Grounding philosophy

GROUNDING PHILOSOPHY

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Two aspects of commonly used definitions of the ideal ground are inconsistent with Maxwell's laws. First, a ground cannot be a "perfect sink or source for currents"; not even the large capacitance of our globe acts as a sink.

Secondly, a "perfect equipotential point or plane" can be a reality for small dc currents only. For alternating currents however, distributed magnetic fluxes near ground leads make the potential concept, as used in Kirchhoff's laws, meaningless. In this situation where network theory fails, we should concentrate on the ground currents and on the circuits in which these currents flow.

Examples are given how these current loops should be designed to minimize impedance and interference. A proper design leads to compact and local grounding and to much reduced currents flowing to Mother Earth.

1. Introduction

Grounding can be interpreted as all design and actual construction work on the low-voltage side of electrical circuits. This makes grounding a very broad subject essential for widely different fields as lightning protection, power engineering and microelectronics. We may nevertheless formulate a simple and general objective of grounding: "Grounding should reduce dangerous voltages to safe values". By grounding correctly we want to achieve the following:

a. Interference voltages across sensitive inputs or across other critical terminals of our circuits should remain low, so that the correct operation of the circuits is not affected.
b. The safety of people must be guaranteed.
c. Breakdown between adjacent circuits should be avoided, by grounding "floating" parts which otherwise could reach high voltages.

Historically the objectives b) and c) were recognized first. With the growing use of electronics the typical EMC objective a) is becoming increasingly important. Since often only very low interference voltages can be tolerated in microelectronics objective a) poses difficult engineering challenges. Of all the literature on the resulting grounding problems we quote here only Jones and Bridgwood [1] who cite many older references.

The technical expertise on grounding available is impressive, but is often more a product of art than of science. A major obstacle for the development of a more scientific description of grounding is - in our view - the deplorable situation that the generally accepted definition of "ground" is incorrect.

In this paper we criticize this definition and describe improved strategies for the activity grounding. Elements of this grounding philosophy have appeared in earlier publications [2,3,4,5].

2. Criticism on standard definitions of "ground"

Most standard definitions of "ground" contain two elements:

1. A ground can absorb or supply current without any change in voltage; in other words the ground should be a perfect sink or source for current.
2. A ground is an equipotential point or plane which serves as a reference for the circuit considered.

2.1 Ground, a perfect sink or source?

A ground can only act as a sink or source for current when charges can accumulate, in other words when a capacitor with sufficient capacity is present. This also follows from the continuity equation for charges

$$\mathrm{div}\,\vec{j} + \partial\rho/\partial t = 0 \qquad (1)$$

When current is absorbed or supplied $\mathrm{div}\,\vec{j}$ differs from zero and consequently the charge density must change.

In the search for the capacitor which collects this charge we first consider the Earth. As an isolated sphere with an average radius of 6367 km the earth has a capacitance of

$$C_A = 4\pi\varepsilon_0 r \qquad (2)$$

which turns out to be 708 μF. The problem is however that although comets, solar wind or spaceships may carry charges to the earth, all "down-to-earth" electrical engineering activities do not influence the complete E-field around the earth at all. Our electrical engineering only produces charge displacements in a small part of the earth surface; consequently we cannot expect any benefit from C_A in our grounding.

We may also consider the capacitance between the earth and the lower layers of the ionosphere at for instance 50 km height. The capacitance between these concentric spheres is

$$C_{AI} = 4\pi\varepsilon_0 \frac{r_1 r_2}{r_2 - r_1} \qquad (3)$$

With r_1 = 6367 and r_2 = 6417 km we find C_{AI} = 91 mF. This large capacitor is indeed present, carries a charge (ionosphere positive) and causes the so-called fair-weather field. Also this capacitor cannot play a role in our grounding because our local engineering activities do no influence the total E-field in this capacitor. That is not true for lightning storms; the charge separation in thunderclouds and lightning transport predominantly negative charges to the earth. On a world wide scale the thunderstorms charge capacitor C_{AI} [6].

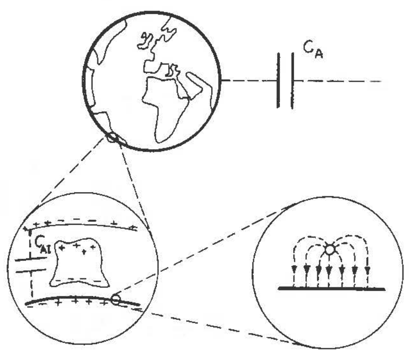

Fig.1: Electric fields on different scales. For our electrical engineering we use only a minute part of the Earth.

When we summarize the situation, (Fig. 1) we conclude that only a small capacitor, that between our charged objects and the earth, may absorb some current. The magic capacitor which could make our ground a perfect sink or source is however absent. The first element of the standard definition of ground is based on an unrealistic fiction.

To arrive at a correct picture we rewrite Eq. 1 with Gauss' law

$$\mathrm{div}\,(\vec{j} + \partial\vec{D}/\partial t) = 0 \qquad (4)$$

Obviously the combined quantity, $\vec{j} + \partial\vec{D}/\partial t$ is divergence-free and has therefore no sink or source. This leads to Kirchhoff's current law (KCL) from circuit theory: the sum of all currents, including the capacitive currents, into any node is zero. An equally correct statement is that any current - if we properly include the capacitive current - must flow in a closed loop.

As a consequence of these (embarrassingly obvious) statements, which are of course also true for grounding currents, we must specify more clearly what a grounding system is supposed to do (see Fig. 2).

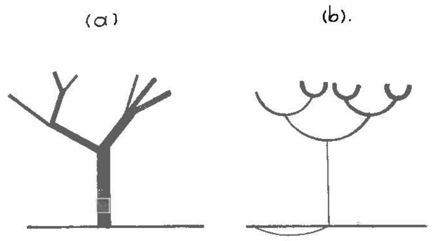

Fig.2: Incorrect (a) and correct (b) picture of a grounding system. The thickness of the lines corresponds to the magnitude of the current.

A grounding system never resembles a sewer system where more and more sewagepipes converge into one main pipe with "unknown" destination. Instead a grounding system is a group of interlinked current loops (Fig. 2b). We make two observations. First of all, Fig. 2b shows only the low-voltage parts of all the circuits and is in that sense incomplete. Secondly the connection to the Earth in Fig. 2b is not unique anymore, but is only another part of a current loop [3,5]. Therefore the connection to Earth is not essential, as is daily demonstrated by digital watches, portable radios, airplanes and satellites. If a connection to the Earth is made we must realize that whenever a current flows into the Earth, this current must leave the Earth somewhere else.

2.2 Ground, a point of equal potential?

This second element of standard definitions of ground implies that a connection to ground fixes the potential of the connected point of the circuit, where the potential value is often taken to be zero. A first, relatively simple complication is caused by the resistivity of the soil; we may correct for that by using the correct grounding resistance, which depends on shape and size of the grounding rod.

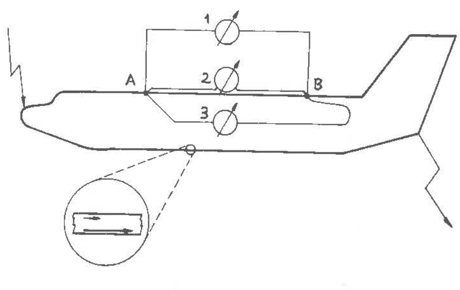

Fig.3: The voltage between the points A and B of an airplane, caused by lightning current, cannot be described by a potential difference; each of the three voltmeters gives a different reading, depending on the loop enclosed by the leads.

A more basic question is whether a highly conducting, say a metal "Earth" would form an equipotential surface. Since the size of the sphere is not important (see Section 2.1) we may consider any metal object, such as a ship, an oil tank, a screen room or an airplane (Fig. 3). In electrostatics such an object forms an equipotential surface. This is also true according to the networktheory, where even wires are assumed to "transport" potentials faithfully.

However, in reality, when we connect three voltmeters between the points A and B we obtain different readings as a result of the distributed time-varying magnetic flux. Voltmeter 2, close to the surface reads $\rho l j(r_2)$, where ρ is the specific resistivity, l the length between the contacts and $j(r_2)$ the current density at the outer surface. Voltmeter 1 sees in addition to that the voltage induced in the outside loop. When the lightning currents are evenly distributed around the tubular body the magnetic field inside the airplane is zero. Voltmeter 3 then reads only $\rho l j(r_1)$, where r_1 is the inner radius. In Fig. 4 the general behavior of these three voltmeter readings is shown. This picture shows

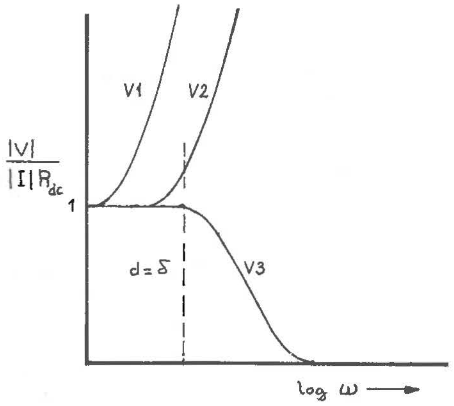

Fig.4: Voltmeter readings as in Fig. 3 as a function of frequency. At low frequencies the dc-resistance determines the voltages; at frequencies where the skindepth is smaller than the wall thickness d the readings V2 and V3 are different. For a steel hull this takes place at quite low frequencies because of the smaller skindepth. The calculations were done with equations given by Kaden [7].

first of all the strong relation with the transfer-impedance of coaxial structures and is secondly most reassuring for airplane electronics since the V3 reading drops quickly to zero at higher frequencies.

For our argument here, it is important to realize that in the loops formed by the voltmeter leads, Kirchhoff's voltage law (KVL) is not obeyed. This is not even true for the small loops in the skin (shown enlarged in Fig. 3) where j and E vary with depth.

3. Distributed inductance and grounding

The failure of the KVL is an immediate consequence of the presence of distributed time-varying flux, as we see from Maxwell's induction law in integral form

$$\oint_c \vec{E}\cdot d\vec{\ell} = -\frac{d}{dt}\int_s \vec{B}\cdot d\vec{S} = -\frac{d\Phi}{dt} \qquad (5)$$

valid for any surface s bounded by contour c. With enclosed flux the closed line integral of E differs from zero and the KVL fails: the sum of the voltages in a circuit loop is not zero. Potentials, as used in electrostatics and in network theory also cease to exist, when we consider distributed inductances, as in Fig.3.

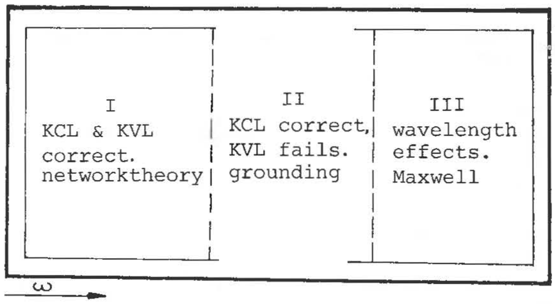

Fig.5: Regions within electrical engineering where different descriptions are required; network theory at the left, the full Maxwell laws at the right. Grounding often falls in the difficult middle region.

One may wonder whether the KVL does not fail much more often in electrical engineering. If electrical engineering can be represented by the large rectangle in Fig. 5 we may distinguish three regions. At low frequency, in region I, network theory can be used, whereas at high frequencies when wavelength effects become important, the full Maxwell description is required, to describe for instance antennas and wave guides (region III). Distributed fluxes are already important at intermediate frequencies (region II), for instance in transmission lines, eddy currents and grounding. In transmission line one avoids the problem by the introduction of an equivalent network and by measuring the voltage only in the perpendicular cross-section. Eddy currents cause the skin-effect, and are also important enough to make thin laminations necessary in 50 Hz transformers. In grounding, the present subject, the leads are often long and have an irregular structure. Since also large currents may flow we are evidently not any more in region I of our diagram and cannot use the standard network theory.

As is demonstrated in Fig. 3 we still have voltage differences even though potentials have lost all meaning. The voltage differences may lead to interference, to breakdown or to a voltmeter reading. With Eq.5 we can always calculate voltages differences; the outcome depends on the lay-out of the leads.

Equation 5 also shows that inductance can only be defined for a closed, or almost closed, current loop. Inductance is a property of the entire loop, and therefore one cannot unambigously localize the "lumped" impedance or the voltage source which simulates the induced e.m.f.

With the failure of the KVL we have lost the duality of current and voltage we were used to in network theory. Since the KCL remains correct we now concentrate on the current and on the circuit in which the current flows (compare Ott's statement in [3]).

4. Grounding philosophy

To design a ground system, based on current circuits we follow a number of steps.

- We must ignore potentials, particularly when they seem to behave wildly, according to the naive picture of network theory.
- We concentrate on the currents in our various circuits.
- We design new, or modify existing current loops such that impedances and coupling to neighboring circuits are minimized. We do this by closing the circuits as compactly and locally as the circumstances allow; this also results in a clearer design.
- We start closing the circuits for the grounding currents in the smallest subsystem. Only after we have solved the local grounding problems we move outward to the next larger system.
- The largest and final ground system (see Fig. 2b) is often partly formed by Mother Earth. We limit the currents to and from Mother Earth as much as possible and let her only play a role when it is absolutely necessary.
- Finally we check by means of Eq.5 whether the voltages at critical inputs are indeed low enough.

Our design method kept magnetic fluxes (self and mutual) small so that we will have fewer deviations from the KVL, than a less compact design would give. Moreover the compact and local approach reduces capacitive or resistive coupling. Generally speaking we may expect the interfering voltages to be small; if not we retrace the steps outlined above.

5. Grounding in various cases

When working outwards from inside the circuits increase physically in size. Induction of currents in ground loops becomes appreciable at ever lower frequencies. The impedance of ground circuits rises, and it becomes increasingly difficult to transport higher frequencies, except by coaxial cables or other transmission lines. These regular structures transport high frequency signals quite well, but may introduce grounding problems at lower frequencies. Well known in this respect is the shield of coaxial cables. The role of this shield and the associated problem of ground loops are discussed in more detail in [5].

5.1 Grounding inside an integrated circuit (IC) or on a printed circuit board (PCB).

In the lay-out of an IC or PCB one designs the current circuits to be closed by a good ground return, as short as possible. Wide ground tracks reduce the impedance and can act as an electrostatic screen between adjacent leads. Decoupling capacitors e.g. for digital circuits must be mounted in close proximity to the IC in order to provide a compact path for the switching currents [8].

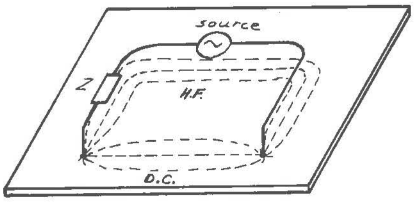

Fig.6: A circuit above a plane, with two connections to the ground. For dc and hf the current patterns in the ground are different.

A common solution of the grounding problem is a plane. In Fig. 6 the return current for dc will flow in the plane according to a pattern that minimizes the resistance. At high frequency the current minimizes the inductance and returns preferentially underneath the corresponding wire (or land) on top. The frequency at which the inductive effects take over depends a.o. on the thickness of the ground plane with respect to the skin depth and on the heigth of the wire above the plane. Any interruption of the ground plane crossing the signal path clearly enhances the susceptibility of the circuit, since it forces the current to deviate from the natural path. However, at the cost of an increased dc resistance one can reduce the plane to strips parallel to the signal leads, thus forming transmission lines, especially on high speed digital PCB's where a continuous ground plane may not be feasible.

5.2 Grounding in an equipment cabinet

Current loops cannot be closed locally at the inputs and outputs of a piece of electronic equipment. In these situations one grounds the low voltage side preferentially to a large sheet of metal; this introduces only little extra resistance and inductance and provides in addition some shielding. In the special case of a continuous metal box, fully enclosing the equipment, one has a good separation between the inside and outside world, the better at higher frequencies. The cabinet then provides the best possible grounding opportunity for both worlds.

5.3 Grounding in a larger system

Larger distances which prohibit local closing, cannot always be avoided between components of a larger system. The ground return leads for power and signal then form loops. The area of the loops can be kept small by putting the leads closely together. In addition one can reduce the flux in the loop by screening, by a closed or U-shaped metal duct between the cabinets.

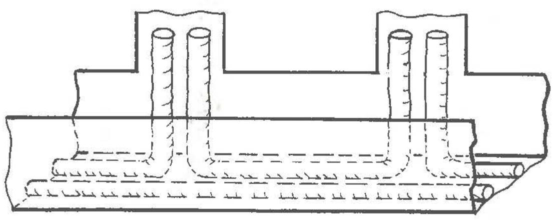

Fig.7: Power and signal leads in a U-shaped metal duct between cabinets.

The combination of the duct and the cabinets (Fig. 7) is topologically identical to a single "wasp-waisted" screen room. A separate safety ground on both cabinets may be imposed by regulations, but it creates another loop, which must be carefully considered [9].

5.4 Grounding on Mother Earth

Here we often deal with loops that only close during fault conditions. For safety reasons one provides a separate, low impedance return lead to earth. This minimizes the voltage between equipment and surroundings in case of failure or short circuit of live lines to earth before switches or fuses interrupt the power.

Lightning is a special case; due to the brilliance of the flash one tends to believe that all current just disappears in the soil. Based on this Franklin developed the lightning protection, a grounded iron rod. Thus an incorrect conception of grounding was firmly rooted; it lived for more than 200 years and generates even nowadays a major problem in EMC. In fact, also in the case of lightning the loop closes, by means of the displacement current between cloud and earth.

In addition the rise time of the current in the flash is short, of the order of 1 μs. Inductive effects must therefore be taken into account and may even be more important than resistive ones, especially close to regions of current concentration, i.e. near impact points. The use of potentials and also the notion of potential equalization by bonding is misleading.

A related misconception shows up when a "clean" Earth connection is requested for expensive equipment. The long separate new connection to Earth introduces interference voltages with respect to the old "dirty" Earth and the building. Local current paths of course provide a much better shorting of interference voltages than the costly detour through resistive soil.

5.5 Single point versus local grounding

A comparison between our proposal of local grounding and the much recommended method of single point grounding reveals the differences in conception. In single point grounding one attempts to minimize coupling between circuits by separate returns for the ground current from each circuit to some point. Thereby the ground circuit is incomplete, the source of interference and, more seriously, a possibly larger common part of the ground circuit is neglected.

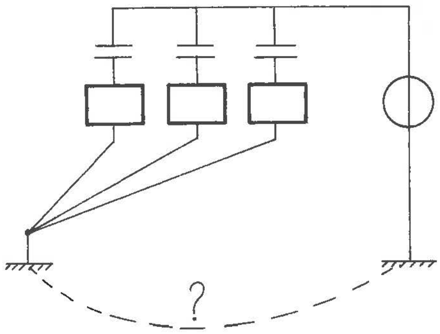

Fig.8: Single point grounding, with source and current path largely unspecified.

In Fig. 8 a compact local ground circuit would be a better choice. In general it is very difficult to decide on a ground system without complete knowledge of circuits and sources. Clearly, grounding on a large metal sheet, as commonly used at high frequencies, closes circuits compactly and locally.

6. Discussion

As is demonstrated in Fig. 5 grounding problems fall often in the difficult intermediate region between the full Maxwell description and the networktheory. On the one hand, networktheory where all fields are conveniently assumed to be hidden inside the impedance symbols, cannot deal with the distributed inductances, which often show up in grounding. On the other hand, we cannot hope to solve the full Maxwell equations for the complicated boundary conditions of the circuits and systems where we encounter grounding problems.

In the resulting situation we have to be careful with our descriptions, our models and also with the words we use. The plea for a correct terminology in grounding discussions is therefore more than an exercise in semantics.

The nouns "ground" or "earth" should be avoided; the "ideal ground" does not exist. (Section 2) and should not exist, even in an "ideal" world, because it would contradict Maxwell's laws.

The activity of designing or constructing the circuits in which grounding currents can flow, is better described by the verb "to ground". In "grounding" we use the basic property of conducting wires or sheets, the ability to carry currents (compare [3]).

The word "potential" should be avoided, since it suggests a unique property of a point in a circuit. Instead voltages depend on the lay-out of the leads of the voltmeter and the leads in the circuit. An appreciable mental effort is required to accept this deviation from network theory, where we indeed label wires according to their potential. In this situation, of a non-conservative E-field, the more restricted word "voltage" should replace the word "potential".

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