1

Introduction to EMC

1.1 Electromagnetic compatibility (EMC)

As an increasing use is made of electrical and electronic equipment there will be, if no precautions are taken, ever more disappointments. Disappointments, because the pieces of electronic equipment in use are found to interfere with each other, as a result of their electromagnetic properties. The currents and voltages in one piece of equipment produce electromagnetic (EM) fields that reach into nearby equipment. These fields exert forces on the conduction electrons in that equipment, which means simply that they induce unwanted voltages and currents - which in turn may cause interference. If all equipment could coexist in harmony, then the world would be EM compatible. This is unfortunately not yet the case - there are still electromagnetic interference (EMI) problems to be solved. That the world is insufficiently EM compatible has also attracted the attention of the lawmakers. On 3 May 1989 the EEC adopted a directive on EMC: electrical and electronic equipment brought on to the market must by 1 January 1992 meet certain EMC requirements (emission and immunity limits) according to EMC Directive 89/336/EEC, which in the meanwhile is amended and updated, and resulted in the new EMC Directive 2004/108/EC.

It is obviously better to anticipate EMC problems, by laying down timely requirements and taking the necessary precautions. That means a few more boundary conditions for the equipment designer, which one might expect to lead to even longer development times and noticeably increased costs. This is fortunately only true if one first designs the equipment in the traditional way, only later doing any redesign necessary to meet EMC requirements. On the other hand, when one takes EMC into account from the start of development, it usually turns out that the total time required is less than with the former approach and that the costs directly attributable to EMC precautions will be low. Indeed, the total cost of the equipment is sometimes lower than before - certainly when viewed “from idea to installed product”.

The need to keep EMC in mind from the start of equipment development, given the present-day distribution density of electronic equipment and its complex circuitry, has led to the emergence of EMC as an intermediate specialization. It is a many-faceted occupation: virtually any electrical or electronic equipment, on its own or in combination, along with all the interconnections, may be involved. As a rule the frequency range in which EM phenomena have to be taken into account is far wider than the band of wanted frequencies of the equipment involved. Moreover, the situation may simultaneously involve wanted and unwanted signals, at levels from very high to very low.

Does this imply that EMC is a wide-ranging specialization? That depends on how you look at it. EMI problems appear in a wide variety of guises - from the robot that, due to an interfering impulse, does something else "off its own bat" to a modern telephone that "spontaneously" treats one to a local AM broadcast. However, the many actual manifestations can still be grouped into a limited number of fundamental problems.

The prevention of EMI problems has become a necessity. We simply cannot afford to wait until the problem occurs, and not only for reasons of finance or economics. Also, the safety of human lives depends, ever more frequently, upon electronic equipment being EM compatible. Preventing EMI problems (or, if they still occur, untangling them after the event) requires a certain amount of fundamental EMC know-how. This book is an attempt to present these fundamentals, in a form that will encourage insight rather than as a set of recipes for tackling specific symptoms.

EMC has becoming a more mature specialization. The IEC (International Electrotechnical Commission) has started to unify the terminology. To further this unification, section 1.2 presents a number of EMC terms and discusses the relationships between them. Other terms will be introduced as they are needed, as in section 1.3, where in general terms the EMI problem will be discussed that makes it necessary for us to consider EMC. In section 1.4 we present a few aspects on the prevention of interference. The chapter concludes with a few notes about this book, followed by a short review of the basic literature on EMC.

1.2 Terminology

1.2.1 Electromagnetic compatibility

Figure 1.1 shows the relationships between some of the terms. At the top is electromagnetic compatibility (EMC) - the ability to perform satisfactorily - that has been defined as the ability of a device, equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment.

The collection of terms "device, equipment or system" is often used at present in official IEC definitions (IEC 60050-161, 2008, also known as the International Electrotechnical Vocabulary (IEV) which can be accessed freely at: http://std.iec.ch/iev/iev.nsf). Depending on the subject being discussed the most relevant terms will be selected.

EMC really means living in harmony with others. It has two main aspects:

1. To function satisfactorily, meaning that the equipment is tolerant of others. Put another way: the equipment is not susceptible to electromagnetic (EM) signals that other equipment puts into the environment
2. Without producing intolerable disturbances, meaning that the equipment does not bother other equipment. Put another way: the emission of EM signals by the equipment does not cause EMI problems in other equipment also present.

The two main aspects, EM emission (EME) and EM susceptibility (EMS) are also presented in figure 1.1. Emission may have consequences both inside and outside the system containing the sources of the disturbance. A similar distinction can be made for susceptibility. A situation without any EMI problems inside the system is said to be intrasystem compatible; it is intersystem compatible when there are no EMI problems between systems. Whereas, the main focus with EMC has been to satisfy the legal enforced requirements, still required to gain access to the European and other Markets, due to the ongoing miniaturization, integration and scaling, the main focus has been altered to intra-system issues in the past few years.

Most European languages use a word in this context that can be recognized as meaning "compatibility". One exception is German, where the word used is "Verträglichkeit" and the abbreviation EMV.

1.2.2 EM environment and disturbance

The definition of EMC also includes the terms EM environment and disturbance. By EM environment we mean: "The (time-variant) totality of EM phenomena existing at a given location" (IEC, 2008). This wide description includes not only wanted and unwanted EM signals, but also the propagation characteristics of these signals - velocity, attenuation, reflections, and etcetera - that are in turn influenced by the local EM properties of the material (relative permeability, conductivity, etcetera). These parameters of the EM environment will in general vary from place to place, making the EM environment itself location and time dependent.

There are several possible ways of describing the EM environment. One approach starts from a description of the sources that may be active: a lightning discharge, a high-frequency heating generator, a commutator motor, a switch-mode power supply circuit, a person who is electrostatic charged, etcetera. Another approach lists the measurable parameters, such as current or field strength, without concerning itself about the specific types of sources involved (see sections 2.3.2 and 2.4.2). Before bringing a piece of equipment into an environment, one could consider determining (measuring) that environment - but then the question arises "What should be measured?" This question can only be answered after another question, "To which EM phenomena is the equipment concerned susceptible?" The latter is usually not well known, although a great deal of experience has been collected about which signals are likely to disturb this or that kind of electronic equipment and what kinds of signals should therefore be measured, so that a high percentage of potential interference problems can be prevented.

With regard to the determination of the EM environment, the parameters of that environment are time-dependent quantities. Equipment that is "switched on" contributes actively to the environment, while all equipment and material present can passively influence it. An example of passive influence is given in the following: When mains-borne disturbances are measured, the levels will depend on the impedance of the mains circuit, which in turn will depend on the equipment connected to it, even if

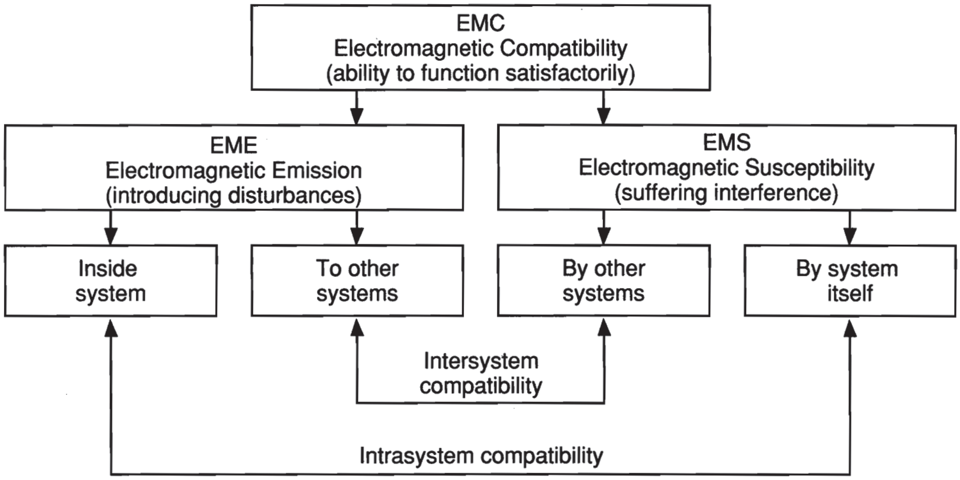

Figure 1.1 - Some EMC terms and their interrelationships.

that equipment itself is not emitting disturbances. Another example is a metal office cabinet, which can be a good reflector of EM fields. The presence or absence of such a cabinet, whether its door is open or closed, can significantly affect the distribution of the field. The presence of a human body standing, sitting, etcetera, will definitely affect the EM-fields to such an extent that it is unusual that people are allowed at close proximity of an EMC test set-up for the sake of reproducibility.

By disturbance we mean "any electromagnetic phenomenon which may degrade the performance of a device, equipment or system or adversely affect living or inert matter" (IEC, 2008). This is another broad classification - particularly since a signal wanted by one person can be an unwanted signal for someone else. An injured athlete will want a 27 MHz signal (free ISM band frequency) from the physiotherapist's diathermic equipment; but an analyst in the neighbouring laboratory will not be so pleased when the blood corpuscle counter goes haywire because its sensor is not protected against the HF field. We shall discuss this kind of problem in section 9.2.

1.2.3 Emission and susceptibility

Let us return to the main aspects of emission and susceptibility. The IEC describes EM emission as "the phenomenon by which electromagnetic energy emanates from a source" (IEC, 2008). The imagery is poetic: water rising from a source and coming to us, partly via a stream (EM energy in a conductor) and partly as vapour via the process of evaporation and transport through the atmosphere (EM energy via radiation). The thing to remember is that both forms of transportation are present simultaneously: where there's a current there's a field. Emission will be treated extensively in sections 2.3 and 2.4.

Susceptibility is described as "the inability of a device, equipment or system to perform without degradation in the presence of an electromagnetic disturbance" (IEC, 2008). Compare the meaning with that of "a person (being) prone to catch a cold". Note that "susceptibility" is preferable to "sensitivity" because it implies an undesirable property, whereas sensitivity is normally a desirable one.

1.2.4 Susceptibility versus immunity

Susceptibility and immunity are complementary concepts - and the definition of immunity is obtained from that of susceptibility by the simple deletion of the "in" from "inability". The change is small but vital - and careless usage has often led to confusion. The two terms have quite different applications. Susceptibility is a fundamental characteristic of a piece of equipment: one can always find an EM environment that will adversely affect that equipment. Immunity on the other hand indicates, when measured in a certain way, to what extent the environment may be EM polluted before the equipment is adversely affected.

When we wish to say something in advance about the immunity of equipment, we can really only do that for specific disturbances that we have injected ourselves. We may know little about the immunity to the same signals entering by a different path - and often nothing at all about the immunity to other types of signals. Suppose you take an anti-flu injection. You are then adequately immune to the flu viruses anticipated by the doctor, but you can still become sick if a new variant turns up - and nothing can be said about your immunity to malaria.

A desired level of immunity is usually reached via precautions based on specific requirements, which include a degradation criterion. As an example of such a criterion, the interfering impulse from a relay in an air-conditioner may be permitted momentarily to jitter the image on a computer screen, but it would be intolerable if that impulse could corrupt the program output. Further concepts and definitions will be treated in the next section.

1.3 Electromagnetic interference (EMI)

1.3.1 EMI model in its basic form

We have already noted that it is the existence of EMI problems that forces us to pay attention to EMC. In this section therefore the EMI problem in its basic form will be examined. The IEC/IEV defines electromagnetic interference (EMI) as "degradation of the performance of a device, equipment or system by an electromagnetic disturbance" (IEC, 2008). This means that the EMI problem can basically be modelled (figure 1.2) in three parts:

1. "Something" emitting EM energy (the source of disturbance)
2. "Something" susceptible to that EM energy (the device interfered with)
3. "Something" between the source and the object (the coupling path)

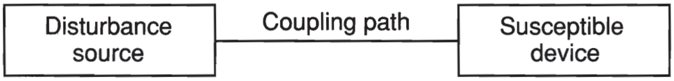

Figure 1.2 - Interference problem in its basic form

In any practical situation, one source may simultaneously disturb several pieces of equipment and several sources may of course disturb a single piece of equipment. However, the basic model for discussions is always that of figure 1.2.

EMI has the same main aspects as EMC: emission and susceptibility. But note that EMI is the interference problem and not - as is often thought - the signal causing that problem. The IEC/IEV reserves the word "interference" for the problem as such and the word "disturbance" for the signal causing it.

One often encounters the term RFI (Radio-Frequency Interference). RFI problems form a subset of EMI problems: those in which at least one piece of the equipment involved is associated with radio communication (radio or TV receiver, walkie-talkie, mobile telephone, broadcast or amateur transmitter, radio beacon, etcetera).

A conclusion that might be drawn from figure 1.2 is that when one element of the model is absent, the interference problem is solved. There are cases in which this approach may be sensible. When a "roaring" source of disturbance is causing many problems, it may make economic sense to suppress that source, meaning "block the coupling path as close as possible to the source". But not every source can be muffled up, a clear example being a broadcast transmitter. A single piece of equipment suffering interference can often be screened off, meaning "block the coupling path as close as possible to the affected equipment". A delicate measurement can, for example, be carried out in a Faraday cage - but expecting everybody watching TV viewing in a Faraday cage is clearly a quite different matter. In general one should therefore adopt a balanced approach to the total EMI problem.

Note that what has been given here before refers to a "roaring" source of disturbance, i.e. a disturbance more powerful than can be allowed for in drawing up basic immunity requirements. When the source can not be qualified as "roaring", it makes sense to do something to the susceptible object, since there is otherwise every chance of another source causing a complaint in the near future.

1.3.2 Levels in the model

The use of "something" in the points 1-3 listed in 1.3.1. is intended to indicate that there are many possibilities, depending inter alia on the level in the model at which one is working. In EMC considerations we may coarsely distinguish four levels, which often partly overlap:

1. System level
2. Equipment (or subsystem) level
3. Circuit-board level
4. Component level

For example: Suppose that an AM broadcast transmitter is interfering with an electronic telephone. When the handset is lifted one hears the broadcast programme, a phenomenon known as "music on the line". At system level the susceptible "something" is the telephone system, cables and the exchange included. At equipment level it is the telephone set. At circuit-board level it is the audio amplifier. At component level, that "something" is a transistor in an integrated circuit picking up and demodulating the RF broadcast signal (see chapter 9), which then becomes audible via the earpiece and is also passed via the line to the exchange and so on to other subscribers.

Also clear is that which coupling path is relevant depends on the level at which the problem is being viewed. At system level the telephone line makes a good receiving antenna for the transmitted signal, while a part is played among other things by the attenuation of radio waves as they pass through the building structure (Goedbloed and Jeschar, 1989). The amount of received signal reaching the transistors depends on the design of the circuit board, important aspects being crosstalk and choice of reference system (chapters 4 and 6) and the circuit topology used. The amount of unwanted signal that is ultimately made audible depends on the design of the audio amplifier (Goedbloed et al., 1983), see also chapter 9. At the source side it is the transmitting antenna array that is the real source of disturbance, so the problem can ultimately only be solved by taking sensible precautions to block the coupling path between the transmitting antenna and the transistors.

1.3.3 Refining the basic EMI model

The basic EMI model can also be viewed with the aid of figure 1.3. At the top are the emitting devices (sources of disturbance), and at the bottom the susceptible devices (victims of interference), with the EM environment in between. Note that a single device can belong to both the source group and the victim group.

Splitting up the problem, using a diagram like figure 1.3, is worthwhile because the requirements that can be specified (and met) with regard to limiting emission and susceptibility depend on just these distinctions. Figure 1.3 gives an example.

1.3.4 Emission

Emission can be subdivided into wanted and unwanted signals taking intended and unintended coupling paths. An example of a wanted signal taking the path intended for is the data signal sent by a factory process computer along a flat cable to the controller of the actual process. When there is internal crosstalk in the computer so that the digital signal reaches the mains lead, the mains lead (plus the wiring to which it is connected) will function as a transmitting antenna for that digital signal. In this

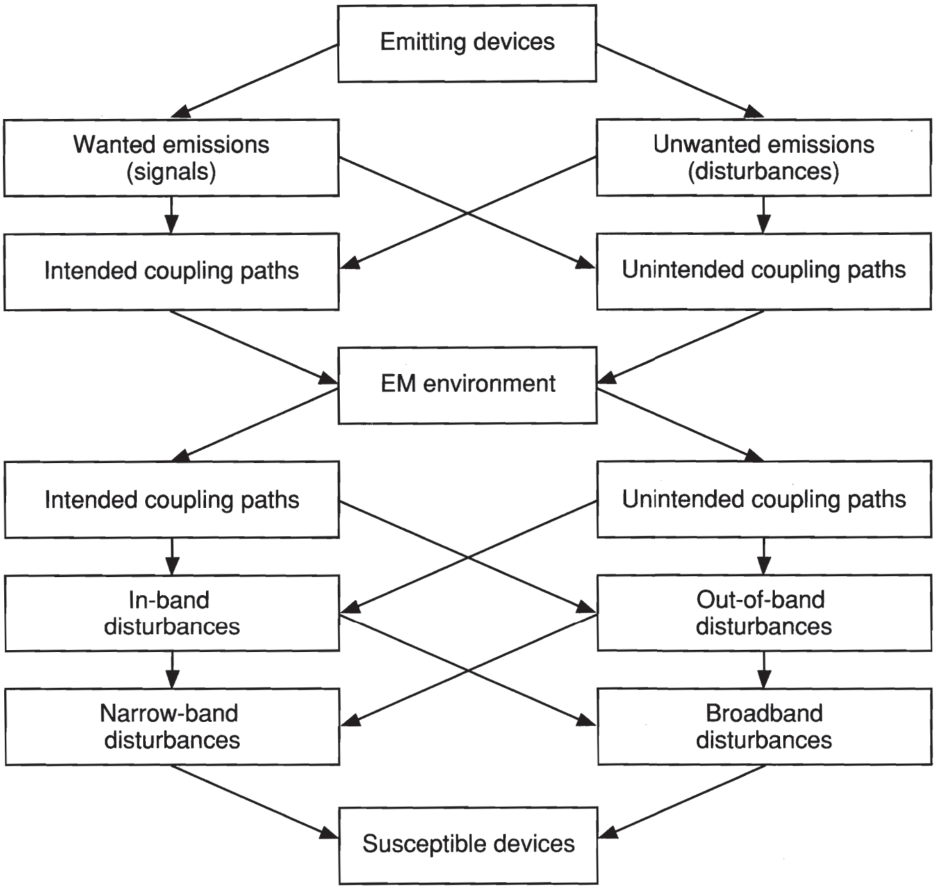

Figure 1.3 - EMI diagram: susceptible devices located in EM environment set up by emitting devices.

case there is a wanted signal taking an unintended path into the EM environment. The transmitted signal might now interfere, for example, with a mobile radio base station, i.e. the receiver will produce "mush" (squelch open) but the expected message will not come. When the mains lead only has to transport 50 Hz signals, the limits that may be specified for the emission of the digital signal can differ from the limits specified for the flat cable. Furthermore, the technical possibilities for suppressing unwanted emission differ between the mains lead and the flat cable.

Do not draw from this example the conclusion that the mains lead is the only unintended coupling path. Any cable, any pipe (e.g. a cooling-water feed), any chink in a metal casing, the opening in the monitor housing of a CRT/LCD, etcetera, can provide an unintended path for both incoming and outgoing signals. Sadly, it is all too often thought that the mains lead is the only item playing a part in the interference problem.

When the computer in this example has a switch-mode power supply (SMPS), the switching signal is clearly only intended for internal use. If that signal does get out, it will always be an unwanted signal following an unintended path. It may be that a wanted and an unwanted signal have (partially) overlapping frequency spectra. If the unwanted signal, at equipment level, gets out by following the path intended for the wanted signal will provide for an awkward problem. Modifying that intended path will modify the situation for the wanted signal as well. The remedy should be sought at a deeper level, in this case at circuit-board level, since that is where the unwanted signal sets out on its (unintended) path of adventure.

The sum of emissions determines the local EM environment, in which potentially susceptible equipment is expected to function satisfactorily. Since just about any signal in that environment can encounter equipment potentially susceptible to it, all signals are normally considered as disturbances, even when they are wanted signals. Some contributions come from close by, others from a (greater) distance, such as broadcast transmitter signals, signals induced by lightning, mains harmonics, and etcetera.

1.3.5 Susceptibility

A disturbance can penetrate a (potentially) susceptible device (figure 1.3) along intended and unintended paths, whereby it can be in-band and/or out-of-band. In-band disturbances contain spectral components that fall within the range of working frequencies (wanted frequency band) of the susceptible equipment. Out-of-band disturbances are obviously those that fall outside that working band.

A closer look at the interference that occurred in the mobile radio base station will be taken here. Clearly, the digital signal radiated by the mains wiring contained an in-band spectral component that entered the base station equipment via its antenna (an intended path). When that unwanted signal is determined by the clock generator in the computer, the spectral components will occur at intervals wider than the bandwidth of the base station receiver. The receiver would therefore see the disturbance as being narrowband so that the interference problem could quite possibly have been solved by slightly changing the computer's clock frequency. It becomes clear that although a digital disturbance has spectral components over a wide band (see section 2.5); the resulting interference problem is of the narrow-band type.

Suppose that in this example there was a video recorder beside the computer and that the switching transformer in the switched-mode power supply (SMPS) was producing a strong magnetic field able to enter the recorder's playback head. The playback head is an intended path for the field from the tape, but an unintended one for the field from the SMPS.

The switching frequency will have a fundamental in the kilohertz range, with spectral components of the unwanted signal from perhaps 30 MHz or above. This band is far wider than that of the video system (5 MHz or 13 MHz (HD)); while very many of the components will lie inside the video frequency band. This means that there is a broadband interference problem. Slightly changing the switching frequency is in this case quite pointless. Furthermore, there is the awkward problem that once the unwanted signal has been picked up by the playback head, there can not be anything done to control it that will not also affect the wanted signal, other than using software filtering algorithms on the data.

These examples make it clear that whether a disturbance has a broadband or narrowband character depends on the bandwidth with which the signal is picked up or observed. Indeed, a single signal can manifest itself both as narrowband and as broadband. When the SMPS switching signal is measured - observed by the video recorder as broadband - with a selective voltmeter having, for instance, a -6 dB bandwidth of 200 Hz or 9 kHz (CISPR, 1987a), the conclusion will be that the signal is narrowband.

1.3.6 Multi-dimensional EMI problem

At the beginning of this section it was noted that several disturbance sources can affect a single piece of equipment. In addition any single equipment will always have several coupling paths, such as all external connections and conduits plus direct radiation of the circuits. The starting point in tackling an interference problem, viewed from the trouble end, is therefore to try to eliminate all but one of the sources and paths so that the basic model can still be used. One aspect of the problem can then be analysed and solved. After that the various paths and sources are allowed back into the problem one at a time, and where necessary dealt with, until ultimately the entire problem has been solved.

Bear in mind that the effect of one type of disturbance source is not necessarily independent of other sources. The computer in this example may be immune to the impulsive disturbance from the air conditioner - unless the mobile radio base station happens to be transmitting at that instant. In the latter case the strong RF signal “uses up” some of the disturbance or noise margin of the digital circuits (section 10.2), with as a result that impulsive disturbances might be able to upset things. In the same way, one coupling path is not necessarily independent of other paths.

1.4 Prevention of EMI

In this section a few aspects of EMI prevention will be discussed - not so much the technology involved, but rather the practical aspects: “What should I do as an equipment user to avoid interference problems, what should be my attitude as an equipment manufacturer, as an installer, as..., etcetera.?” What comes to the fore indicates a clear need for a certain EMC policy (Braxton, 1988; Hürlimann, 1987; Chesworth, 1982).

In reality it is with the user that EMI prevention must start, before the equipment is purchased. It is the user who knows best which equipment will have to work within other equipment’s EM environment - and who therefore can best specify the EMC requirements. Many users will reasonably object to the imposition of this role: “Look, I just want the equipment to do what I’m paying it for to do...” Users will none the less have to learn at least to ask questions about the aspects of emission and susceptibility of the equipment to be purchased. This is, after all, just like asking questions about the suspension of a car, when one is buying it in the knowledge that one will be driving long distances on bad roads.

Alas, answers to EMC questions are not always forthcoming. An immunity question is for instance often met with “the mains voltage must be 230 V_{AC} plus or minus 10%”. The supplier is aghast at such questions as: “Is the equipment immune to 6 kV discharges of static electricity?”; “Is the equipment immune to high- frequency fields of 3 V/m?”; “Is the equipment immune to a complete dropout of a half cycle of the mains supply?”, “Is the equipment immune to an impulsive disturbance on the mains of 1500 V, with a rise time of 5 ns and lasting 50 ns?”; and “Is the equipment immune to a 50 Hz magnetic field with a strength of 80 A/m?” This small list of questions on immunity is certainly not exaggerated, indeed, it is already internationally recommended (see chapter 12).

1.4.1 Specifications and installation guidelines

Imagine a user who has EMC expertise, or who has found a supplier with that expertise, with whom he or she is discussing his or her EMC needs. The starting point in achieving an EM-compatible system is the drawing up of an EMI matrix. An example of this for equipment level will be given later in this section. From this matrix one can derive EMC specifications for the equipment and/or EMC guidelines for the installation of the system. When the equipment meets these specifications (and if you have done our homework properly), there will be no problems.

If equipment does not meet the EMC specifications, the next step is to study the alternatives - to work out a sensible course of action. This will lie somewhere between “modifying the equipment to bring its EMC up to spec” and “making up the leeway with installation guidelines”. How this choice turns out will depend strongly on the practical situation, so it is not possible to give specific guidelines. There are, however, a few points worthy of consideration:

- Which EMC specification is not being met?
- On emission: is the equipment a source of disturbance for other equipment?
- On immunity: is the equipment easily interfered with by other equipment?
- How much equipment of that type is to be installed and in which EM environment(s)?
- What will it cost to bring the equipment up to EMC specs? And what will it cost if, instead, a problem is risked – and occurs?
- What about safety and legal responsibility for an accident?
- Will the equipment be designed and built in-house or will subsystems be bought in, so that I must provide the buyers with EMC training and detailed EMC specifications?
- And so on...

When drawing up installation guidelines one should bear in mind that once the system is working the user will quickly forget what those guidelines were intended to achieve. There is every possibility that a minor or "temporary" modification of the system will cause a (major) interference problem. When the EMC of a system depends entirely on installation guidelines, there will have to be rigid EMC discipline throughout the working life of the system.

An equipment manufacturer can in principle draw up an EMI matrix for the subsystem and circuit-board levels, based on the user's EMC specifications. This approach may give acceptable results with a large system, for once-only on-site assembly. If the manufacturer is sensible, however, he will in good time put himself in the user's shoes, drawing up meaningful EMC specifications and then proceed to meet them. Alternatively the manufacturer can apply the internationally recognized IEC standards. Examples of these standards are: for emission at frequencies above 9 kHz, those of IEC/CISPR (Comité International Spécial des Perturbations Radioélectriques) and for immunity those of the IEC Technical Committee 77 (see chapter 12).

Statutory limits for emission and immunity are applicable from January 1992 onwards throughout the EC. Several countries, such as Germany, have been imposing such limits for some time. Suppose there are no statutory limits (yet) - may an equipment manufacturer then ignore EMC? In principle he may. The manufacturer will not, however, be the first to lose market share to a competitor whose products do meet sensible EMC specifications, nor will production costs be as low as those of a competitor who makes a practice of applying EMC requirements to all products and production equipment, with the attendant advantage of a shorter run-through time.

1.4.2 Example of an EMI matrix

Figure 1.4 shows an example of a user's EMI matrix. Suppose that a laboratory area for semiconductor devices is to be installed (Goedbloed, 1987a). The equipment required is: an air-conditioner ("air-con"), a "sputter" unit in which strong HF fields (RF generator) are used to deposit thin layers of metal on a semiconductor surface and a computer-controlled oven to "bake" the semiconductor wafers. There are also one or more operators and of course the surroundings, the rest of the outside world.

In figure 1.4 the equipment is listed horizontally as prone to suffer interference (susceptibility) and vertically as possible sources of disturbance (emission). A minus sign in a matrix box means "no EMI problem possible", a plus sign means "EMI problem" and an asterisk means "EMI problem possible, but it has been shown that it will not occur". The objective is to get a minus sign or an asterisk in each box.

Suppose that figure 1.4 is an intermediate result of the study. We can now draw the following conclusions:

1. The main diagonal contains only minus signs - intrasystem compatibility has been observed (or presumed).
2. The computer is clearly a susceptible object - immunity requirements will have to be drawn up for it.
3. The operator and the outside world are clearly part of the scenery.

		Susceptibility					
		Air-con	RF gen.	Oven	Computer	User	Outside w.
Emission	Air-con	–	–	–	+	–	–
	RF gen.	–	–	+	+	*	*
	Oven	–	–	–	*	–	*
	Computer	–	–	–	–	–	*
	User	–	–	–	+	–	–
	Outside w.	–	–	–	+	–	–

Figure 1.4 - Example of a user's EMI matrix.

Let us now look more closely at the plus signs and the asterisks.

1.4.2.1 Air-conditioner (Air-Con)

The air-con contains relays and electromechanical valves that produce transients at switch-on and (above all) at switch-off. These transient impulses can interfere with the computer, via a coupling path that includes the mains wiring. The accompanying impulsive fields can also induce disturbances in the sensing lines connected to the computer, causing interference. The computer will therefore have to meet certain immunity requirements.

It is, however, also very sensible to specify emission limits for the air-con - because it is a source of disturbance that will probably upset everything digital in its environment. Emission limits for the transients can easily be met by the insertion of, for example, RC-networks or snubbers (chapter 11). Designers of air-cons should either take these precautions as standard or else specify exactly (in the service documentation) what components are needed and where. Alas, (too) many of these designers are well versed only in the workings of heat exchangers. If the air-con is made to meet certain emission requirements, it is quite possible that the computer's basic immunity will be sufficient, so that no further measures will be needed.

1.4.2.2 RF generator

The RF generator will often operate at an ITU "free frequency", for example 13,56 or 27,125 MHz. The International Telegraph Union (whose business is to protect radio services) specifies no emission limits for these frequencies (CISPR, 2009) so that emission may only be limited by safety requirements. The safety limits for these frequencies are at about 30 ... 60 V/m (measured close to the equipment and dependent on the time average of personnel exposure to the field). These values are much higher than the 3 V/m mentioned earlier in this section.

One should raise the matter, in good time, with the supplier of the sputter unit. The supplier should be able to state:

- which limits are normally applied and
- which modifications will be needed if the unit is found to exceed, say, 3 V/m at a distance of 1 metre.

When it is clear that the latter limit will be met, one can issue an installation guideline: "No equipment potentially susceptible to RF fields, not even that meeting the 3 V/m immunity criterions, shall be placed within 3 metres of the generator."

The 2 metre difference between the 3 V/m boundary (at 1 metre) and the boundary of the "forbidden zone" (at 3 metre) is a safety margin, necessary to allow for emission and immunity testing according to agreed procedures, neither of which necessarily gives 100% cover. The reason is that emission and immunity both depend on the final placement of the equipment, in particular on the layout of cabling and other conduits that behave as transmitting and receiving antennae. The standard test procedures are, however, usually designed to be reproducible, so that the results of measurements on different makes and types of equipment can be compared with each other.

It will be clear that a good test, at best, can approximate real-life situations (very) closely - but not for 100% - hence the use of margins (IEC, 2008). If one compares the standard emission and immunity test procedures with one's own situation, it is possible to estimate the extent to which the tests will be representative of that situation. This comparison will then lead to agreement about the test procedures and to installation guidelines - above all those concerning the layout of all cables and conduits - to ensure that the results of the agreed tests remain sufficiently representative.

In figure 1.4 it is assumed that the sputter unit has been checked for safety, hence the asterisk in the RF generator/operator box. The asterisk in the RF generator/outside world box reflects the assumption that the limit of 3 V/m at 1 metre will be realized and that it is reasonable to expect the fall-off of field strength with distance, along with attenuation of the RF signal by the reinforced concrete wall, to keep the field strength outside the laboratory area below 0,1 V/m. Experimental setups in neighbouring areas, which cannot be required to meet the 3 V/m immunity criterion, should then none the less function correctly.

There is no absolute certainty that the sputter unit will never cause an interference problem, either inside or outside the laboratory. Suppose the RF generator breaks down and is repaired on the spot: there is every chance that the EM screening will have been removed during the repair, so that (very) high field strengths may occur.

The specification of the computer might indicate that it would be immune to the anticipated RF fields. Nevertheless put a plus sign in the matrix - because the computer has to control the temperature in the oven - and the oven thermocouple could be a good antenna for the RF field. The relatively strong RF signal that would then reach the computer's A/D converter (ADC) is also the reason for the plus sign in the generator/oven box, since non-linearity in the semiconductor devices in the ADC will rectify or fold-down the RF signal, so that what will be converted is the total DC voltage (thermocouple output plus rectified HF). The computer will in turn adjust the oven temperature until this incoming signal matches the programmed set point, resulting in a display on the monitor of the correct temperature - but, unfortunately, in a quite different actual temperature inside the oven. For this part of the system it will therefore be necessary to draw up immunity requirements, which can certainly be met by a correct application of capacitors (section 9.3.2). The immunity requirements make sense anyway, bearing in mind the wide use of wireless communication devices.

1.4.2.3 Oven

The high currents through the oven produce magnetic fields that can upset the deflection of the electron beam in the monitor CRT, causing the image to "jitter" slightly. This will not in itself affect the system reliability. If, however, the jitter starts to irritate an operator, unpleasant things might happen. The oven/computer box of figure 1.4 gets an asterisk, since the oven and computer form a single system, designed and tested by a single supplier.

The same high currents can produce magnetic fields around the oven's mains supply and protective (safety) earth cables (chapter 6), and therefore also in the "outside world". In that outside world we must, for example, ensure that these cables are kept well away from electron microscopes, which would otherwise no longer achieve their full resolving power.

It will be pointed out in chapter 7 that it is difficult, and therefore expensive or even impracticable, to screen-off 50 Hz magnetic fields. Meaningful emission limits cannot be imposed, so that in the first instance everything depends on careful planning of the mains cable layout and choice of protective earth points - i.e. on the installation guidelines. In figure 1.4 it is assumed that these guidelines are (or will be) drawn up, that they will be observed and that the work will be inspected.

1.4.2.4 Computer

It is assumed in figure 1.4 that the computer meets the emission limits of European Standard EN 55022 (CENELEC, 2007 and again amended in 2007) so that it will not cause any interference problems in the "outside world".

1.4.2.5 Operator

One of the great plagues for digital equipment is the discharge of static electricity (Mardiguian, 1986), usually referred to as ESD (Electrostatic Discharge, see chapter 11). The computer will certainly be susceptible to this phenomenon, unless ESD immunity has been specified for it. It is impossible to impose direct emission limits on ESD - but one can impose indirect ones. What is meant by this is: arrange things so that static charges cannot build up, by using special floor coverings or treatment, by correctly choosing clothing (including shoes) and by maintaining the correct relative humidity.

1.4.2.6 Outside world

The outside world, the surroundings of the laboratory area, can always provide unexpected disturbances. It therefore makes sense to demand certain basic limits (minimal requirements). The computer must, for instance, tolerate short mains dropouts due to switching by the power company.

This concludes the discussion of a user's EMI matrix. We hope to have made clear that a good look in advance can identify many potential EMI problems, at a moment in time when they can still be prevented easily and solved inexpensively. The various digressions will, hopefully, give the (imaginative) reader enough handholds for setting up his or her own EMI matrix.

1.4.3 Signal-to-disturbance and signal-to-noise ratios

In the final chapter of this book the EMI matrix will again be discussed. By that time the reader will, hopefully, have a clearer idea of how to decide when a matrix box merits a plus, minus or asterisk. What one must in fact do is check, for all critical points in the circuit, that the wanted signal: S is sufficiently strong compared with the sum of disturbance: D and noise: N, although the comparison itself may not necessarily be that simple. With EMC it is no longer enough to take the signal-to-noise ratio S/N on its own, what has to be considered is the ratio S/(D + N).

Depending on which is more important at any critical point we usually check either the signal-to-disturbance ratio (eq. 1.1) or the signal-to-noise ratio (eq. 1.2).

$$\frac{S}{D+N} = \frac{S}{D} \tag{1.1}$$

$$\frac{S}{D+N} = \frac{S}{N} \tag{1.2}$$

In the case of the thermocouple circuit, which in the EMI matrix was under siege by the RF field, the choice would be for S/D, because the noise in that circuit is insignificant and D > N is usually permissible. In the case of the mobile radio base station besieged by the digital signal, the relevant ratio is S/N within the receiver bandwidth and the requirement to be met is D < N*.

*Most available literature still uses the term "S/(I + N)" where we use "S/(D + N)". We shall, however, follow the IEC in reserving the "I" for interference (the problem) and "D" for disturbance (the signal causing it).

1.4.4 Costs

Costs always play an important role, so everybody concerned should understand the cost/availability diagram of figure 1.5 (Ott, 2009). The intention behind this diagram is to impress the fact that practical, convenient and cost-effective measures originate with precautions taken in the research and design phases - the trend lines for cost and availability already intersect in the test phase. So: design from scratch with EMC in mind.

If EMC considerations are withheld until the start of production, there is every chance (particularly with digital circuitry) that the first sets coming off the assembly line will not meet statutory requirements (2004/108/EC). At that moment the cost price will explode with redesign of ICs, printed circuit boards, altering software, reprogramming of production machines, deliveries later than contract date, etcetera.

There are not only statutory requirements to be met. Some equipment users also specify EMC requirements - often more stringent ones. This is because the lawmaker's starting point is: "Thou shall not make Thyself unto a Nuisance for thy Neighbour", implying that there will be on average a considerable distance between a disturbance source and a possible interference problem. At the user's site, however, the disturbance source will often be installed in close proximity to other equipment, so that there will be a relatively high likelihood of interference. Ensure therefore that there will be no need for costly precautions at the user's site, to achieve interference-free operation of the equipment. Beware of the loss of goodwill.

1.5 About this book

This first chapter has been something of a general introduction. Next, chapter 2 presents ways to describe the electromagnetic environment. It can be taken as a

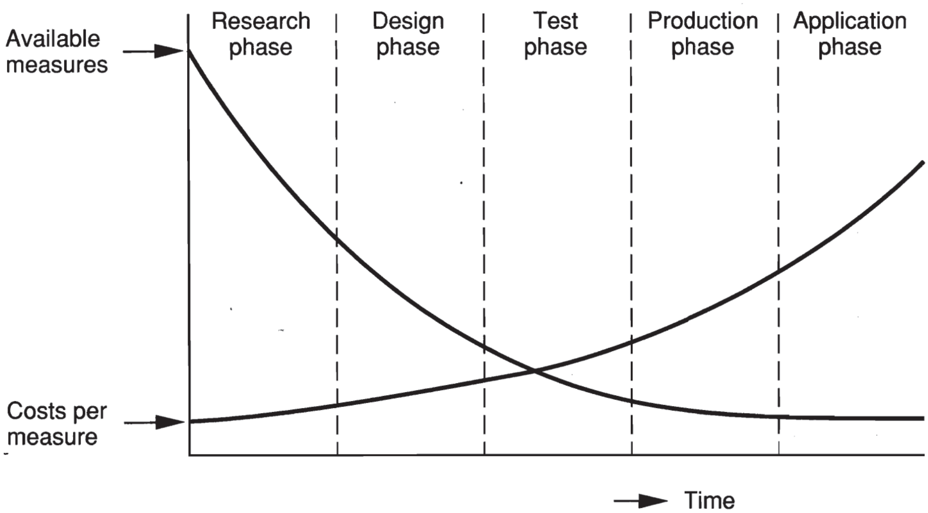

Figure 1.5 Availability of EMC measures, and the associated costs, as functions of time.

technical introduction to the book. It discusses the basis of a number of electromagnetic phenomena, gives a little practical signal analysis and has something to say about decibels (dB) and often-used units.

Most EMI problems occur because it is forgotten that a current (i.e. charge carriers in motion) is always accompanied by a magnetic field and a voltage by an electric field. A more complete discussion would, moreover, show that every time-variant field always has both a magnetic and an electric component.

Chapter 3 (EMI properties of passive components) and chapter 4 (Crosstalk) are intended to bring the field concept into the description of circuits. The “extras”, compared to a description without field influences, are due mainly to the network of conductors interconnecting the components. One of the main tasks of the EMC specialist is the careful design (and layout!) of this conductor network. Some authors defend the theorem that, as a result of the fields, Kirchhoff’s laws are no longer valid. I disagree with this view, and so no doubt would Kirchhoff (1824-1887), if he could. When the fields are brought into the description, which is no more than completing the picture, Kirchhoff’s laws will predict the correct results.

The various effects are described wherever possible by means of equivalent circuit diagrams. The diagrams used are those valid for the “low-frequency approximation”, meaning that they apply when the dimensions of the system are significantly smaller than the wavelength of the disturbance under consideration. This is not such a serious limitation as it may appear, because if the LF circuit already predicts trouble, the complete circuit (valid at all frequencies) will do the same. In the various chapters it will be indicated when the system does not allow that LF approximation.

Chapter 5 (Cables) and chapter 6 (Earth and reference) are applications of the theory treated in chapters 3 and 4. Cables merit separate treatment because in many interference problems the signal cables, mains cables and other conduits (lines for water, gas, and etcetera) provide the main coupling paths. Practical experience marks chapter 6 as one in which some widely accepted ideas must go out with the rubbish - Mother Earth is simply not a bottomless cesspit for any and every disturbance. Attention will be drawn to the fact that currents flow in closed circuits (loops) - a point often forgotten during the design of earth and reference systems.

The first half of chapter 7 (Screening) presents a new theory on the attenuation of fields by metal planes. This theory is applied, in combination with earlier material, in the second half of the chapter. Chapter 8 (Filters and electrical separators) covers two large classes of components used to suppress interference. Attention is drawn in this chapter especially to the limited possibilities of these components, whether that is due to a basic property of the component or to the way in which we apply that component. Chapter 8 is really just an application of chapters 3-7.

The concept “application of theory’ is used several times to indicate that the amount of new material is limited. EMC know-how is neither a "fortuitous" ability to memorize hundreds of rules nor has it anything to do with magic. It is no more (but also no less) than the correct application of normal fundamentals. Students on EMC courses I have taught often say "We really had all the necessary knowledge already, but we didn't realize how we could (and should) apply it to achieve EM compatible circuit design." Furthermore, when the text contains a "see..." it is rarely the intention that the reader should immediately dig up that cross reference; the idea is rather to point out that EMC is, after all, not such a wide field as one might think.

Chapter 9 (Non-linear phenomena) takes EMC fundamentals a step further, considering mainly the susceptibility of semiconductor circuits to disturbances at frequencies outside the band of wanted signal frequencies. Many problems with out-of-band disturbances still occur because many designers do not look beyond the band edges of the wanted signal.

Chapter 10 examines a few aspects of the youngest generation of circuits, the digital ones. For EMC this is a very EM noisy generation, and the very youngest ones - the high-speed digital devices - are the noisiest. Some people think that it is very difficult to confuse digital devices, because they know so well what is "yes" and what is "no". If, however, a certain borderline (the disturbance or "noise" margin, a few volts) is exceeded, the derailment is complete, so that the devices have to be re-educated, i.e. the only way out is the "master reset".

Impulsive disturbances (chapter 11) can upset digital circuits in particular. Besides disturbances due to the opening and closing of switches (particularly when there is inductance in the switched circuit), those due to ESD are very good at penetrating deeply into a circuit and there exceeding the disturbance margin. Most attention will go to ESD as a source of disturbance, since for the correct functioning of digital circuits it is "Public Enemy no. 1". ESD as the destroyer of actual devices is not normally considered part of EMC work, although there will be a few remarks made about that subject.

The book concludes with information about EMC activities by statutory bodies and large international organizations regarding the limits for emission and immunity.
Besides the theory, this book contains a quantity of practical experience - the result of a great deal of EMI "fire fighting". The step from fire fighting to fire prevention requires both guidance and training. We have found that students value the opportunity to observe the basic effects via simple experiments, using the kind of materials that are invariably to hand in electronics-oriented surroundings. The experiments are described in this book.

Of the English-language books on EMC it is a great pleasure to mention that by Ott (1988 and 2009), to which there will be regularly referred to, to supply the reader for more information. For designers it is a useful book that pays a great deal of attention to the understanding of the phenomena. Another useful book is that by Tim Williams

(1996) “EMC for product engineers”. Also mentioned should be the books by Don White, which contain useful information but are sometimes of the cookery-book type with relatively few real explanations and often ignoring the validity range of the models used (White and Mardiguian, 1985). There are also two EMC periodicals in English (IEEE Transactions on Electromagnetic Compatibility, a journal of the IEEE Electromagnetic Compatibility Society, New York, and EMC Technology & Interference Control News, Interference Control Technologies Inc., Gainesville, Virginia). For those interested in the mathematics behind EMC, the numerous books of Clayton R. Paul are recommended. There are of course other EMC books and non-inclusion of one here certainly does not imply a criticism of the quality of that book.

The number of conferences on EMC is decreasing: the International Symposium and Exhibition on EMC which was held on odd years, usually at the Electrotechnical University (ETH) in Zurich has now gone internationally; the International Wroclaw Symposium on EMC is held on even years in Poland is merged with EMC Europe from 2010 onwards. There is also a yearly EMC conference in the USA as well as in the Far-East, held by the IEEE. Another one deals with EMC at the IC level, EMC Compo, which is held throughout Europe and might go international too.