ELECTROMAGNETIC COMPATIBILITY

IN POWER ELECTRONICS

László Tihanyi

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Foreword

Electromagnetic compatibility (EMC) has come a long way from the "black magic" approach of the early 1960s to an almost exact science, with its analytical methods, measurement techniques, and simulation software. Three decades ago, all existing handbooks on EMC could be counted on the fingers of one hand, but today they could occupy several shelves in a respectable library.

However, although there is an abundance of books covering the many radio-frequency aspects of EMC (e.g., noise reduction in analog and digital circuits, shielding theory and practices, math modeling of EMI radiation and coupling, EMI testing, lightning and electrostatic discharge, and so on), only a very few books are available that thoroughly address the EMC side of power electronics.

László Tihanyi's book goes deeply into practical details of power supply components' noise generation, diode recovery, and the SCR noise spectrum. It performs a thorough, but very practical, examination of the parasitic behavior of EMI filters, capacitors, and inductances, and how they affect the filter transfer function, sometimes turning the expected attenuation into gain.

Finally, a rigorous but, again, very practical analysis is presented for the time-to-frequency conversion of single impulses, including their often-neglected energetic aspect.

—Michel Mardiguian
St. Rémy les Chevreuse, France
October 1994

Preface

In the course of their daily routine, experts in the field of power electronics more and more often encounter the problem of high-frequency interference. In practice, EMC issues usually are ignored until a problem is revealed by testing or in normal operation. As a result, EMC fixes tend to be applied at the test or even production stages of product development, which can lead to solutions that are unsatisfactory, unnecessarily expensive, or both.

To avoid this situation, those who are involved in design, development, production, and operation of semiconductor equipments must be able to identify and solve EMI problems as early as possible. These individuals must acquire a grasp of practical noise reduction techniques without actually becoming professional EMC engineers. Although a great deal of written material on EMC has appeared in technical journals and symposium records, these sources constitute a collection of miscellaneous subjects which do not always interrelate and are difficult to use in engineering practice. This book brings together a cohesive package of information on the somewhat specialized subject of EMC in power electronics, thereby saving the reader from the task of sorting through hundreds—perhaps thousands—of volumes of marginally related material. It is intended to be useful to newcomers to the EMC field as well as those who are already fighting stubborn EMI problems.

Laszlo Tihanyi
Budapest, Hungary
June 1994

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Introduction

The role of electrical energy in our everyday lives has grown by leaps and bounds during the twentieth century. In the early decades of the 1900s, experts in most fields took a direct approach to achieving their goals, without much regard for or understanding of the negative side effects of their technological innovations. Thus, the deleterious consequences of rapid development came into the limelight only later. In recent decades, some of those consequences have reached international proportions, making it necessary to study them, with the ultimate aim of reducing or eliminating the disagreeable effects.

One such problem is environmental electromagnetic pollution. Unacceptably high-level electromagnetic disturbances can prevent electrical and electronic devices, apparatus, and systems from operating properly in a common electromagnetic environment. A device is considered to be electromagnetically compatible only if its effects are tolerated by all other devices operating in the same environment. To ensure that this compatibility exists, a relatively new engineering discipline, *electromagnetic compatibility* (EMC), has evolved. EMC is the field of electrical engineering that studies, analyzes, and solves electromagnetic interaction problems.

Achieving EMC requires us to view disturbances from two distinct viewpoints: *electromagnetic emissions* and *electromagnetic susceptibility*. Because electromagnetic noise propagates by conduction and radiation, the scope of problems outlined above continues to broaden (see Fig. 1.1).

Because *electromagnetic interference* (EMI) first emerged as a serious problem in telecommunications (or, in particular, broadcasting), EMC tends to be discussed, even to the present day, within the scope of telecommunications technology. However, there are limitations to this approach.

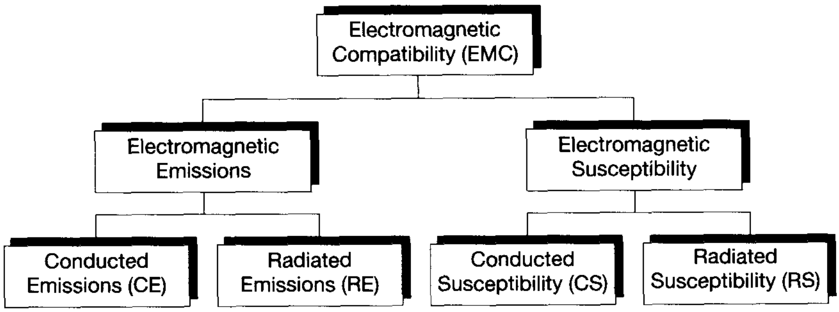

FIGURE 4.1 Areas of electromagnetic compatibility

In the first half of this century, electromagnetic disturbance sources, for the most part, were limited to motor-driven machinery and switching apparatus. But with the rapid spread of power semiconductors and power electronic systems, interference levels on power mains have increased significantly in intensity and frequency of occurrence. This trend is universally forecast to continue. At the same time, the world is becoming more densely populated with devices that are increasingly sensitive to electromagnetic disturbances. In industrial spheres, electronic control systems, data processing equipment, and other sensitive devices play an increasingly important role.

These developments have produced quite a serious situation. In telecommunications, adequate methods for computing and solving EMC problems have been developed over the years. Unfortunately, many of these methods cannot be applied directly to the field power electronics, which has its own peculiarities. The scope of this book, therefore, is to provide a wide overview EMC principles while highlighting EMC engineering practices that are specifically applicable to power electronics.

EMI produced by power semiconductor equipment decreases rapidly above the range of a few megahertz. In various standards and specifications, high-frequency disturbances that affect power mains are limited to the range of 10 kHz to 1,000 MHz. Because different EMC solutions are applicable to different frequency ranges, this book emphasizes EMI suppression in the range of 0.15 to 30 MHz. Likewise, discussion of susceptibility issues is limited to this frequency range, with particular attention given to impulse-like noise phenomena.

After a brief history of the development of EMC standards in Chapter 2, Chapter 3 provides a general description and classification of EMI. Chapter 4 deals with methods for measuring conducted high-frequency disturbances, and Chapter 5 surveys EMI specific to power electronic equipment. The characteristics of circuit elements used for noise suppression are the subject of Chapter 6. In Chapter 7 EMI suppression methods used in semiconductor and electromechanical devices are summarized. Chapter 8 explores various aspects of EMI filter circuits, and EMI filters methods are discussed in Chapter 9.

Moving into the realm of susceptibility, noise-withstand capability tests are described in Chapter 10, and Chapter 11 offers a look at the primary EMS reduction techniques for power electronic equipment. Finally, Chapter 12 addresses filter circuit design for EMS reduction, with particular emphasis on impulse-like disturbances.

2

History of EMC Standardization Efforts

Since the emergence of EMC as a field of inquiry, suppliers of electrical energy have looked for applicable solutions. Difficulties in achieving EMC have become greater with the fast proliferation of equipments that generate high-frequency EMI and electronic devices that are susceptible to these interfering signals.

For the sake of providing the proper power quality, two objectives must be achieved. On the one hand, HF emissions that can be imposed on the power mains must be limited; on the other hand, we need to elaborate on current EMS test methods with the goal of reducing the electromagnetic susceptibility (EMS) of devices on the consumer end of the power grid.

Efforts to establish acceptable HF disturbance emission levels, however, have run up against several difficulties. Many years ago, experts examined HF pollution of the mains. Initial efforts to achieve EMC in this realm focused on limiting the HF emissions of equipment connected to the mains. Preliminary EMI measurement methods were developed at that time, and several limits for HF emission of electrical equipments were determined. A more comprehensive study of EMS came into being only in the second half of this century, stimulated by more widespread use of electronic devices [33, 54, 84, 114, 151, 223, 293, 305, 306].

CISPR (Comite International Special des Perturbations Radioelectriques, or International Committee for Radio Interference) was the first international organization authorized to promulgate international recommendations on the subject of radio interference. CISPR was founded in Paris, in 1933, by representatives of countries that had become concerned with the problem of radio frequency interference. In early discussions, they agreed that the primary job would be to document standard EMI measurement methods and to determine internationally acceptable noise level limits. The founding conference proposed to establish a common commission in the IEC (International Electrotechnical Commission) and UIR (Union International de Radiodiffusion, or International Union of Broadcasting) to facilitate the preparation of recommendations. CISPR held two plenary sessions before World War II to deal with the determination of acceptable noise levels and establishment of standard EMI measurement techniques.

After World War II, the UIR was not reconvened, and CISPR became a special committee of IEC. CISPR differs from other study groups insofar as several other international organizations participate in CISPR's work with observer status. CISPR's preliminary efforts were to publish a set of documents that would describe widely applicable requirements for EMI measurement equipment and techniques. This effort was largely completed in 1961.

During a 1973 plenary session held in the USA (Monmouth College, West Long Beach, New Jersey), a decision was made to reorganize CISPR. Existing subcommittees were disbanded, and six new subcommittees were established in their place. A decision was made to hold regular subcommittee sessions in the future. The attendees also established the working methodology of the subcommittees and determined an order for publication of the subcommittees' results. The new subcommittees and their interest areas were created as follows:

- *Subcommittee A: Interference measuring devices, measurement methods.* Subcommittee A was charged with describing the requirements for detectors of EMI measuring instruments and methods for statistical evaluation of measurement results. The subcommittee made a revision of Publ. 16 which, first of all, discussed the circumstances of detectors used to measure average values. This job was required by the continuing growth of narrowband emissions. During the revision, in addition to current and voltage measurements, measurement techniques for energy and electrical and magnetic field components were also studied. Other topics for Subcommittee A included the definition of a line impedance stabilization network (LISN) applicable to the measurement of heavy currents (i.e., >25 A), a description of requirements for coaxial cable shielding and tests for cable shielding performance, as well as a review of existing methods for measuring the insertion loss of EMI filters.
- *Subcommittee B: EMI from industrial, scientific and medical apparatus (ISM).* This subcommittee is responsible for the promulgation of test methods applicable to equipment that generates intentional HF signals, and for the establishment of adequate limit values for HF disturbances. The committee has completed a revision of Publ. 11, and a warning note has been added recommending that stricter limits might be necessary for microwave ovens below 5 kW because of their widespread use in the home. The subcommittee also was charged to study whether the test methods and limits for domestic appliances were applicable in the range above 30 MHz. For terminal noise voltages in the range of 0.15 to 30 MHz, the limits were already determined

to be acceptable. In addition, the subcommittee was asked to study EMI of heavy-current or high-voltage thyristors.

- *Subcommittee C: Noise caused by high-power cables, high-voltage equipment, and electrical traction.* Tasks of this subcommittee, at the time of this writing, were extended primarily to EMC problems caused by insulators applied in high-voltage energy transmission. The committee's work on Publ. 18 was finished in 1986 and, following that, its agenda was extended to performing a more thorough examination of EMC problems related to high-voltage dc energy transmission.
- *Subcommittee D: Ignition interference from motor vehicles, combustion engines, and related subjects.* Examination of noises produced by motor vehicles are included in subject field of this subcommittee. Updates of former works were issued in the report of Publ. 12. The committee conducts an ongoing effort to define EMS requirements for vehicular electronics.
- *Subcommittee E: EMS of radio and television receivers.* In Publ. 13, this subcommittee issued its standards covering EMS test methods for receivers. Its mission at the time of this writing concerned two major fields. First, they will work closely in cooperation with IEC Subcommittee 12. Second, they are in the process of setting standards related to EMS in telecommunication systems, focusing on HF impulses in the frequency range up to 30 MHz. Results will be issued as Publ. 20.
- *Subcommittee F: EMI in domestic appliances, fluorescent tubes and similar devices.* This subcommittee issued an update of its former efforts in Publs. 14 and 15. In subsequent periods, they intend to take a special look at solutions for EMC problems caused by portable hand tools and fluorescent tubes. In the framework of this mission, they will review safety questions and the effects of HF disturbances peculiar to impulses. This subcommittee's field of interest also covers the determination of requirements for narrowband measurements. Studies will be made to determine new limits for narrowband emissions.

Through diligent effort, these subcommittees have issued some very useful recommendations. Limits for EMI emission of electrical equipments first were established only for the frequency range 0.15 to 30 MHz, thus meeting broadcast requirements. These limits were later extended downward to the frequency range of 10 to 150 kHz. CISPR requires the measurement and attenuation of HF emissions in the frequency range of 30 to 300 (1,000) MHz.

Increasing attention is being devoted to the study of electromagnetic disturbances in the frequency range of 1 to 18 GHz. The examination of emissions in this frequency range is driven primarily by the growing need for space telecommunications.

With semiconductor equipment (ranging from power electronics to household appliances) coming into general use, the requirements for clean mains power have become increasingly strict. The degenerating situation also has hampered international trade. In the framework of CENELCOM (Comite Coordination Européen des Normes Electriques pour le Marche Commun, or European Coordination Committee of Electrical Standards in the European Common Market), a decision was made to establish a Common Standardisation Committee to create a standard for electrical equipment emission limits.

The Common Standardisation Committee, formed in 1970, immediately linked itself with representatives of electrical energy suppliers and electrical household appliance manufacturers. The Common Market was enlarged in 1973 and, following that, CENELCOM was reorganized under the name of CENELEC (Comite European de Normalisation Electrotechnique, or European Electrical Standardisation Committee).

CENELEC established three Subcommittees. Subcommittee CC3 or, according to the German abbreviation (Normen Komission) NK3, dealt with EMI and semiconductor household appliances. The standard issued in 1975 under EN 50006 limits the harmonics of numbers 3 to 15 and the disturbances responsible for flickering. The draft standard deals separately with phase-controlled thyristor equipment. Additionally, the standard draft touches upon applied technologies, the validity sphere, and calculation methods. The standard draft EN 50006 was published in CENELEC countries immediately after its acceptance, without any alteration. After the preparation of the standard draft, Subcommittee CC3 was terminated.

Thereafter, several countries turned to the IEC with a request to take up the problem of EMI with regard to semiconductor apparatus connected to mains. For surveying this special field, the IEC established a new subcommittee under the mark TC77. The Subcommittee TC77 works in cooperation with several nations and CISPR. To deal with the heterogeneity of the subject matter, duties were distributed between five special groups as follows:

- Working Committee #1: Terminology
- Working Committee #2: Mains impedances and LISNs
- Working Committee #3: Harmonic and nonharmonic electrical noise produced by electrical household and other similar equipment, included dc components
- Working Committee #4: Voltage fluctuations caused by electrical household and other similar equipment
- Working Committee #5: Harmonic and nonharmonic electrical noise produced by television sets

During statutory meetings, the groups created a detailed work outline covering the entire scope of EMC subject matter.

Many EMI problems exist that cannot be solved merely through examination and measurement of electrical equipment emissions and determination of acceptable emission levels. Therefore, there is also a need to examine the susceptibility of electrical apparatus to ensure that a transient or distortion on the mains cannot cause a malfunction or, at the extreme, a breakdown.

After World War II, the CEE (Commission International de Reglementation en vue de l'Approbation de l'Equipment Electrique, or International Committee of Electrical Equipment Approbation Standard) began to deal with the subject of electrical equipment EMS. Twenty-two European countries are included in CEE. In addition, two observers take part in its work. Through the early 1970s, CEE made an effort to summarize safety requirements for household appliances and other similar equipment. In the middle years of the 1980s, its work expanded to studying the EMS of electrical equipment containing electronic units.

CEE published a recommendation related to the protection of electrical equipment against transient disturbances, titled CEE 229-SEC UK 101 F 72 (1972-Sept). The recommendation covers specific data for test voltages and methods, as well as the test signal generator circuit. The recommendation prescribes measurement methods for several kinds of disturbing signals. Voltage pulses imitate transients formed by switching processes. The tests offered included the addition of an ac voltage with a frequency differing from the mains frequency. This test answers whether the electrical apparatus can be operated safely on mains with a remote control system. Another test, employing a short-duration voltage cutoff, serves to simulate disturbances generated during a momentary short-circuit on the mains (during which time all users suffer a voltage cutoff until a fuse or other device clears the fault).

IEC joined the study of EMS requirements in the early 1960s. This subject was first addressed by IEC Subcommittee TC65; later, Subcommittee TC77 joined in the effort. In the course of their work, these subcommittees lent support to CEE in many respects.

The study of the EMS of electrical equipment and articulation of measurement methods, as well as the compilation of recommendations and standards for this field of EMC, has been the specialty of IEC Subcommittee TC65. According to plans, the results of this group's work will be published in a standard draft IEC 1000 in the early 1990s. Subcommittee TC77 also will take part in compiling this draft standard. The secretariat document TC77B(4) reveals existing and planned EMS test methods that will be involved in the final text. No doubt, also, CISPR will include the examination of EMS problems in electrical equipments in its program. Signs of this opening are evident in Publications 13 and 20, which deal with EMS in radio and television sets.

Subcommittee TC65, at the time of this writing, is working on EMC problems in industrial automation and process control systems. The result of this work has been issued in IEC 801. Fields of study are indicated in the list of chapters, which is as follows: