Reliable Systems Design using Current Boundaries

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1 Introduction

Many years ago, I started my career as an electromagnetic compatibility (EMC) educator. The reason to teach EMC were some irregularities at the company where a fresh crew of young engineers had been assigned to design and build modern 4-layer double-euro sized printed circuit boards (PCBs) using fast digital logic, to save cost and time over the expensive complicated 20+ layer, much smaller company specific PCB versions that were built before. Unfortunately, the logic devices had become much faster than their predecessors and the boards did not work! It turned out that many other companies were facing the same problems: cross-talk and transmission line effects on PCBs made the, originally independent, hardware modules interfere with each other. It was difficult to build the increasingly complex hardware. A true Hardware Crisis. A similar thing had happened to software engineering (SE) two decades earlier: the Software Crisis [1]. It had become increasingly difficult to produce software as the programs became larger. One programmer could no longer solve the problem on his own and many programmers had to work together on the task.

The answer to this challenge was modularization. The individual programmers would write modules that would then be combined as building blocks for the larger program. My SE colleagues told me, that principle was copied from the hardware engineering (HE) disciplines: cars were built from engines, gearboxes, wheels and chassis for decades already.

SE copied our hardware modularity but, apparently, we in HE overlooked something. The true reasons for this modularity are hierarchy and abstraction [2]. Consider the complete system is built as a hierarchy of independent building blocks of ever-increasing complexity. At the hardware bottom, we find components and modules that can be bought on the market. These are used to build larger assemblies with a more complex behavior. This process repeats until the desired hardware platform behavior has been achieved and continues in the SE disciplines. At every level, engineers combine assemblies from the preceding layer to create building blocks that are more complex. The second essential element is abstraction. Abstraction means that the engineer using a building block has no need to know what is inside. He or she can go blindly by the specifications of the block. This is why the software engineering disciplines focus on the creation of “loosely coupled, coherent modules” as building blocks [3]. In an effort to make their behavior as independent as possible of the behavior of other modules. Mirrored into the world of hardware, they would -at least- be electromagnetically independent i.e. compatible.

Software engineering borrowed modularity from hardware engineering. However, at that time their primary reason - module independence allowing abstraction and hierarchy - was less obvious to the hardware engineer. As hardware becomes more complex and faster, electromagnetic independence is at stake. The current boundary is a concept that allows the electromagnetic separation of modules at any level in the hardware platform within a system. Hence, it is a powerful tool to boost system reliability and maintainability.

The problem in the realization of large programs and, more generally, huge engineering projects is the, so-called, semantic gap. In a nutshell, this is the difference in the language spoken by the customer in comparison to the language of the component supplier. For example, for a complex space telescope, the customer talks in terms of images of galaxies in bent universes while the hardware platform designer is faced with irregular behavior of his transistors and integrated circuits. One person cannot possibly cover all these disciplines from component behavior to working space telescope. This means hundreds of engineers, each with their own specialisms, are working together in hierarchical layers to eventually design, build, test and deliver the complete system.

2 Definition of the Current Boundary

Going by the introduction, the assignment of the EMC engineer is to help make hardware modules independent. Such that designers at a higher hierarchical level can combine these modules going blindly -abstraction- by their specifications. The proposition of this paper is to show how simple it is to meet that requirement, focusing on the electromagnetic interference (EMI) aspects using current boundaries. The term (electromagnetic-) barrier was first mentioned in [4] for the same purpose. The term current has been added in this paper to indicate the barrier, further called boundary, which is a more appropriate word in the context of this paper, functions by short circuiting common-mode currents. The current boundary is a concept or metaphor in the realm of EMC bonding [4], [5], [6]. Maybe, the best way to introduce the current boundary (CB) is to show how it separates electromagnetic environments, considering a system as a combination of cable-interconnected cabinets.

2.1 The Cabinet Level Current Boundary

Figure 1 shows a simple mains-power Common-Mode (CM) current loop. The loop being formed by the cabinet's mains cables, their interconnecting input-output (I/O) cable and the building mains cabling, closing the loop. Any CM noise currents generated by other equipment on the mains or induced by fields in the environment may flow in this loop even when the equipment is off and, in general, the cabinet designer has no control over them. In addition, CM currents can be generated by either or both of the two cabinets when switched on.

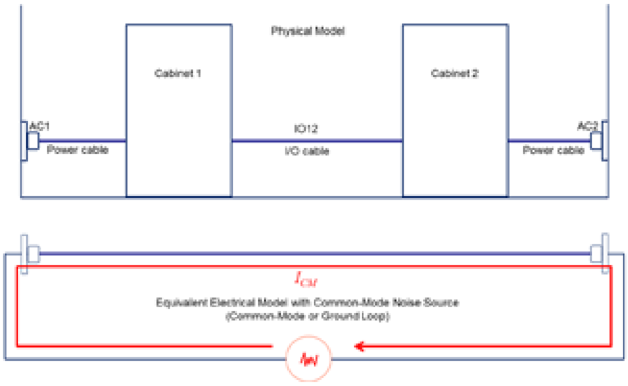

Figure 1: Mains Power CM-Current Loop

As shown by the Equivalent Electrical Model in Figure 1, the resulting CM- current will flow through the cabinets. If nothing is done, the noise currents on the cables may pollute the cabinet-internal environments. A CB can now be built for each cabinet as shown in Figure 2. Figure 2a. shows the original CM-current path through one of the cabinets. In Figure 2b. the routing of the CM-path is changed. Finally, in Figure 2c. the newly created inner-loop is short circuited. This is called CB type I. It prevents the CM current from flowing through the cabinet. A CB is a short circuit for CM currents. Is this a new, groundbreaking technique? No! This trick is as old as the radio and is used by all designers of high-frequency analog electronics: otherwise, these will not work. The problem is that designers of fast digital logic often have not been exposed to these analog effects during their education. A similar situation exists for machine builders and installers who are increasingly using fast switching controllers and sensitive transducers to boost the value of their traditionally electro-mechanic systems. Therefore, the task for the EMC educator is to translate the method into simple experiments in the realms of the different HE disciplines to teach this trick.

Then there is some fine-tuning to be done. The CB is inherently a measure against conducted interference (CI). The short circuit is crucial as it separates a large CM current-loop[1], into two loops. To avoid mutual induction cross-talk, loop areas on both sides of the CB should subsequently be reduced. Whether complete shielding is necessary, depends on the (noise) frequencies at play. If the major threat is a relatively low-frequency lightning induced CM-current, the CB alone may be sufficient. Another important aspect is that a CB works in both directions: it keeps external CM-currents out but also keeps cabinet-internal CM-currents in. In practical applications, the CB is usually shaped as a connector- or EMC-gland plate as shown in Figure 3. Preferably, the CB should be mounted at one location only on a cabinet. More than one connector-plate implies there is a CM-current path between them, which needs to be carefully defined. An inherent assumption is that CM and Differential-Mode (DM) currents in cables are separated by cable shields. The shields carry the CM-currents and these currents are then transferred to the CB via the, low-impedance, EMC-glands or metallic connector shells. If there is no cable-shield, e.g. on a power cable a normally low-pass filter must be installed at the CB to separate the CM-currents from the DM currents. This filter technique assumes the DM currents are low frequency, traditionally the alternating current (AC) mains while the CM currents are high frequencies. As before, the CM-currents are passed to the CB in this case through the filter CM-path to flow back to their source via other connected cables. A quantitative approach to CBs can be found in [7].

2.2 Cable Protection using Current Boundaries

At the inter-cabinet level, CB type II is used to protect and/or separate cables. In modern installations equipment and cabling is tested for emissions and immunity implying the cabling in itself is adequate for the signals transported over them and the level of disturbance in the environment. However, for extreme threats like exposure to direct lightning, extra protection is called for against the sheer I × R voltages that occur. In such cases, extra protection can be obtained from a metal strip following the cable from cabinet-CB to cabinet-CB with a low impedance connection to both: a metal cable tray [6, pp. 33-35], [8]. Often, structural metal, available in the installation, can be used. The important requirement is this continuous conductive path from cabinet-CB to cabinet-CB while the cable(s) under protection should be kept as close to the metal as possible (to reduce loop areas) [6, page 38].

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[1] Often called ground-loop as conductors involved in CM loops are often cable shields and structural parts, connected to protective earth (PE) for safety.

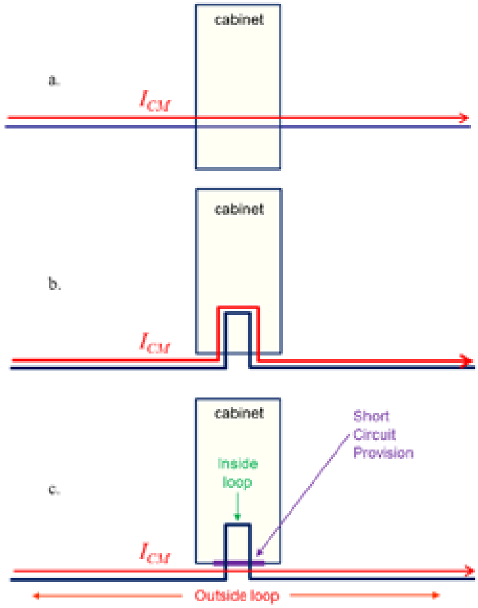

Figure 2: Provision of a CB Type I

Figure 3: Connector Plate (or CB type I) as part of a Shielding Cabinet

The metal strip forms a low-impedance short-circuit across the cable as a preferred path for a threatening CM-current, keeping the cable close to the strip reduces the loop between them. In some standards, e.g. [9], cable categories are distinguished from sensitive to disturbing in combination with a required separation distance between those categories. It is important to note that such distances imply the presence of a common metal strip or floor CB without which separation distances have no meaning. It short circuits the length of the cable and serves as a return path for cable-generated CM-currents. These return currents will select a path that minimizes induction which is called the proximity effect as it is the path closest to the cable and actually separates cables on the strip by reducing the mutual induction between them (M_{12}) as shown in Figure 4.

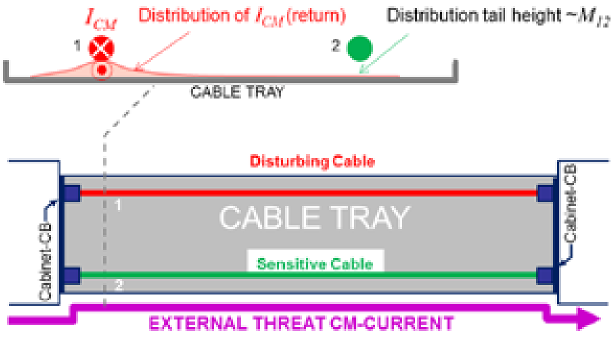

Figure 4: Metal Cable Tray (CB type II) to Protect and Separate Cables

2.3 Cabinet Shielding

A complete metal shielding of all circuits within a cabinet is CB type III. This type is appropriate when protection against electromagnetic (EM)-fields in the environment is necessary or when the environment needs to be protected against fields emitted by the circuits in the cabinet. Like the other two, a type III CB short-circuits CM- currents, here induced by the fields. An example is shown in Figure 5. Type III CBs can be nested like the well-known Matryoshka dolls, shown in Figure 6. To maintain a proper shielding behavior, any conductors entering or leaving the enclosure pass through a type I CB. The shield itself can serve as connector plate as shown in Figure 5. Part of the shield can be used as type II CB.

3 Locate CBs at Natural Transitions

Once current boundaries are explicitly introduced in hardware design and production, it is a valid question to ask a designer, "Where do you plan to have your current boundaries?" Choosing natural transitions as cabinet/equipment walls is a good choice.

Figure 5: Shielded Enclosure (CB type III) with Connector Plate (CB type I)

Keep in mind that during the system life-cycle modifications may be necessary and illogical current boundaries are a nightmare for maintenance personnel. A filter could be an example. Formally, it should be mounted in the CB. Often filters are mounted inside a cabinet i.e. some distance removed from the CB e.g. when the CB itself is exposed to weather. Possibly the cabling should be shielded from CB to the filter Adequate documentation in this respect is a requirement for system maintainability and hence reliability over its life cycle.

Figure 6: Matryoshka dolls as metaphor for nested type III CB

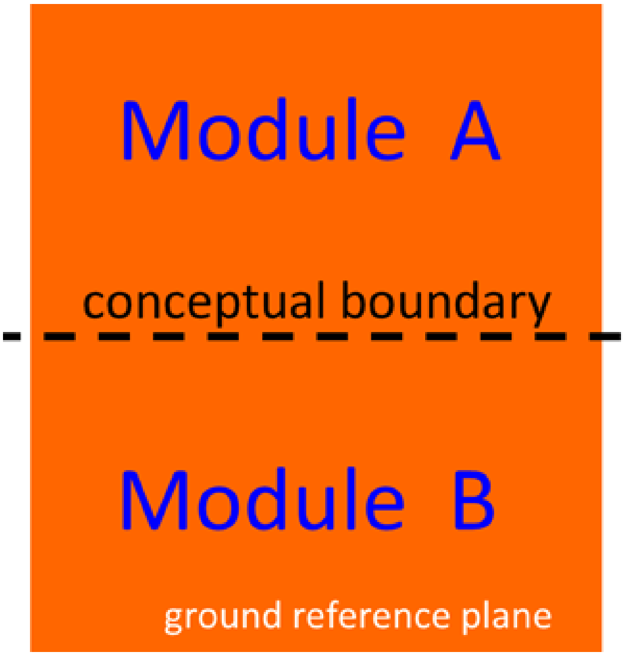

Figure 7: Conceptual CB drawn on PCB board layout

4 Creating CBs on PCBs

As mentioned, large and complex systems are built as hierarchies of modules or building blocks starting from components available on the market and assembled into ever more complex building blocks until the complete hardware platform is realized. In this process, proper care is given to current boundaries for each newly created module. This nesting of modules with current boundaries is the true meaning of multipoint grounding. [10, p.126], [11, p.796] CBs can be applied at any level inside the hardware hierarchy, even between sections of a printed circuit board (PCB)! Since the CB is a physical boundary, the board-layout must be considered. On the board, an imaginary line is drawn where the CB should appear. This is shown in Figure 7. Note that in the PCB case there are no cables. Only signal traces with inherently DM signals: intended voltages and currents[2]. All traces find their return in a ground reference plane (GRP) integrated into the board[3]. Any PCB-trace crossing this boundary is now treated such that it is not possible to carry any noise from one side of the CB to the other. This is shown in Figure 8. The steps to create the CB (type I) on the PCB are:

1. Consider all traces crossing the drawn boundary line in all layers of the board;
2. Recreate each functional signal at the boundary using an active interface device (buffer). What it does is generate a new (clean) copy of the original signal. At the same time, any noise acquired on the trace is (re-)moved to the GRP. For signals going both ways, e.g. bus lines. a bi-directional transceiver should be placed here;
3. A DC (e.g. power) line is provided with a capacitor to the GRP, suitable for the noise frequencies on that line. Officially this capacitor forms a low-pass filter in combination with the inductances inherently present in the PCB traces on either side of the CB;
4. Traces leaving the board through a connector are treated identically (the board edge connector is a natural transition and should be a CB type I).

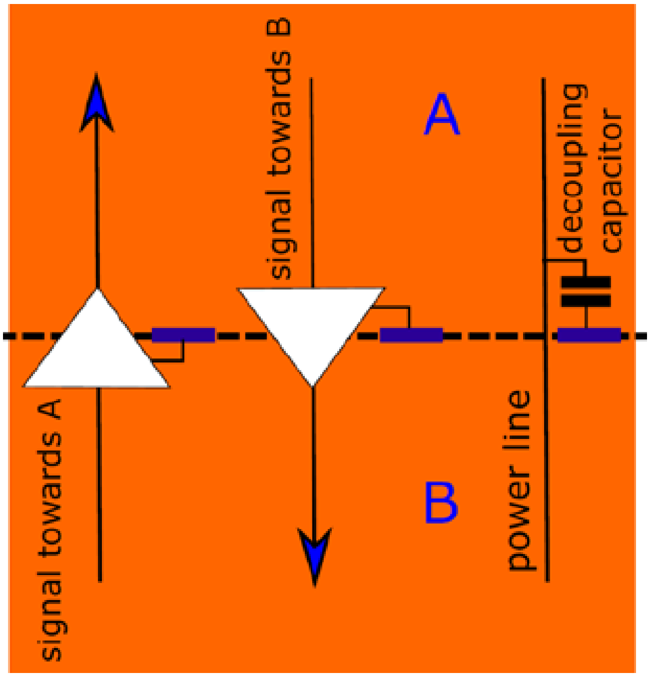

Figure 8: CB on PCB with boundary measures

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[2] Differential pairs of traces used as high-speed transmission lines could be considered as PCB cables.

[3] This is a CB type II and a conditio sine qua non for a high-speed PCB: without it, this approach does not work

5 Conclusion

As mentioned in the introduction, system reliability (and safety) depend heavily on the correct behavior of all building blocks at all times. EMI is a major threat that often manifests only in the final integration and tests phases of the system. It is shown that creating electromagnetically independent modules is easy if a few simple steps are consistently followed. The method pivots on two essential systems engineering aspects:

1. Hierarchy: Building the system as a layered structure with increasingly complex behavior where modules from a lower level serve as building blocks for higher-level modules.

2. Abstraction: Hiding the inner workings of modules from the engineers that use them as building blocks. This in order to reduce complexity.

The concept of the current boundary (CB) is the universal approach to the latter abstraction aspect. Experienced EMC engineers use it under various names: zones for lightning protection [12], regions on navy ships [13]. The process of building adequate CBs at the equipment and system level is usually referred to as grounding and bonding [14]. The link to the abstraction aspect is often not made explicitly. The layered application of current boundaries is the true implementation of what is referred to as multi-point grounding.

For the systems engineer it is important to realize that hardware modules should be as mutually independent as software modules. If the hardware modules are electromagnetically independent, the aspect of abstraction can be realized which is vitally important for system reliability and maintainability due to the semantic gap. Abstraction also hides the effects of EMC measures, which could be mentioned as a negative side effect. Project managers may not want to pay (extra) for invisible measures so constant awareness-building efforts are usually required to obtain adequate funding in a larger organization. For that reason, it is EMC and cost effective to integrate EMC into the development process instead of having it as a separate discipline in the organization.

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Abbreviations

AC	alternating current
CB	current boundary
CI	conducted interference
CM	common-mode
DC	direct current
DM	differential-mode
EM	electromagnetic
EMC	electromagnetic compatibility
EMI	electromagnetic interference
GRP	ground reference plane
HE	hardware engineering
I/O	input-output
PCB	printed circuit board
PE	protective earth
SE	software engineering

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Biographies

***Frits Buesink** (M'09) received his B.Sc. in 1973 and his M.Sc. in 1977 at the University of Twente Enschede, The Netherlands. He has been involved with EMC Education since 1989, in industry, at Thales in the Netherlands as a Senior EMC Engineer, educating several hun-*

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Frank Leferink *(M'91–SM'08) received his B. Sc. in 1984, M.Sc. in 1992 and his Ph.D. in 2001, all in electrical engineering, at the University of Twente, Enschede, The Netherlands. He has been with THALES in Hengelo, The Netherlands since 1984 and is now the Technical Authority EMC. In 2003, he was appointed as (part-time, full research) professor, Chair for EMC at the University of Twente. He has published over 250 papers. Prof. Dr. Leferink is chair of the IEEE EMC Benelux Chapter, a member of ISC EMC Europe, and Associate Editor of the IEEE Transactions on EMC.* **EMC**

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