pulse-shaped electromagnetic fields.

Simulators are available for the free radiation of pulse or CW (continuous wave) fields. Current injection test equipment for pulse and CW is also available. Since the systems to be tested are usually too large to be accommodated within the test volume of the simulators, it is often necessary to carry out extrapolations and supplementary tests, for example a combination of radiation and current injection, or scale tests.

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