

Linear EMC-methods applied to power systems

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Linear EMC-Methods applied to Power Systems

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Abstract

Electromagnetic interference can cause problems in power engineering where more and more electronics is installed in the close vicinity of high power circuits. We derive a widely useful concept to solve these EMC-problems using Maxwell's laws. It turns out that we have to be careful with magnetically induced voltages. Fortunately an analysis of current flow and current loops remains a good starting point to relate disturbance currents and the dangerous interference voltages at the inputs of electronics. This relation can often be described by means of the transfer impedance. Grounding structures with a low transfer impedance, which can protect cabling and electronics, are described. Calculations, linear extrapolation and easy test measurements for experimental verification are possible.

Introduction

Electromagnetic Compatibility is especially important in power systems where interference may occur because:

- * The power levels in the system and the corresponding amplitudes of voltages and currents are high enough to disturb or seriously endanger human beings and electronic equipment.
- * The frequencies of the currents and voltages in the power system differ widely: dc, 50 Hz or 60 Hz and very high frequencies caused by non-linearities, in particular by gas discharges.
- * Discharges occur in the system as a result of i) occasional failures of the insulation, ii) switching by means of circuit breakers or disconnectors and iii) lightning striking the large size grid and the elevated high voltage lines.

A positive factor for the development of electrical engineering has been the high level of immunity of humans for electrical interference. Our nerve cells are moderately sensitive for low frequency currents, and quite insensitive for high frequencies. This made it possible to work with electrical equipment without too extensive precautions. For instance melting wire fuses are widely used even though it takes some time before they interrupt the power; the

remaining short duration electrical pulse does not seriously endanger people.

It is interesting to speculate how electrical engineering would have developed if humans had been as vulnerable to interference as modern electronics is; probably much more slowly and against much public opposition.

The situation is different for electronics, which is becoming more and more sensitive to disturbances. We list three reasons.

- * Gate insulation and channel dimensions will be even smaller in newer versions of integrated circuits.
- * The bandwidth of modern electronics tends to increase; therefore more interference couples in for the same external disturbance.
- * Newer chips operate at lower supply voltages; the thresholds for interference become therefore lower.

In addition electronics is being used for more and more tasks; also in substations and power plants we tend to find more electronics and fewer people. Obviously we should solve the EMC-problems of electronics and a general protection concept, preferably with a clear theoretical base, would lead to a better understanding, a simplified design and clear maintenance rules.

In the search for a general protection concept we use Maxwell's theory, as the best model available. In many, but not in all situations this model can be simplified to the less accurate circuit theory based on Kirchhoff's laws. In the paper priority is given to scientific arguments; we ask the reader for clemency if this occasionally leads to discrepancies with electrotechnical standards.

We start with a discussion on grounding where we emphasize either the current flow in abnormal situations, or the wish to keep potentials close to zero by means of grounding.

1 Current flow or zero potentials

In power engineering we recognize the importance of current flow in abnormal situations, more than in other fields of electrical engineering. Examples are:

- In a three phase cable or high-voltage line a zero-sequence current may flow.

- Usually the net current carried by a two lead power cord remains small; this current may trip a safety circuit breaker when it exceeds a given value, for instance 30 mA.

Similar currents may flow in information or telecommunication systems in abnormal situations; a signal cable for instance may carry, in addition to the signal currents a net current, the so-called Common Mode (CM) current. This CM-current is often related to interference, but in these fields people are less aware that these currents may flow.

We will argue in this paper that EMC-problems can generally be solved by an analysis and a rerouting of interference currents. However we first discuss the potential concept, where grounding wires are expected to be at zero potential.

Historically already in electrostatics objects could be grounded. Grounding set the potential equal to zero. No current flow was necessary, after a short transient phase.

The same approach is often followed in dc-systems and in 50 or 60 Hz systems; the aim of grounding is then to keep the potential as close as possible to zero. Current flow in the grounding leads may cause large resistive voltage drops and consequently shifts in local potentials which ideally should remain zero. This problem can be reduced by the use of grounding leads with a larger cross-section.

There are however more basic problems with this grounding concept, which we discuss in the following sub-sections.

1.1 Is the reference potential essential?

The connection between the electrical system and ground is supposed to make the potential of the "cold sides" of the circuits in our system zero, thereby removing the uncertainty in the value of all potentials in our system; an uncertainty which exists in the ungrounded, "floating" situation. This resembles fixing the integration constant in a calculation, by means of a correct boundary condition.

We can also compare grounding to dropping an anchor to prevent drifting of a ship. Both in the case of anchoring and in the case of grounding we however only move the problem to the next level; we restrict the position relative to the seabed, or the potential difference relative to the "reference" ground. Note that for calculations on our circuits we only need potential differences between points, and never the value of the potential itself. In other words the connection to an external "reference potential" is in itself not necessary for the correct operation of a circuit, as is obvious from portable equipment or equipment in airplanes or satellites.

In practice many electrical circuits are connected to Mother Earth (abbreviated from now on as M. Earth). The reason is not the trustworthiness of the potential of M. Earth, but rather because we want to limit i) the voltage difference between our electrical system and the globally present M. Earth, and ii) voltage differences between our system and neighboring systems which are also connected to M. Earth. By the same token the anchor should protect a ship in a

storm against hitting a nearby coast or other anchored ships. Note that this argument brings up the important role of the electrical environment in grounding.

1.2 Current in the grounding connection?

Could we have just one grounding connection? From the point of view of the potential one grounding lead would be sufficient, just as one anchor can prevent the drifting of a ship. However the anchor should take up forces to be useful. Similarly the grounding connection is only useful when it carries current. This current may flow only occasionally, as in a lightning conductor, but that current is essential in case of a strike.

In the earlier mentioned example of electrostatics a grounding lead carries no current when the conditions are really "static". This situation is however rare; all sorts of changes occur, a small and slow current carried away by a wrist-strap avoids electrostatic charging of a person, or a very fast current flows in spark discharges. Preferably grounding and grounding currents should avoid problems in all situations.

1.3 The circuit for the grounding current.

Accepting that the grounding connection must carry current to be effective, we have to specify the circuit in which that current flows. It can be shown that Kirchhoff's current law (the sum of the currents to a node in a circuit is zero) is in full agreement with Maxwell's laws. In fact Maxwell's laws lead to a farther reaching conclusion. As follows from the conservation of charges the algebraic sum of the conduction currents through any closed surface must be equal to $-dQ/dt$ where Q is the net charge enclosed by the surface. Writing the enclosed Q in terms of the electric flux density \mathbf{D} through the surface by means of Gauss' law we find that the following surface integral is zero for any closed surface:

$$\oiint \{ \mathbf{J} + \partial \mathbf{D} / \partial t \} \cdot d\mathbf{S} = 0 \quad (1)$$

where \mathbf{J} is the current density and $d\mathbf{S}$ a small surface element. Bold quantities are vectors; the surface integral must be taken over the entire closed surface.

Equation 1 can also be expressed in simple terms: for any closed surface the algebraic sum of the conduction currents and the displacement currents through that surface is zero. The conduction currents flow as a distributed \mathbf{J} , or as a current I concentrated in a wire; the displacement currents flow both in "installed" capacitors and in "parasitic" capacitors related to the physical size of our components.

Equation 1 reduces to Kirchhoff's current law, when the closed surface is chosen around a node in an electric circuit. However Eq. 1 is valid for any closed surface around a current-carrying wire which brings us to the conclusion that currents always continue; this means that currents always flow in closed loops.

As a consequence of this there are always at least two grounding connections to a system; a single connection is not effective since it cannot carry current. We are always dealing with ground loops!

In the case of lightning the current seems to flow in only one current channel. However the second current path is present in the form of the capacitance between the cloud and the ground. In this capacitor a distributed displacement current density $\partial \mathbf{D} / \partial t$ flows when the voltage between cloud and ground collapses. A similar argument can be given for antennas above a ground plane; also there displacement currents close the circuit.

2 The Common Mode circuit.

The two boxes in Fig. 1 are connected by a signal cable. In this cable Differential Mode (DM) currents carry signals; these DM currents flow in both directions leaving the net current in the cable zero. The cable can however also carry a net current, the CM current. This CM current returns through the grounding connections and the ground plane underneath the boxes. Note that both boxes are always to some extent connected to the ground plane, by wires or at least by parasitic capacitance. In many electrical or electronic systems the CM-circuit plays an important role in the EMC behavior of the system.

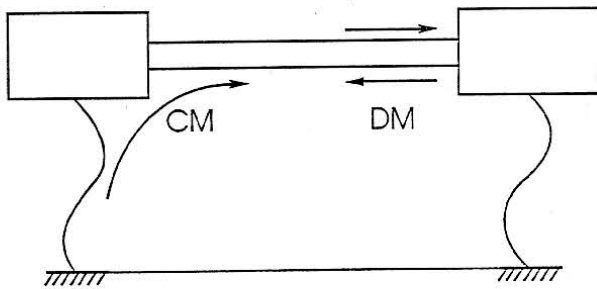


Fig. 1 The signal cable between the two boxes carries a DM-current. In addition a net current, the CM-current may flow in the larger circuit through the grounding connections of the boxes. The CM-current is often a disturbance current.

The CM circuit can be large in size and is often not well designed. We have to watch this CM circuit since it is present as an unavoidable "ground loop". Objections against ground loops generally focus on the "stray" currents in the loop.

2.1 Stray currents in a ground loop.

In its simplest form a ground loop is a closed circuit with little resistance, in which stray currents may flow. These stray currents can be harmful. This is indeed the case in dc situations; there currents are difficult to control; a "vagabonding" current in the soil could find holes in the insulating coating of a buried metal pipe and continue in the metal.

At higher frequencies the situation is much better; even if a return current has the freedom to spread out in M. Earth or over a copper layer on a printed circuit board (PCB), it remains close to the "forward" current above the Earth

surface or above the copper layer. Let us consider possible current loops in M. Earth or in the copper layer. In these loops the ratio of inductive to resistive impedance, $\omega L/R$, becomes large compared to one, at high frequency and in circuits of large size. Lenz' law is then satisfied which means that the currents in the loop tend to make the magnetic flux enclosed by the loop zero. This pushes the magnetic field out of the conducting medium; the minimized remaining flux is that outside the conductors; in addition the "return" current flows close to the "forward" current.

For this reason multi-point grounding and copper ground planes on PCB's are useful at high frequencies. The currents in the ground plane, having freedom, "spontaneously" show excellent EMC-behavior. Fluxes remain small and this reduces the coupling between adjacent circuits.

3 Voltages inside a loop

The voltages inside a current carrying loop, for instance a ground loop, are not easily specified at frequencies where the inductance of the loop is important. The reason is that inside the coil the E-field results from: i) charges distributed at the surface of the conductor generate E-fields, E_c and ii) the changing magnetic flux inside the loop induces an E-field, E_i . The E_c -field in itself is a conservative field, which means that for all closed integration paths:

$$\oint E_c \cdot d\ell = 0 \quad (2)$$

The E_i -field is non-conservative and obeys, again for all closed integration paths:

$$\oint E \cdot d\ell = - \partial / \partial t \{ \iint B \cdot dS \} = - \partial \Phi / \partial t \quad (3)$$

Note that Eq. 3 is Faraday's law, describing the EMF induced in a contour which encloses a changing magnetic flux Φ . Equation 3 is primarily valid for the induced E_i -field, but since closed contour integrals of E_c are always zero (Eq. 2), Eq. 3 is also valid for the complete E-field, a complicated mixture of E_c and E_i . Therefore we may omit the subscript of E in Eq. 3.

Another description which stresses the complicated nature of E-fields in a region where a changing magnetic flux is present is the general equation [1]:

$$\mathbf{E} = - \text{grad } U - \partial \mathbf{A} / \partial t \quad (4)$$

where U is the scalar potential and A is the magnetic vector potential, defined as:

$$\mathbf{B} = \text{curl } \mathbf{A} \quad (5)$$

The two terms on the right hand side of Eq. 4 can roughly be identified with the two E-fields, E_c and E_i ; the mathematical details necessary for a more precise identification are omitted here. Equation 4 in itself already shows the complexity of the total E-field; to find E we need to know the scalar potential U and the three components of the vector potential A.

In electrical engineering however, potentials are generally, often tacitly, related to Kirchhoff's voltage law: "when we go around in a mesh the sum of the voltages is zero". This resembles Eq. 2 closely, with the difference that Eq. 2 is

about E-fields whereas Kirchhoff's voltage law only deals with voltages across the abstract impedance symbols in the equivalent circuit.

In the equivalent circuit no fields are present since their effects have been hidden in the voltage-current relations of the various impedances. In fact in the equivalent circuit, and in circuit theory in general, components are treated in a very abstract manner. An inductance for example, is a black box with a simple voltage $L di/dt$ across its terminals. This is perfectly acceptable for a coil with its terminals outside the flux region.

The coils which we install in our systems, usually have a core in which the flux is concentrated and have their terminals on the outside, where only the simple, conservative E_c field of the charges on the leads is present. As long as we stay outside such coils, circuit theory is valid.

However, in the CM-circuits which are important for EMC, we are inside the coil and we have to deal with the complicated, non-conservative E-field of Eqs. 3 or 4. Inside the coil Eq. 2 is not valid. That means that voltages, which are given by line integrals $\int E \cdot d\ell$ become ambiguous; they depend on the actual integration path chosen. To find voltages we have to use Eq. 3, applied to the correct contour to give us $\oint E \cdot d\ell$.

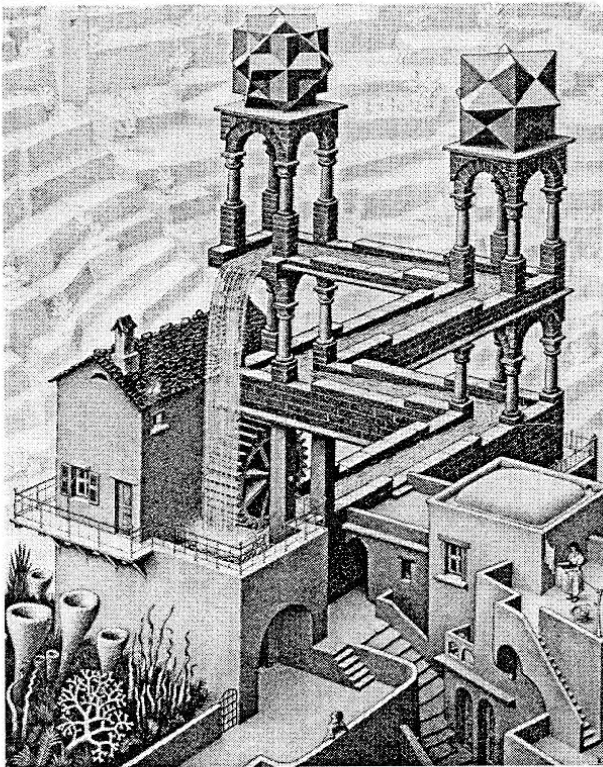


Fig. 2 M.C. Escher's "Waterfall". Impossible closed circuit for flowing water. However if interpreted as a coil enclosing a vertical and time-varying magnetic field the picture is realistic. The E-field in the "metal" of the coil is zero; whereas an appreciable field is present between the

terminals. © 1997 M.C. Escher Cordon Art - Baarn-Holland. All rights reserved.

A picture which illustrates this point very nicely is Escher's "Waterfall" (Fig. 2). In the conservative gravitational field such a flow of water is impossible and Escher cleverly creates an optical illusion based on Penrose triangles [2]. In electrical engineering however the situation is perfectly possible. The zigzagging water conduits could be replaced by a coil enclosing a vertical time-varying magnetic field. The induced EMF then shows up as a voltage difference between the terminals (top and bottom of the waterfall); inside the metal of the coil there is however no E-field since E_c and E_i add up to zero. This is perfectly true if the terminals of the coil remain open; in case a current is allowed to flow the resistivity causes a small E-field in the metal.

The problem is that voltages inside the coil depend on the integration path, just as the height in Escher's picture depends on the path. Whereas Kirchhoff potentials are uniquely determined by the circuit parameters, we are now in a confusing situation with many voltages, and we wonder which voltages are relevant.

3.1 Which voltages are important?

Faraday's law (Eq. 3) is always valid; it may reduce to Kirchhoff's voltage law, but induction effects, when present are also covered. Equation 3 is correct for any closed integration path; we gain however more insight with a well chosen path, for instance along the leads, just as we do in Kirchhoff's voltage law. Now however we do not go around in an abstract mesh in an equivalent circuit, but follow a closed path in three dimensions, with fields present.

To determine voltage differences between two points, A and B, we calculate $\int E \cdot d\ell$; this requires a detailed knowledge of the E-field along the path from A to B. We can also connect a real or an imagined voltmeter with its two leads to A and B. If the voltmeter has a large impedance Z_m , the E-field in its leads is zero and a voltage equal to the integral $\int E \cdot d\ell$ from A to B shows up across Z_m .

When we use Eq. 3 to calculate the voltage, the voltmeter with its leads forms only a part of the integration path, which we close via the circuit we are examining. The right hand side of Eq. 3 contains the flux Φ , enclosed by the chosen path. Obviously whenever $\partial\Phi/\partial t$ is important the measured voltage depends on the actual location of the measuring leads.

In Fig. 3a two voltmeters are connected to the points A and B on the outer surface of a current-carrying cylinder. The first contribution to the integral $\oint E \cdot d\ell$ is the resistive voltage drop between A and B along the outer surface. This voltage drop is the product of specific resistivity, local current density and the length of AB. In addition a voltage $-\partial\Phi/\partial t$ is induced in the loop formed by the measuring leads. This

induced voltage is equal to $M \partial i_{\text{prim.}} / \partial t$, where M is the mutual inductance between the primary circuit (tube and current supply) and the secondary circuit (part of the tube and the measuring leads). Obviously the value of M is different for the two voltmeters.

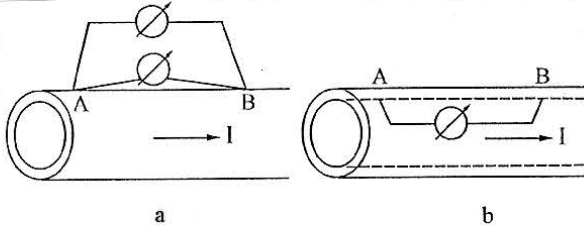


Fig. 3 a) The voltage between two points A and B of a current carrying tube is ambiguous at higher frequencies; the two voltmeters show different readings; b) a voltmeter with its leads inside the tube sees only the resistive drop along the inside surface of the tube. At a high enough frequency the skin effect causes this voltage to go to zero.

3.2 Protection by means of a small transfer impedance

The confusing situation with the voltages also brings opportunities for EMC-protection. In Fig. 3b we show a situation, where the primary conductor is again a tube and the voltmeter leads are now inside the tube. Since cylindrical symmetry dictates that the B-field inside the tube is zero, also M is zero. The voltmeter reading then equals the resistive voltage drop between A and B along the inner surface of the tube. This voltage divided by the total current in the tube is called the “transfer impedance”, Z_T , of the tube. At higher frequencies the skin effect enhances the currents near the outer surface. The current density at the inner surface and the value of Z_T are accordingly reduced. To describe this effect we introduce the skin depth δ , given by:

$$\delta = (2 \rho / \mu_0 \mu_r \omega)^{1/2} \quad (6)$$

where ρ is the specific resistivity of the metal, μ_0 the permeability of vacuum, μ_r the relative permeability of the material and ω the frequency of the alternating current. For a tube with a wall thickness d , small compared to the radius r , the value of Z_T is given by [3]:

$$Z_T = R_{DC} \{x / \sinh(x)\} \quad (7)$$

where R_{DC} is the resistance for direct current, and where $x = (1+j) d / \delta$. At increasing frequencies, for which $\delta < d$, Eq. 7 shows a rapid drop of Z_T ; a good approximation for the absolute value of Z_T is then:

$$|Z_T| \approx 2\sqrt{2} R_{DC} (d/\delta) e^{-d/\delta} \quad (8)$$

The tube with internal leads of Fig. 3b obviously shows a possibility to transport signals safely from A to B, almost irrespective of the disturbance current. The points A and B could be far apart points in a substation, in a high-voltage tower or in a power plant.

4 Approach to solve EMC-problems

The preceding sections brings us to the formulation of an approach to solve EMC-problems [4,5].

- When we are “inside a coil” (as in Fig. 3) no simple equivalent circuit can be given and therefore we cannot use Kirchhoff potentials. To come to correct values of the voltages we have to use Maxwell’s theory, or at least Faraday’s induction law.

- First of all we concentrate on the current flow. The currents still obey Eq. 1, and Kirchhoff’s current law. This familiar behavior helps to identify the closed current paths, in particular for the disturbance currents. Note that in complicated geometries elaborate calculations may be required to find the current distribution.

- Next we analyze the magnetic fluxes associated with the currents. In the flux region the time-varying magnetic fluxes make the electric field non-conservative.

- Voltages between far away points then become ambiguous, since the outcome of the line integral $\int \mathbf{E} \cdot d\mathcal{L}$ is path dependent. Only those “far away” voltages are important where voltmeters and their associated leads define an integration path.

- The “nearby” (DM) voltages across sensitive inputs (or ports) of electronic equipment, which are the truly dangerous voltages for the electronics, are quite well defined and can generally be described by a transfer impedance, the interference voltage divided by the disturbance current. In the EMC context the term “input” includes any pair of terminals via which interference could enter into the system; not only the regular signal inputs but also outputs and the mains input.

- We modify the lay-out of the grounding system to redistribute the disturbance currents. In addition we choose “grounding structures” (GS, as described in Section 5), metallic tubes or conduits, cable shields, connectors, connector panels and cabinets with a low transfer impedance.

4.1 Emphasis on currents and new definition for grounding

The above recommendations to concentrate on currents and to be wary of Kirchhoff potentials can also be expressed in the following way. A common recommendation in detective stories is to search for the lady, or in French “Cherchez la femme”. In EMC-problems we should first of all try to identify the current paths: in French “Cherchez le courant”. In both cases neither the lady nor the current are necessarily the culprit; however knowing the lady or the current helps to solve the problem.

The list of recommendations led us to formulate a new definition of grounding [5]:

“Grounding provides a set of interconnected paths for currents, designed to have a low transfer impedance Z_T , in order to keep the interference voltages at the inputs of sensitive equipment low.”

5. Useful Grounding Structures

Grounding structures (GS) with a low Z_T create locally a favorable EM-environment. A GS for the protection of cables and wiring (5.1) may take the form of a plate, a conduit or a tube. These GS's protect the cables which run inside, or parallel to them. Protection means here that the CM-current is largely carried by the GS, rather than by the cable; as a result no appreciable CM-voltage shows up at the end of the cable. In 5.2 we discuss GS's which protect electronic instruments. Here the GS carries the CM-current around the electronics, in many cases even around the metal housing of the electronics.

An attractive feature of these GS's is that the protection is linear. This means that results from calculations or test measurements can be extrapolated to other types of disturbances, even to very intense disturbances. In high-voltage research or in power engineering in general this is a very useful property. Measurements with injected, relatively weak disturbances can test whether the equipment in a substation or in a power plant has been correctly installed in terms of EMC.

5.1 Grounding Structures for cables and wiring

We start with a pair of wires between two boxes as in Fig. 1. If the input impedance of the box on the right is high the CM-current flows over the lower (the grounded) wire. The interference DM-voltage which shows up across the input impedance of the right hand box can be written as $Z_T I_{CM}$; here Z_T behaves as an $R + j \omega M$ impedance. The resistive part corresponds to the resistance of the lower wire; the mutual impedance part corresponds to the magnetic flux through the rectangular area between the wires, per ampere CM-current. A much lower Z_T is obtained if we replace the lower wire with a plate or even better a conduit. The CM-current now sees not only a lower dc-resistance, but in addition the current concentrates itself at higher frequency near the ends of the plate or at the four "corners" of the conduit. This gives a much lower resistive voltage drop in the metal directly underneath the wire. The magnetic flux between wire and GS gives a small M , in particular at frequencies when the currents are concentrated in the corners. Note that at high frequency the field lines are forced to go around the plate or the conduit; the stretching of the field lines reduces the flux between wire and GS and therefore M is reduced.

A completely closed tube is the best, but in real situations not always a practical GS. The transfer impedance for a tube has already been given by Eqs. (7) and if $\delta < d$ by Eq. (8).

In Fig. 4 the four GS's discussed are sketched; typical values of the M , which is the dominant contribution to Z_T at high frequencies, are given in the figure. Note that M is essentially zero for the tube. Fig. 5 shows magnetic field lines around a conduit at high frequency. These lines are also lines of constant M ; the values of M are given in the figure.

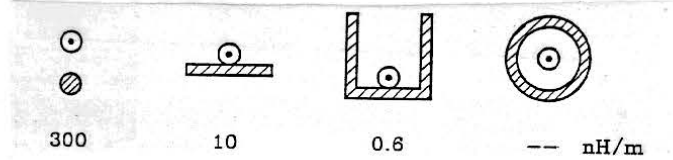


Fig. 4 Sketches of four grounding structures running parallel to cables. Typical values of the mutual inductance part of Z_T are given in the figure.

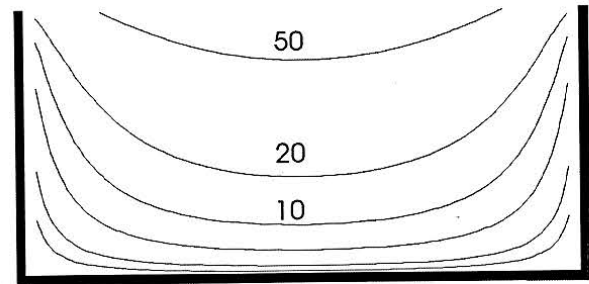


Fig. 5 Magnetic field lines inside a current carrying conduit at high frequency. These lines are labeled in terms of the mutual inductance (nH/m) between conduit and a lead inside the conduit. The labels for the lowest three field lines are 5, 2 and 1. The M -values depend on the height to width ratio; $1/2$ in this figure.

We now consider a coaxial cable inside the conduit (or the tube) with the cable shield connected at both ends to the conduit. The current in the cable braid adjusts itself at high frequency to reduce the flux between conduit and cable, according to Lenz' law. Since the above discussed M is small, only a small fraction of I_{CM} flows over the cable shield. The transfer impedance for cable and conduit combined is therefore small; in fact proportional to the product of the Z_T 's of cable and conduit separately [6]. Calculations and measurements on various GS's, including steel conduits have been reported in [7]. Note that construction elements in buildings or installations, such as steel I-beams can also be used as GS.

5.2 Grounding Structures for electronic instruments

Cables, power cords and grounding wires connected to an electronic instrument may carry CM-currents in, or out; our task is to keep the CM-currents away from the electronics. A metal panel with all connectors close together may give the CM-currents the opportunity to cross over with only a small coupling to the electronics. In earlier publications [8] we proposed an EMC cabinet (Fig. 6), which we have been using successfully for ten years. The five metal walls of such a rectangular cabinet are continuous over the full perimeter, the front is open for easy access to the electronic equipment. All cables enter the cabinet at the back panel. Shields of coaxial cables are circumferentially connected to the panel; power enters the cabinet through a filter well bonded to the

panel. In this manner all disturbance currents cross over on the back panel. This results in a very low Z_T between the external CM currents and the electronics inside the cabinet. This reduction of Z_T is in practice more important than the shielding; in most cases the cabinet door can remain open.

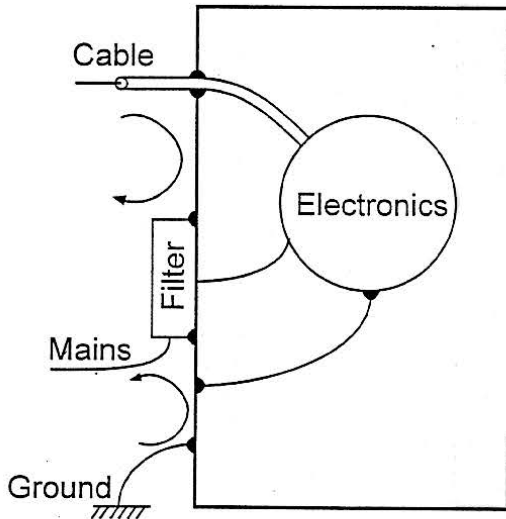


Fig. 6 An EMC-cabinet provides a path with low Z_T for CM-currents which cross over on the back panel, away from the electronics.

Kiosks in substations can also be constructed as EMC-cabinets [9] to protect the instruments against the CM-currents. The immunity of the instruments is then considerably increased as can be tested by injecting CM-currents as in the well-known Bersier test [10].

The EMC-cabinet does not help if the disturbances have already coupled into the incoming signal cables. In power engineering this problem can often be circumvented. If the desired incoming signals are large, a good quality attenuator mounted on the rear panel of the cabinet can attenuate the interference together with the signal. If only a limited band width signal is of interest a good quality filter should be used, again mounted on the rear panel. In a number of cases the sources of the signals are differentiating (Rogowski coils or small capacitors); in that case a good quality integrator restores the signal and at the same time reduces the interference.

6 Applications

Others have used similar GS's [11] a.o. in NEMP protection, and in pulsed plasma physics experiments. We have developed and tested our theoretical approach and GS's during many years in high-voltage research, for measurements in a number of substations and power plants, for the protection of electronics against lightning and for pulsed-power, energizing intense pulsed corona reactors [12].

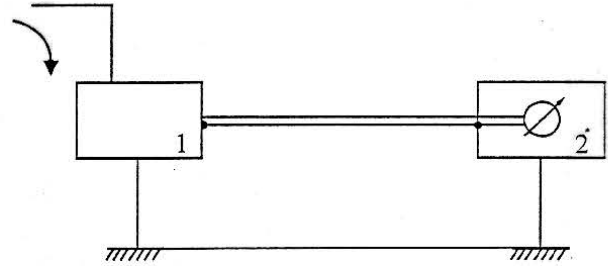


Fig. 7 A disturbance current entering box 1 may cause too large a DM-voltage at the end of the cable to box 2. A grounding structure parallel to the cable solves this problem even though a larger part of the disturbance current flows to box 2.

A diagram which illustrates an interesting aspect of the approach is given in Fig. 7. A disturbance current enters box 1, on the left; we want to reduce the interference in box 2, on the right, even though a cable is present between the two. The classical approach is to improve the grounding of box 1. This will result in some, but not sufficient reduction of the CM disturbance current I_{CM} along the cable. In our approach we accept this I_{CM} , but reduce the Z_T of the signal connection, for instance by installing an extra GS parallel to the cable. In this manner the DM voltage at the end of the cable, in box 2 can be reliably reduced.

We solved EMC-problems in essentially this situation in:

- * A radio relaying station [13] struck by lightning: box 1 was the antenna; box 2 the transmitter room. Parallel to the antenna cables a conduit reduced the I_{CM} on the cables. Since the RF cables had already a low Z_T the GS for the protection of the electronic instruments (in box 2) was very important here.

- * In an open air 150 kV substation [14] HV switching caused a transient current to the transformer housing (box 1). This led to interference in the control room (box 2). Fig. 8 shows measured results in two extreme situations: 2.3 kV to the local ground without any return wire parallel to the lead and less than 1 volt with both a cable shield and a conduit parallel to the lead.

- * In a nuclear power station a 100m ventilation stack [15] (box 1) was struck by lightning. Some of the lightning current was also flowing on instrumentation cables between stack and building, and in particular also to the electronics (box 2) monitoring the outflowing air

More applications are given in [15]. The methods described can be adapted to the seriousness of the expected disturbances. In addition the methods can be implemented at various levels, on the PCB, in the connectors or at the connector panel, in the cabling and wiring [16] or close to the source of the disturbance.

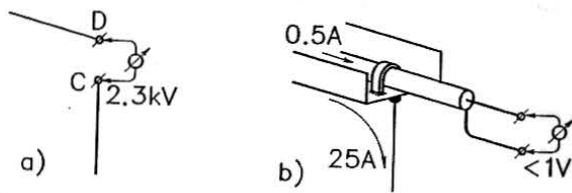


Fig. 8. The voltage at the end of a lead from power transformer to control room, without any parallel return wire and with a cable shield and a conduit in parallel. Note that even though a disturbance current flows to the control room a quite low DM-voltage is measured.

7. Acknowledgments This paper summarizes also work carried out by many colleagues and students of our group, whose names show up in the list of references. In addition we thank Dutch utility companies for their cooperation in measurements in the field and the Netherlands Technology Foundation (STW) for financial support.

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