Power Quality

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Edited by

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and Mircea Ion Buzdugan

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To all those people who are working for getting a better World and to all those who might benefit from it

To my wife Alicia for her patience and collaboration and also to our son Juan José.
—Manuel Pérez Donsión

To my wife Nadine for her permanent support and to my sons Tudor and George.
—Mircea Ion Buzdugan

“Most of the fundamental ideas of science are essentially simple, and may, as a rule, be expressed in a language comprehensible to everyone”.

—A. Einstein

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FOREWORD

Power quality is a very broad subject, covering all stages of power systems engineering, from the generation, transmission, distribution levels to the end-users. It is a complex matter involving many different topics. Consequently power quality issues are most often difficult to solve, an optimal solution being usually a mix of solutions for each specific case.

The complexity of power quality issues gave birth to plenty of definitions of the term, sometimes conflicting, meaning different things to different people involved and an umbrella concept of the individual types of disturbances in the chain of modern distributed energy systems.

Lately, the interest in power quality became more and more important for suppliers, manufacturers and customers. Suppliers are interested in the quality of their service, manufacturers have to build equipment compliant to a sum of standards and regulations with respect to power quality and finally customers want in their turn to have comfort and a quiet life in using electrically powered products.

Unfortunately, high speed semiconductor devices with fast switching capability and the emerging digital era in control and signal processing became the main enemies of electrical power quality. They determine increasing emitted interference and on the other hand increased interference susceptibility.

It is almost unanimously accepted that there are some main factors determining an increased need to solve and prevent power quality problems: the increased use of sensitive equipment which in their turn have an increased ability of generating disturbances, end users have an increased awareness of power quality issues and the deregulation of the power industry.

Finally overall efficiency of power systems represents an indicator of the stage of development of a nation.

Following these objectives, hundreds of researchers, scientists, and engineers attend every year the International Conference on Renewable Energy and Power Quality and this book originated from ten years of their contributions. It contains a selection of the best papers presented at the ICREPQ conferences from 2003 to 2012.

The papers have been selected by a team of voluntary reviewers. At the end of this process only about 3% of all presented papers have been selected. Considering that each paper has been already reviewed before to be accepted for the conference, the selected papers represent "the best of the best". Moreover, the authors have modified and updated the original contribution as a chapter of this book.

The conference is held in Spain, every year a different city is involved. In the last ten years the following cities have been involved: Vigo (9-11 April 2003), Barcelona (31 March-2 April 2004), Zaragoza (16-18 March, 2005), Palma de Mallorca (5-7 April, 2006), Seville (28-30 March, 2007), Santander (12-14 March 2008), Valencia (15-17 April 2009), Granada (23-25 March 2010), Las Palmas de Gran Canaria (13-15 April 2011), Santiago de Compostela (28-30 March 2012).

In these conferences 3102 papers have been submitted, 2022 have been accepted and 1788 have been presented, which confirms a high level of participation and answers to the intention of the organizers to give an opportunity to academics, scientists, engineers, manufacturers and users from all over the world to come together in a pleasant location to discuss recent development in the areas of Renewable Energy and Power Quality.

All published papers are available at the website:
http://www.icrepq.com/

With reference to power quality, the conference includes but it is not limited to:

Topics include, but are not limited to:

- Electromagnetic compatibility (EMC)
- Power Quality in Transport and Distribution.
- Economic Studies of the Power Quality
- Low-frequency conducted disturbances: Voltage deviations, voltage fluctuations/flicker, voltage dips and short interruptions, harmonics and inter-harmonics, transient over-voltages, voltage unbalance (imbalance), temporary power-frequency variations.
- Sources, effects and mitigation methods of the disturbances.
- FACT (Flexible Alternating Transmission Systems)

- Measurements of the power quality in networks, industrial installations and Laboratories; Equipment, procedures and measurement methods; Standards.
  -Modelling and simulation of the power quality. Software tools.
- Transmission of the disturbances
- Filtering techniques
- Power factor compensation. Capacitor switching techniques
- Optimization techniques
- Communication, internet and artificial intelligence.
- Permanent monitoring techniques and online diagnosis
- Intelligent energy delivery systems. Uninterrupted power supplies
- Expert systems applications
- Devices, equipment and power systems. Control centres
- Specific problems and studies cases
- Power quality influence in deregulated markets
- High frequency disturbances (radiated)
- Data security and electromagnetic pulses.
- Protection against natural and intentional EMI
- Power Quality Teaching

The main benefit of reading such a book is the possibility to have in a unique book a selection of the best contribution to the power quality exploitation and evolution during the last decade.

On the other hand the book has the benefit of a good representation; authors of the selected contributions are spread all over the globe, from far Asia to the USA and from Australia and New Zeeland to Canada, the specific issues they depicted being of crucial importance.

Finally, the purpose of this book is to provide an up-to-date reference useful for researchers, technicians and engineering looking for the state of art in the field of renewable sources. The book contains both theoretical and practical applications and is divided into seven parts:

Part I: Power Quality Disturbances
Part II: Power Quality Survey
Part III: Power Quality Analysis
Part IV: Power Quality Modelling and Optimisation
Part V: Harmonics and Interharmonics
Part VI: Filters and Power Conditioners
Part VII: Power Quality in Power Converters.

To Whom this Book is Addressed

This book is intended primarily to meet the demands of professional engineers and researchers dealing with power quality, it should also prove useful to postgraduate level students. It can be used as a reference book for engineers, physicists and mathematicians interested and involved in operation, project management, design, and analysis of power quality issues. Each chapter contains references that allow the treated topic to be further deepened.

ACKNOWLEDGMENTS

First of all thanks to Professor Manuel Perez Donsion, University of Vigo (Spain) for the tireless and valuable effort in the organization of the ICREPQ conferences.

In its early stage, the project has been coordinated by Prof. Inmaculada Zamora, from the University of the Basque Country, Bilbao, Spain, when a group of members of the International Steering Committee have selected the most representative contributions. Even though it was an exciting work, the process was equally rigorous and time consuming, so they deserve all our consideration and gratitude and it is a moral duty to remember them here. They are Professors:

- Patricio Salmerón Revuelta from the University of Huelva, Spain
- Mario Mañana Canteli, from the University of Cantabria, Santander, Spain
- Antonio Bracale from the University of Naples Parthenope, Italy
- Jan Iwaszkiewicz from the Institute of Electrotechnics, Gdansk, Poland
- Mircea Ion Buzdugan from the Technical University of Cluj-Napoca, Romania

Thanks to Cambridge Scholars Publishing, the publisher of this book containing the most valuable papers of the ten years of the International Conference on Renewable Energy and Power Quality (ICREPQ).

Last but not least all the authors deserve particular thanks and our gratitude.

How to Use this Book

This book can be used in different ways. By looking at the titles of each part, the reader can identify the fields of interest. Each chapter is self consistent since it comes from a scientific paper. References of each paper are useful to achieve further information.

BIOGRAPHIES OF THE EDITORS

Manuel Pérez-Donsión received his MSc in Industrial Engineering from Catalonian Polytechnic University in 1980 and his PhD from Vigo University in 1986. In 1987 he became a Full Professor.

Among other academic positions he was the Dean of the Escuela Técnica Superior de Ingenieros Industriales y Minas from 1995 to 2001. From 2001 till to 2004 he was also the Head of Electrical Engineering Department.

He is member of the International Steering Committee of ICEM and member of the Scientific Committee of different conferences, congress and journals.

He is the president of the following associations:

- European Association for the Development of Renewable Energies, Environment and Power Quality (EA4EPQ),
- European Association for the Development of Electrical Engineering (EADEE)
- Spanish Association for the Development of Electrical Engineering (AEDIE),

He is also vice-president of the Portuguese Association for the Development of Electrical Engineering (APDEE).

He was awarded the Gold Insignia of the “Green Week Foundation” and four prizes of the “Electrical Engineering Journal”.

His main research interests are linked to:

- Power Quality
- Renewable Energy with special emphasis in Small Hydro Power and Wind Energy.
- Electrical Machines Modelling, Diagnostics and Control

- Permanent Magnet Synchronous Motors
- Transient Stability of Electrical Power Systems.

He is author of two research books and other four books, more than one hundred research papers some of which were presented at national and international conferences, and others were published in relevant journals. He has also been involved with several research projects.
Currently he is teaching Quality and Utilization of Electrical Energy and Control of Electrical Motors to undergraduate students and Special Electrical Motors, Renewable Energies and Power Quality.

Mircea Ion Buzdugan received his MSc in Electrical Engineering at the Technical University of Cluj-Napoca in 1979 and the MSc in Economics at the University “Babes_Bolyai” of Cluj-Napoca in 1993. Between 1980 and 2006, he was technical manager and CEO of several Romanian industrial companies. He also received his PhD in Electrical Engineering and in 2006 he joined higher education. From 2012 he is the dean of the Faculty of Building Engineering at the Technical University of Cluj-Napoca (Romania).

He is vice-president of the Romanian Association of Engineers (AIIR) and president of the Transylvania Branch of the Romanian Society of Electrical Installations and Automatic Control. He is member of the International Steering Committee of ICREPQ and of other different conferences and journals.

His main researches are linked to: Electromagnetic compatibility and Power Quality.

He is author of five books, more than seventy papers presented at national and international conferences or published in journals or book chapters.

He was also involved in several research projects as project manager or team member.

Currently he is teaching Fundamentals of Electrotechnics and Electrical Machines to undergraduate students and Electromagnetic Compatibility and Power Quality to postgraduate students.

PART I:

POWER QUALITY DISTURBANCES

CHAPTER ONE

ARE POWER QUALITY AND ELECTROMAGNETIC COMPATIBILITY DICHOTOMOUS?

MIRCEA BUZDUGAN[1] AND HORIA BALAN[1]

Abstract

This chapter is intended to present the close relationship between power quality and electromagnetic compatibility. It is well known that in the study of these two concepts different frequencies are involved and consequently, different standards, techniques, and measuring instruments are considered. However, a deeper understanding reveals a close interaction between physical phenomena involved in the two fields of research. Basically it is a matter of looking closely for possible reactions of one phenomenon into another range of the frequency spectrum. The interaction itself is evolving from one kind of issue to another and therefore a dichotomous treatment could make the observer skip the essential, hidden beyond the appearance. Poor power quality can result in problems with electromagnetic compatibility and noise. In what follows, a case study will be presented in which electromagnetic radiated interference turns into conducted interference, and finally into an apparent power quality issue. Looking for the solution of the problem in terms of power quality is superfluous, causing a loss of time and resources, since the main cause must be searched beyond its appearance.

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This chapter is the based on the revised version of the paper presented at the International Conference on Renewable Energies and Power Quality (ICREPQ'08).

1. Introduction

Does a physical dichotomy between power quality and electromagnetic compatibility exist?

As a matter of fact, the dichotomy between power quality and electromagnetic compatibility is mostly present in the mind of specialists, rather than being a physical reality, and consequently, the present approach is intended to dismantle it.

Over the last years interest in power quality has become more and more important for suppliers, manufacturers, and customers. Suppliers are interested in the quality of their service, manufacturers have to build equipment that is compliant to a sum of standards and regulations with respect to power quality, and customers want to have comfort and a quiet life using electrically powered products.

Unfortunately, high-speed semiconductor devices with fast switching capability and the emerging digital era are in control, and, along with signal processing, are the main enemies of electrical power quality.

On one hand, pieces of equipment need power quality, being less tolerant of voltage and current disturbances, but on the other they represent the main source of electromagnetic perturbations in power lines.

In literature, one can find plenty, sometimes conflicting, definitions of power quality, related more or less to the performance of equipment or to the possibility of measuring and quantifying the performance of the power system (see the IEEE Standards and the IEC and EN Standards). For instance, the Council of European Energy Regulators' Working Group on Quality of Electricity Supply speaks about voltage quality and includes the following disturbances: "frequency, voltage magnitude and its variation, voltage dips, temporary and transient over-voltages, and harmonic distortion", without mentioning explicitly "current quality", which is probably implicitly considered where it affects the voltage quality [1].

The point of view here is again that current quality is a concern only if it affects voltage quality. This difficulty of distinguishing between voltage and current disturbances is one of the reasons the term "power quality" is generally used. The term "voltage quality" is reserved for cases where only the voltage at a certain location is considered. The term "current quality" is generally used to describe the performance of power electronic converters connected to the power network [2].

Today, both low and high-power equipment is powered more and more by power electronic converters, generating a broad spectrum of distortion, which is obviously rising. However, high-frequency transients do occasionally receive attention as causes of equipment malfunction, and are generally not well covered in the power quality literature. For example, even the European standard, EN 50160, [3] gives useful information for variations (voltage fluctuations, dips, interruptions, etc.), which are regulated disturbances, but nothing for events (fast transients) which are not.

In the authors' opinion, there is no power quality in the presence of electromagnetic interference, i.e. the process by which disruptive electromagnetic energy is transmitted from one electronic device to another via radiated or conducted paths (or both) [4]. In this respect, every disturbance is a power quality issue, even the IEC and EN standards distinguish between an (electromagnetic) disturbance and (electromagnetic) interference: "A disturbance is a phenomenon which may degrade the performance of a device, piece of equipment, or system, or adversely affect living or inert matter" [5]. In power quality terms, any deviation from the ideal voltage or current can be considered a disturbance. Interference is much more strictly defined, being the actual degradation of a device, equipment or system caused by an electromagnetic disturbance.

Technical literature is also abounding in definitions for electromagnetic compatibility (EMC), but perhaps the most synthetic and eloquent one is that EMC consists as the absence of effects due to electromagnetic interference (EMI) [6].

Since electric and electronic systems penetrate more deeply into all aspects of society, both the potential for interference effects, and the potential for serious EMI-induced incidents increase.

Electromagnetic interference (EMI) is a serious and increasing form of environmental pollution. The threat of EMI is controlled by adopting the practices of electromagnetic compatibility (EMC), which has two complementary aspects: First, it describes the capacity of electrical and electronic systems to operate without interfering with other systems, and secondly, it describes the ability of such systems to operate as intended within a specified electromagnetic environment.

Interference can propagate from a "source" to a "victim" via the mains distribution network to which both are connected. This is not well characterised at high frequencies, especially since connected electrical loads can present virtually any RF impedance at their point of connection.

On the other hand, electromagnetic compatibility includes intra-system and inter-system electromagnetic interference. Difficulties arise when intra-system meets inter-system, when the two approaches are confused one with the other, or at the interface where they meet.

Furthermore, the transfer of electromagnetic energy (with regard to the prevention of interference) is broken into four subgroups: radiated emissions, radiated susceptibility, conducted emissions, and conducted susceptibility.

There are basically two classes of EMC requirements that are imposed on electric and electronic systems: those mandated by governmental agencies, and those imposed by the product manufacturer.

The legal requirements are imposed in order to minimise the interference produced by the product. However, compliance with these EMC requirements does not guarantee that the product will not cause any interference. On the other hand, EMC requirements that manufacturers voluntarily impose on their products are intended to result in customer satisfaction (in order of reliable). Compliance with both of these EMC requirements is critical to the success and the good reputation of the product in the marketplace.

Regulatory agencies impose limits on these conducted emissions because they are placed on the utility power system net of the installation.

The utility power distribution system in an installation is a large array of wires connecting the various power outlets, from which the other electronic systems in the installation receive their AC power. It therefore represents a large “antenna” system from which these conducted emissions can radiate quite efficiently, causing interference in the other electronic systems of the installation. Thus the conducted emissions may cause radiated emission, which may then cause interference. Ordinarily, the reduction of these conducted emissions is somewhat simpler than the reduction of radiated emissions, since there is only one path for these emissions that needs to be controlled: the unit’s power cord. However, it is important to realise that if a product fails to comply with the limits on conducted emissions, compliance with the limits on radiated emissions is a moot point. Therefore controlling conducted emissions of a product has equal priority with the control of radiated emissions [7].

For ease of measurement and analysis, in the commercial tests, radiated emissions are assumed to predominate above 30 MHz, while conducted emissions are assumed predominant below 30 MHz.

There is of course no magic changeover at 30 MHz, but typical cable lengths tend to resonate above 30 MHz, leading to anomalous conducted measurements, while measurements radiated fields below 30 MHz will of necessity be made in the near field closer to the source, giving results that do not necessarily correlate with real situations.

At higher frequencies, mains wiring becomes less efficient as a propagation medium, and the dominant propagation mode becomes radiation from the equipment or wiring in its immediate vicinity.

Perhaps the most important aspect of becoming effective at EMC design is to begin thinking of the non-ideal behaviour of electrical components, in addition to the ideal behaviour that we have been taught to keep in mind.

If one thinks only in terms of ideal behaviour of electrical and electronic components, we will not be able to see or anticipate the non-ideal electrical paths, and hence will not be able to consider other possible causes for conducted or radiated emissions. Therefore, we will have inadvertently reduced the possibilities for correcting EMC problems, and will not have the ability to see a schematic beyond its appearance.

However, a huge problem still remains from the point of view of the frequency range. Power quality is confined in the low frequency range, i.e. from DC to maximum 3.5-5 kHz. Conducted interference is studied, starting from 100-150 kHz. Consequently a large unexplored gap remains between 5 kHz and 100 kHz. In this latest range of frequency there are no standards and no measuring methods.

As a conclusion, there is no physical dichotomy between power quality conducted and radiated interference. There is a chain reaction, turning one phenomenon into the other. Power quality issues may determine conducted or even radiated interference and vice versa.

The present approach will demonstrate, using a case study, the multiple connections between them.

2. A conducted interference problem [8]

Distribution line hardware can generate radio-frequency interference (RFI). Such interference can impact the AM and FM bands, as well as VHF television broadcasts. Most power-line noise is from arcs across gaps on the order of 1mm, usually at poor contacts. These arcs can occur between many metallic junctions on power-line equipment.

Arcing generates broadband radio-frequency noise from several kHz to over 1,000 MHz. Power-line interference affects lower frequency broadcasts more than higher frequencies. The most frequently affected from low to high frequencies are: AM radio (0.54 to 1.71 MHz), low-band VHF TV (channels 2 to 6, 54 to 88 MHz), FM radio (88 to 108 MHz), high-band VHF TV (channels 7 to 13, 174 to 216 MHz), and UHF (ultra-high frequencies, until about 500 MHz).

In the case studied below, a severe reverse problem has been analysed and solved. It is about a practical situation in which AM broadcasting stations inject conducted RF emissions in the overhead low-voltage power lines, with electromagnetic interference affecting the operation of certain equipment.

The problem occurred in the vicinity of two radio broadcast stations (amplitude modulated, carrier frequencies f_1=1152 kHz, f_2=909 kHz, and the corresponding output powers P_1=400 kW, P_2=200 kW).

Due to the proximity of the stations, the electronic circuitry of some types of gas central heating (heating power of 24 kW) installed in residences presented malfunctions and gave frequent error messages on the interface display.

Apparently it was a power quality problem, but it was not that situation. The issue was consequently translated in another range of the frequency spectrum, and the RF perturbations injected in the low voltage network were checked.

A spectrum analyser, HM 5014, and the line impedance stabilisation network LISN HM 6050-2, from Hameg Instruments have been used, the test setup of which is presented in fig. 1. One can see that the connection of the LISN is somehow atypical, in the sense that the spectrum analyser was connected to measure the incoming RF interference from the low voltage grid, and not from the equipment. Normally, the conducted emissions generated by equipment under test (EUT) in the supply grid are evaluated using the line stabilisation network and the spectrum analyser, but in this case, the setup was reversed.

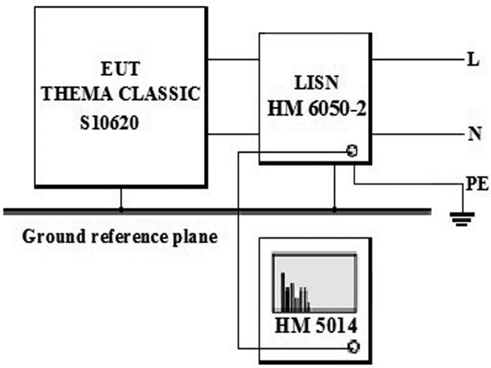

Fig.1: Setup for measuring conducted interference emerging from the low voltage lines.

Inside the LISN, the voltage lines are terminated with a network having well-defined impedance with respect to the PE wire. The line stabilisation network is nothing else than a filtering circuit, the EUT being connected to the supply AC lines through a low pass filter (Fig. 2).

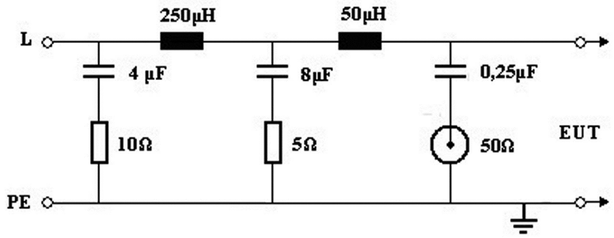

Fig. 2: LISN circuitry between L and PE

The determining components for the impedance of the network are the 50-µH inductance and the 5-Ω resistor. The rest of the components serve in decoupling the low voltage supply grid.

A supplementary filter may also be used between the LISN and the spectrum analyser, in order to prevent the spectrum analyser from being affected by the high order harmonics of the supply grid. This filter must maintain 50-Ω impedance, and reduce insertion loss in the frequency range of interest as much as possible (ideal 0 dB).

The signal for EMC measurements performed using a spectrum analyser or an EMC receiver is available after passing through a high pass filter. The asymmetric noise signals in supply lines L and N of the EUT are provided by two identical networks. They can be selected to be consecutively available at the output port of the signal port of the LISN.

According to the European specifications, the maximum allowed RF noise level injected in the public low voltage network in the frequency range 150 kHz to 30 MHz must be situated below 52 dBµV.

Measurements revealed a RF interference spectrum with levels exceeding 72 dBµV (20 dBµV in plus with respect to the standardised quasi-peak limit, and 30 dBµV in plus with respect to the standardised average limit), at the frequency of the carrier and its odd harmonic components, both on the L and the N conductors (fig. 3). The graph depicts the situation in linear scale.

In the logarithmic scale the situation is better depicted for the low frequency range.

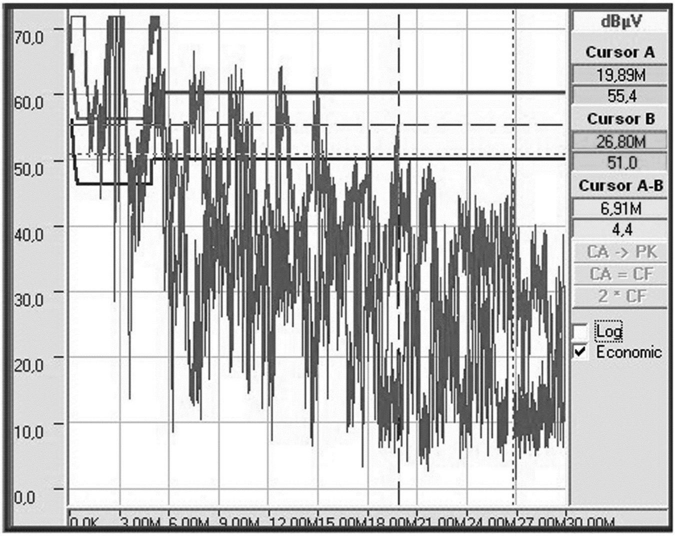

Fig. 3: RF conducted emissions injected in the public low voltage grid by the radio broadcasting stations. (Linear scale)

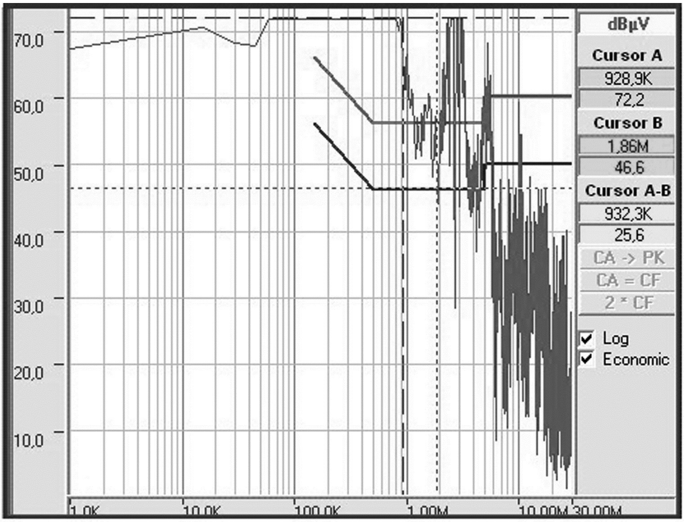

Fig. 4: RF conducted emissions injected in the public low voltage grid by the radio broadcasting stations. (Logarithmic scale)

The RF signal injected in the low voltage power line has levels of between 68-72 dBµV, but no one can quantify their influence between 1 kHz and 100 kHz, while there is a lack of standards and measuring standard equipment in this range of frequencies.

The immunity tests (surge, burst, dips, and interruptions) carried out using an immunity testing equipment (best EMC from Schaffner Instruments) for the electrical circuitry of gas central heating revealed the conformity with the basic standard for electromagnetic compatibility, EN 61000-4.

In its turn, central heating injects conducted RF perturbations in the low voltage grid. The level of these RF perturbations has been measured with a normal setup, similar to the one depicted in fig. 1 (the LISN was directly connected). The tests revealed the conformity with the basic standard for electromagnetic emissions, EN 50011, as can be seen in fig. 5, the RF perturbation levels being below the average and the quasi-peak standardised limits, in the frequency range of 100 kHz - 30 MHz.

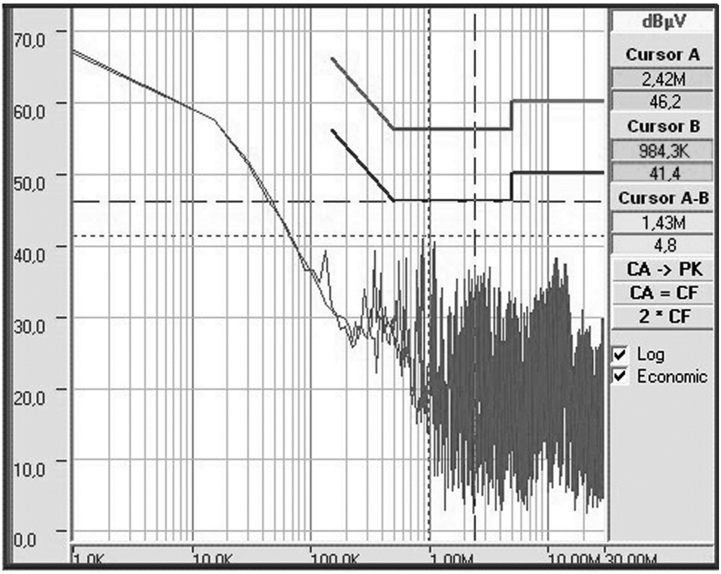

Fig. 5: RF conducted emissions of the gas heating central (Logarithmic scale).

Although the gas central heating fulfilled the EMC compliance, it can be seen that at the frequency of interest (the carrier frequency of 1 MHz),