FINAL PUBLISHABLE JRP REPORT

JRP-Contract number	IND60
JRP short name	EMC
JRP full title	Improved EMC Test Methods in Industrial Environments
Version numbers of latest contracted Annex Ia and Annex Ib against which the assessment will be made	Annex Ia: V1.0 Annex Ib: V1.0
Period covered (dates)	From 01 July 2013 To 30 June 2016
JRP-Coordinator	
Name, title, organisation	Mustafa ÇETİNTAŞ, TUBITAK, Turkey
Tel:	+90 262 679 50 00 (ext. 2020)
Email:	mustafa.cetintas@tubitak.gov.tr
JRP website address	http://www.emc-industry.com/
Other JRP-Partners	
Short name, country	CMI, Czech Republic INTA, Spain LNE, France METAS, Switzerland SIQ, Slovenia SP, Sweden VSL, Netherlands

REG1-Researcher (associated Home Organisation)		
Researcher name, title	Frank Leferink	Start date: 01 July 2013
(Home organisation Short name, country)	UTwente, Netherlands	Duration: 22 months
REG2-Researcher (associated Home Organisation)		
Researcher name, title	Ferran Silva	Start date:01.July.2013
(Home organisation Short name, country)	UPC, Spain	Duration: 18 months

Report Status: PU Public

EMRP
European Metrology Research Programme
Programme of EURAMET

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

TABLE OF CONTENTS

1 Executive Summary 3
2 Project context, rationale and objectives.. 4
2.1 Context.. 4
2.2 Objectives 6
3 Research results 7
4 Actual and potential impact 30
4.1 Direct Impact.. **Error! Bookmark not defined.**
4.2 Dissemination Activities .... **Error! Bookmark not defined.**
4.3 Examples of early impact 31
5 Website address and contact details 32
6 List of publications.. 32

1 Executive Summary

Introduction

Testing electromagnetic compatibility (EMC) to comply with the EMC Directive is essential for all electrical and electronic products. It must be guaranteed that unintentional generation, propagation and reception of electromagnetic energy does not cause interference or damage the product itself, or those nearby. EMC measurement and validation are necessary during product development, as well as for commercial products. The standard EMC tests are: conducted emission, conducted immunity, radiated emission and radiated immunity including GSM (Global System for Mobile Communications) immunity.

The Problem

Emission tests assess the electromagnetic energy emitted or released into the environment, either deliberately or accidently. These can be conducted emission, referring to emissions via cables, power, communication or other, or radiated emission. Immunity tests assess the ability of the equipment to function correctly when exposed to unwanted electromagnetic energy or disturbance signals, again either through cables or through the air.

There are only a few standards that specifically detail EMC testing of large equipment, and they emphasise the need for in-situ measurements. The standard EN 55011 details on-site radiated emission measurement techniques based on moving the receiving antenna around the equipment and measurements that can be made from the outside wall of a building housing the equipment. Despite the fact that EN 55011 emphasises the need of measurements in industrial environments it only refers to radiated emissions. The current standards which deal with on-site tests, do not cover conducted emission, conducted immunity and radiated immunity tests. The major aim of this project was to fill this gap, by improving and developing test methods for industry.

There are existing non-standard alternative EMC test methods used in industry, instead of the laboratory tests, but most of these methods are not supported by any European standard and there is no satisfactory validation or correlation between these alternative methods and the standard laboratory methods. Understanding the performance and evaluation of existing alternative EMC test methods currently being used in industry and the development of new alternative methods are crucial for European industry. The correlation between the alternative methods in industry and the standard methods is necessary so that traceable measurements in industrial environments can be carried out.

In addition, the standard EN ISO 17025 (for accredited calibration activities) provides a set of requirements to assure the quality of test results of the laboratories by inter-laboratory comparison of EMC tests. However there are no adequate EMC test devices available for large scale in-situ measurements, particularly for immunity testing where there are no test devices. Therefore, the project will develop concepts and EMC test devices that may be used for inter-laboratory comparisons for both emission and immunity tests.

The Solution

In response to this problem, the project set out to improve the existing alternative methods which are already used in industry and to establish their correlation with corresponding laboratory tests and prepare their uncertainty budgets/calculations. Secondly, this project also developed new alternative EMC test methods to standard EMC tests in accordance with the needs of European industry by accomplishing the following objectives;

- Improvement and development of alternative conducted emission test methods
- Improvement and development of alternative conducted immunity test methods
- Improvement and development of alternative radiated emission test methods
- Improvement and development of alternative radiated immunity test methods
- Development of new reference sources for emission and immunity tests

Impact

The project outputs have been shared widely with the metrology, instrumentation and industrial communities. Workshops disseminated the project outputs and liaised with stakeholders in the industrial, standards and research communities. Around 50 papers reflecting the project were presented at a variety of prestigious EMC conferences and journals. The work contributed to the standardisation activities of CISPR meetings, and the time domain measurements, in particular, were taken up by industry.

CISPR is a part of the International Electrotechnical Commission (IEC) which sets standards for controlling electromagnetic interference, or EMC, in electrical and electronic devices. The project results were presented in the meeting of the subcommittee CISPR/I/WG2 which oversees the important CISPR standards that are relevant to large, distributed or high current equipment, as in the scope of the project. There was also interest from the subcommittee CISPR/A/WG1/A (on measurement of radio interference and statistical methods) which has decided to create a working group to work on LISN calibration issues. Subsequently LNE has become a member of this working group.

The time-domain methodology developed by Universitat Politècnica de Catalunya has been included in Annex B of IEC 62920 standard. This is one of the most important outputs of the project because IEC 62920 covers EMC requirements for solar photovoltaic energy systems that are usually large and distributed, and especially need improved or developed EMC test methods. The standardisation activities will continue with the support of the IEC members, and will try to incorporate the new time-domain methodologies into the new edition of CISPR 11. The project covered test methods which are jointly utilised by several EMC standards, and the testing methodology is similar and common to most of EMC standards. Therefore contributing to EMC standards via CISPR/A and CISPR/I will mean that in due course the project's contributions will be disseminated to the other subcommittees and put into other relevant standards. This means that the project will have an impact on all the other EMC standards which are likely to be applied large and high-current EUTs.

Most of these international standards produced by CISPR are then adapted for European (EN) standards by one of recognised European standardization organizations: CEN, CENELEC or ETSI for the targeted directive such as the European EMC directive. Therefore these standards are key to complying with the EMC Directive.

LISN manufacturers and laboratories such as a manufacturer from France and a company from Turkey have shown great interest in LISN adaptors produced during the project and would like to purchase adaptors. Laboratories and manufacturers also have been showing great interest in the conducted immunity round robin device and harmonic reference device which have been developed in the project.

Many laboratories were keen to purchase the conducted immunity devices and to participate in conducted immunity inter-laboratory comparison tests, because there had been no opportunity for this in the past.

The alternative conducted emission test methods improved in the scope of the project have been evaluated and employed by one of the stakeholders in Turkey and found very efficient.

Finally, the time-domain measurement method developed in the project was successfully utilised in in-situ emission measurements of a large fixed installation in the premises of one of the company Mecalux S.A. The excellent results achieved at the in-situ measurements highlight the benefits of this novel time-domain measurement method.

The results of this project will have an impact directly on industrial manufacturers who need on-site EMC testing due to the size of their products and/or high currents, and also on EMC testing laboratories which often have to perform non-standard EMC tests on site. It will help industry, especially SMEs, to evaluate their products during the design stage. This will ultimately allow companies to have confidence that their products conform to the EMC directive and can enter the marketplace.

2 Project context, rationale and objectives

2.1 Context

All equipment within the European Market has to fulfil the essential requirements of the European EMC Directive. The normal approach is to show compliance with basic test requirements and testing electrical and electronic products is a must before entering the market. Actually, EMC measurement and validation are necessary during the whole period of development of products; however, development, implementation and maintenance of an EMC measurement facility in accordance with standards are heavy loads for industry. Using facilities in EMC laboratories is a solution but is expensive and time consuming and in addition, it is not always possible to use standard laboratory EMC methods for some EUTs which are large, stationary or with high currents.

EMC measurements are usually performed in accordance with international standards within the controlled environment of an EMC Test Laboratory. The European EMC Directive, which applies to all electrical and electronic equipment, requires EMC conformity for physically large equipment, installed systems and distributed and complex systems as well as for smaller items such as consumer electronics. This means that strategies have to be developed to demonstrate that large systems do conform to the protection requirements of the EMC Directive and also with market driven EMC requirements. An essential part of these strategies is the provision of test data and hence the need to carry out testing 'on-site' or 'in-situ' in industrial environment.

There are only a few standards that specifically detail EMC testing of large equipment and they only emphasise the need for in-situ measurements for radiated emissions. One of the examples is EN 55011 - a product standard concerned with Industrial, Scientific and Medical (ISM) equipment. This standard details on-site radiated emission measurement techniques based on moving the receiving antenna around the equipment and measurements that can be made from the outside wall of a building housing the equipment with the following sentences: “For equipment which is not tested on a radiated emission test site, measurement shall be made after the equipment has been installed on the user’s premises. Measurements shall be made from the exterior wall outside the building in which the equipment is situated at the distance”. In spite of the fact that EN55011 emphasises the need for measurements in industrial environments only for radiated emissions, the performance and characterisation and also the correlation of the method with the real radiated emission measurement are still very open in EN55011. One of the other rare standards dealing with on-site EMC tests is EN 50121-3-1, the product standard describing radiated emission measurement techniques for railway rolling stock. Tests in this standard are included for both a static vehicle and the vehicle in motion, however also for this standard, many points such as the effects of the absence of OATS, anechoic chambers and correlations with the laboratory tests are open. Moreover, in the current standards which partly deal with on-site tests, support is only for radiated emission tests and not for other in-situ EMC tests from international EMC standards like EN55022 for conducted emission, EN61000-4-6 for conducted immunity and EN61000-4-3 for radiated immunity. One of the major aims of the project was to fill this gap and has already started to have an impact on the standards with its outputs.

On the other hand, there are existing non-standard alternative EMC test methods used in industry instead of the laboratory test methods and these have been used increasingly in industry in spite of the fact that most of these are not supported by any European standard. In addition, performance and characterisation were not clear yet because there was insufficient work in this area to date. Research on the performance and evaluation of alternative existing EMC test methods used in industry and the development of new alternative methods were crucial for the European industry. An extensive correlation was required between the alternative methods in industry and the standard methods so that this would lead to traceable measurements in industrial environments. Moreover, techniques to determine the uncertainty of measurements were needed to comply with the required reproducibility of measurements. This project has played an important role to meet these needs by improving the current alternative methods and also developing new methods.

In addition, the standard EN ISO 17025 provides a set of requirements to assure the quality of test results of the laboratories by inter-laboratory comparison EMC tests. However, the participation of accredited EMC test labs to inter-laboratory comparisons was rarely encountered. The main reason was that there were no simply adequate EMC devices available for comparisons; especially the lack of reference devices for immunity testing. Even worse, there was no reference document or standard that describes this problematic issue. Therefore, it was of great importance to develop concepts and EMC test devices that could be used for inter-laboratory comparisons for both emission and immunity tests. Besides, EMC testing is not a straightforward operation but requires a full set of different operations. For the accreditation, it was very difficult to properly assess the competence and skills of a calibration laboratory, since there were few methods to test the whole test chain as well as the correct handling by the laboratory personnel. It was therefore very convenient to have EMC test devices that could be used for comparison (bilateral or multilateral) and system checking. These devices could also be used to compare different test facilities, for example the immunity to conducted disturbance. As a consequence, the need for EMC test devices was not only a “desirable feature” but a requirement in accordance with the EN ISO 17025. Test laboratories and accreditation bodies were facing the problem that there was practically no provider for comparisons as required by EN ISO 17025. It was therefore very important to find a solution for harmonising the qualification of EMC test laboratories and test methods. The project has also filled this gap and produced three types of reference sources; conducted emission, conducted immunity and harmonic sources.

2.2 Objectives

The goal of this project was to evaluate the possible improvements for existing alternative EMC methods already adapted for industry and also to develop new alternative test methods in accordance with industrial needs.

The link between the alternative EMC test methods used by industry and test methods defined in standards has been established. The EMC measurements considered included emission and immunity measurements in the frequency range from 9 kHz to 18 GHz in conducted and radiated disturbance measurement set-ups.

There are many alternative EMC test methods which use less expensive materials, approaches and devices, for instance, reverberation chambers, current clamps, etc. Most of which are not standardised yet. In industry, some test methods defined in standards are implemented as a concise version with less defined environment. Sometimes the test methods defined in standards to characterise the EMC behaviour of large-size products or mounted systems are complex and very expensive and in some cases impossible. It is therefore clear that adapted methodologies and procedures for industry were needed.

Very limited research was done to improve the de facto situation and facilities in the past. There was limited connection established to relate measurement results of alternative EMC test methods with the standard tests in industry. In addition, uncertainty evaluation of alternative EMC set-ups was crucial for industry and guidance in determining the critical points to improve performance and provide an uncertainty budget would be valuable to industry.

As a result, the main aim of this project was to focus on the performance, characterisation and improvement of the already existing alternative test methods, and then to establish extensive correlation between the existing alternative methods used in industry and the standard test methods together with the uncertainty calculations. This project has also focused on the development of new alternative test methods in accordance with the needs of industry for all types of EMC tests. The investigated EMC measurements included emission and immunity measurements in the frequency range from 9 kHz to 18 GHz in conducted and radiated disturbance measurement set-ups.

Consequently, the project has addressed the following scientific and technical objectives;

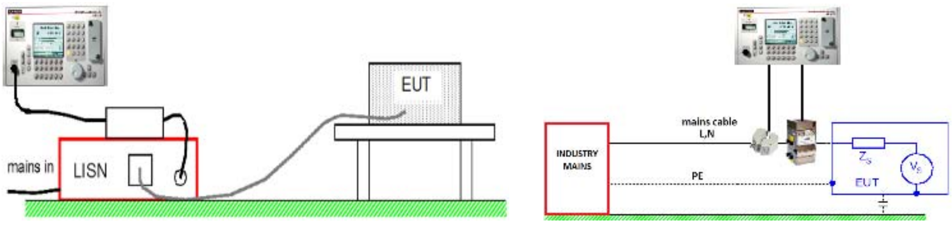
- To evaluate, improve and develop alternative test and measurement methods for **conducted emission** tests in industry.
- To evaluate, improve and develop alternative test and measurement methods for **conducted immunity** tests in industry
- To evaluate, improve and develop alternative test and measurement methods for **radiated emission** tests in industry
- To evaluate, improve and develop alternative test and measurement methods for **radiated immunity** tests in industry
- To develop concepts and tools for the EMC test devices to be used in inter-laboratory comparisons for both emission and immunity tests through;
    - Evaluating correlations between alternative test methods and those defined in standards
    - Developing test specimens and tools for the EMC tests which can be used in inter-laboratory comparisons for both emission and immunity tests.
    - Evaluating the traceability of these existing and newly developed alternative EMC test methods
    - Providing guidance documents for application of improved and newly developed alternative EMC tests in industry, including calculations of uncertainty and usage of correlation data.

3 Research results

The research results of the project are presented in detail below on the basis of the test type.

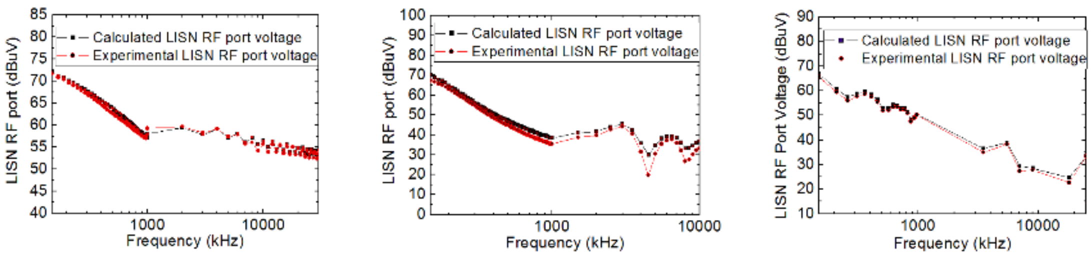
- Conducted emission tests

For conducted emission tests, correction factors that link industry to the test laboratory were successfully obtained for actual EUTs such as a drill, a UPS (Uninterruptible Power Supply) on actual mains without LISNs (Line Impedance Stabilisation Network) jointly by TUBITAK, INTA, REG(UTwente) (see Fig.1 and Fig.2). In this research, VSL and REG(UPC) specially focused on impedance measurement methods along with uncertainty calculations and developed new impedance measurement methods such as three probe method to be used in the alternative conducted emission methods.



(a) (b)

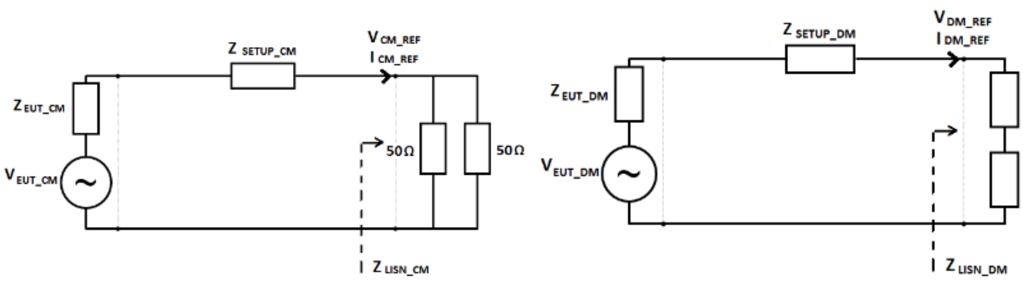
Fig 1. Conducted emission setups that have been linked (a) laboratory setup, (b) industrial setup



(a) (b) (c)

Fig 2. Comparison of alternative method results based on the impedance measurements and standard method results for (a) a CM reference device, (b) a drill, (c) an UPS

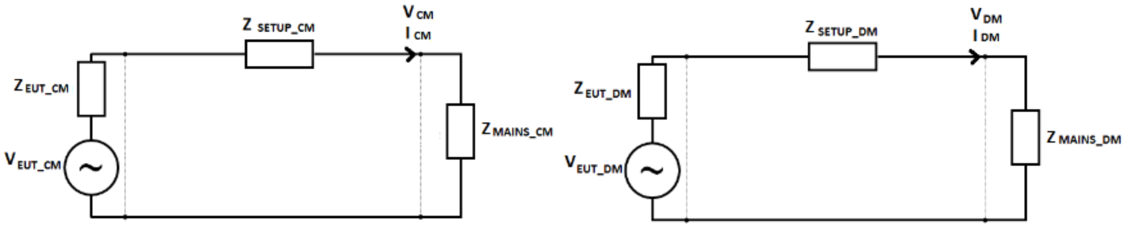
The proposed alternative conducted emission measurement method is completely based on the separate impedance measurements of the EUT, used cables and supply. Emissions coming from an EUT are classified as CM (Common Mode) and DM (Differential Mode) and measured in laboratory environment with the use of LISNs. The circuit models of conducted emission measurements for CM and DM in a laboratory environment are presented in Fig.3.



(a) (b)

Fig 3. Circuit models of conducted emission measurements in laboratory environment (a) CM circuit model, (b) DM circuit model

On the other hand, unlike the laboratory environment, the alternative methods for industry have the circuit model shown in Fig.4.



(a) (b)

Fig 4. Circuit models of alternative conducted emission measurements in industry (a) CM circuit model, (b) DM circuit model

Finally, all the impedance measurements lead to correction factors between the reference emission setup with the reference LISN and the alternative setup without the reference LISN as given in equations (1) – (4) with the assumption that CM and DM interference voltage sources inside the EUT are constant.

$$K_{Current\_CM} = \frac{I_{CM\_REF}}{I_{CM}} = \frac{Z_{EUT\_CM} + Z_{SETUP\_CM} + Z_{MAINS\_CM}}{Z_{EUT\_CM} + Z_{SETUP\_CM} + Z_{LISN\_CM}} \quad (1)$$

$$K_{Current\_DM} = \frac{I_{DM\_REF}}{I_{DM}} = \frac{Z_{EUT\_DM} + Z_{SETUP\_DM} + Z_{MAINS\_DM}}{Z_{EUT\_DM} + Z_{SETUP\_DM} + Z_{LISN\_DM}} \quad (2)$$

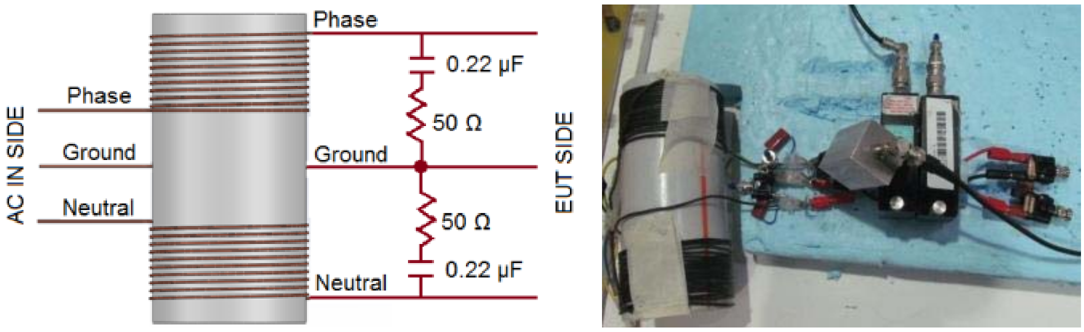
$$K_{Voltage\_CM} = \frac{V_{CM\_REF}}{V_{CM}} = K_{Current\_CM} \cdot \frac{Z_{LISN\_CM}}{Z_{MAINS\_CM}} \quad (3)$$

$$K_{Voltage\_DM} = \frac{V_{DM\_REF}}{V_{DM}} = K_{Current\_DM} \cdot \frac{Z_{LISN\_DM}}{Z_{MAINS\_DM}} \quad (4)$$

These factors are very essential and expected to form correlation between the laboratory and the industry. If the LISN usage is not possible due to some restrictions, measurement of the current (I_{DM} and I_{CM}) with a current clamp or measurement of the voltage (V_{CM} and V_{DM}) with a CVP is the only way to perform the measurement in industrial environment. However these measured values do not make any sense without knowing the impedance values of the EUT, used cables and supply, for that reason the correction factors obtained in (1) - (2) for current and in (3) - (4) for voltage will form the connection between the reference conducted emission method and alternative conducted emission methods. After calculating the theoretical factors based on the impedance measurements, I_{DM} and I_{CM} (or V_{DM} and V_{CM}) measured in industry are linked to I_{DM_REF} and I_{CM_REF} (V_{DM_REF} and V_{CM_REF}) in the reference setup and finally the voltage measured at the RF port of one of LISNs is predicted as given in (5) as the worst case. In (5), Z_{SINGLE_LISN} is the impedance of a single LISN.

$$|V_{LISN}| = \left(\frac{|I_{CM\_REF}|}{2} + |I_{DM\_REF}|\right) \cdot |Z_{SINGLE\_LISN}| \quad (5)$$

In addition to the successful measurements on actual mains, the design and research of a LISN simulation (dummy LISN) and improvement in usage of the CISPR16 voltage probe have been finalised collaboratively by TUBITAK, VSL, REG(UPC) and REG(UTwente). It has been demonstrated that they can be used as an alternative conducted emission test method to the standard LISN method when standard LISNs and current probes are not available due to limitations such as high current, unknown impedance (see Fig.5).

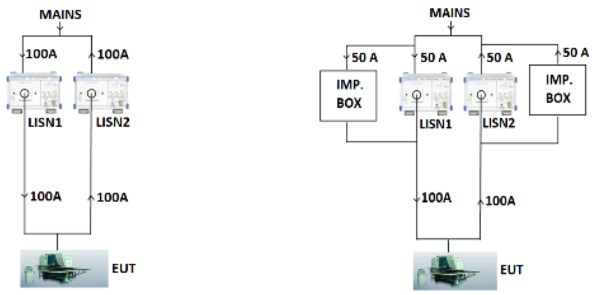


(a) (b)

Fig. 5. LISN simulation (a) diagram, (b) photo of actual use

All the results obtained in alternative conducted methods were successfully connected to the measurements on the LISN RF port. Several conducted emission alternative test methods (such as current and voltages probes) were evaluated and a detailed report highlighting the benefits and constraints of each method has been produced.

If the sole reason is the high current for not being able to use LISNs, TUBITAK and VSL have jointly introduced another alternative method called “Parallel Impedance Box” method which includes the impedance boxes or 50 ohm-terminated LISNs parallel to the active LISN as a shunt. Similarly, this method also includes the impedance measurements but do not rely on current probe and CVP measurement results. Instead, it relies on the measured values on the active LISN. In this method, the supply current can be divided into several parts which are less than the current limit of a single LISN so that the active LISN is able to measure the voltage without damage due to high supply current.

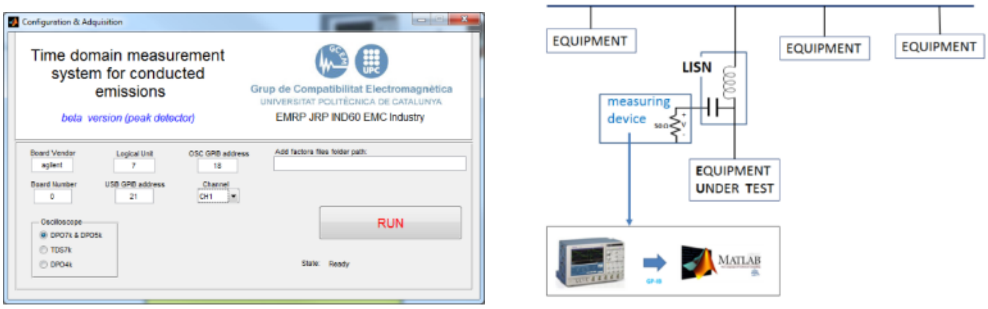


(a) (b)

Fig. 6. Demonstration of “Parallel Impedance Box” method (a) reference method, (b) alternative method with impedance boxes parallel to active LISNs

The “Parallel Impedance Box Method” is summarized in Fig. 6. As seen in Fig. 6, a supply current of 100 A as an example is split in half in order to keep the current below the LISN current limit (50 A in our example). In Fig. 6, the impedance box may be a circuit similar to a LISN or a LISN with 50 ohm termination or even a RF filter for this purpose.

In addition, a new time-domain conducted emission alternative test method based on an oscilloscope has been successfully developed and tested collaboratively by REG(UPC) and INTA. The final result is a fast reliable new testing method. Time domain emission measurements allow the reduction in the time needed to cover all the frequency range required by the standards. The one shot oscilloscope measurement is very useful in difficult measuring scenarios (for example industrial in situ measurements). Also, new impedance measurement methods have been developed by REG(UPC) to be used in industry to assist in evaluation of conducted emissions. Uncertainty calculations have been completed for the improved and developed conducted emission test methods (see Fig.7).



(a) (b)

Fig. 7. Time domain conducted emission method (a) screen of designed software, (b) time-domain conducted emission measurement setup

It is well known that carrying out radiated and conducted EMI measurements is challenging in large fixed installations scenarios. In comparison with the tests performed in an electromagnetic compatibility (EMC) test laboratory, in-situ measurements have a common and meaningful issue related to the inherent uncontrolled environment conditions as a LISN is not available during the tests. With the aim to improve the measurement of the disturbances at large fixed installations, the full time-domain methodology has been developed and validated with a measurement campaign (see Fig. 8). The results obtained conclude that the main troubles of in-situ measurements can be partially solved by using a time-domain approach. Moreover, through the different comparisons done, it has been shown that it is also possible to obtain as good results in terms of accuracy as with an EMI receiver.

Fig. 8. A Time-Domain EMI measurement system.

The current capabilities of hardware and previous studies demonstrate that it is feasible and reliable to perform time-domain measurements instead of frequency sweeps to obtain the spectral information of the interference. Therefore, in this research project, REG(UPC) has developed a measurement system based on time-domain captures to overcome these main difficulties that recurrently appear when in-situ measurements are carried out. In general terms, a TDEMI measurement system can be described by the block diagram shown in Fig. 9. The TDEMI measurement system is based on capturing the interferences employing an oscilloscope and post-processing the data with a standard laptop.

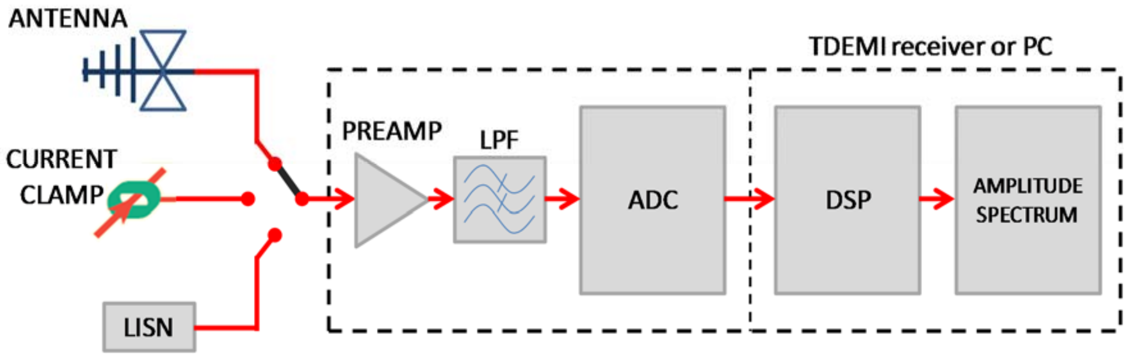


Fig. 9. Block diagram of a Time-Domain EMI measurement system.

Regarding the main benefits observed, the time-domain methodology aids the test technician to overcome challenges such as the changes of background noise, evaluate accurately all the EUT functional modes (even the short lasting ones) and reduce significantly the effective measurement time. As it has been shown, one key aspect is the multiple channel synchronous measurement capability, this allow us to carry out conducted disturbances measurements at three-phase power supply lines employing the multiline voltage probe.

Also, new impedance measurement methods have been developed by VSL to be used in industry to assist in evaluation of conducted emissions. The measurement is done in time domain. A multi-tone signal is injected through an injection probe and the generated loop currents in the circuit are measured using a receiver probe and a monitor probe. The method is able to measure load impedances at “power on” condition and obtain accurate results which the other methods in literature cannot realize at this lower frequency range. Besides, simple measurement instruments and mathematical deduction make this method easy to be implemented wherever the measurement is needed (see Fig.10 and Fig.11).

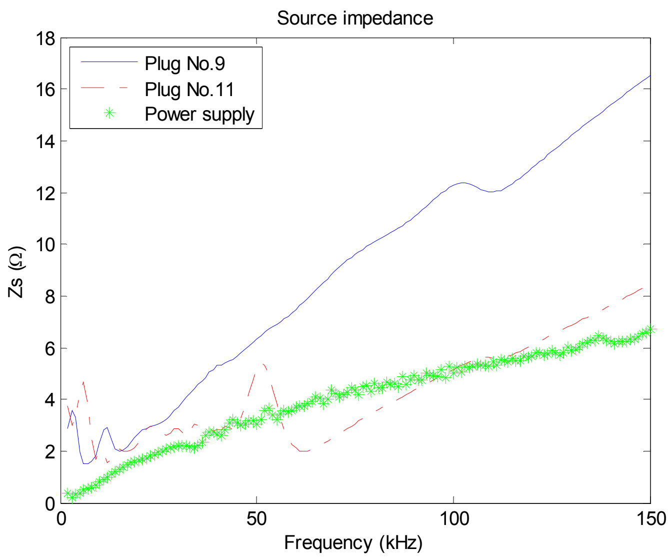
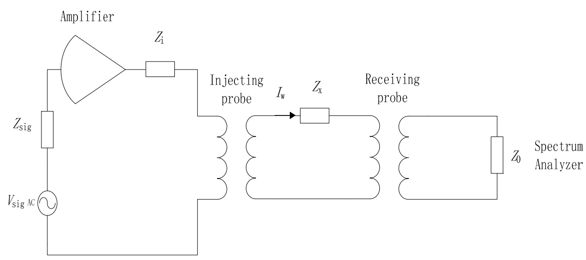
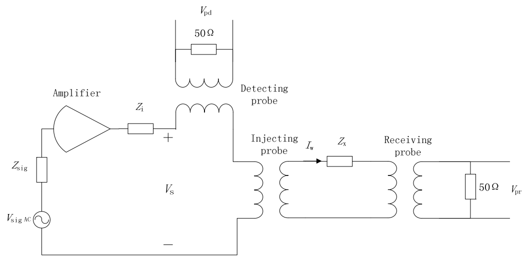


Fig. 10. Grid impedance measurement results



(a)



(b)

Fig. 11. Improved and developed impedance measurement methods (a) two-probe method, (b) three probe method

To perform the LISN calibration, the input impedance (defined as the impedance at the EUT terminal with respect to reference earth) is measured as well as the insertion loss (the loss in volts measured between the EUT port and the measurement output port) and the voltage division factor (ratio of input voltage, at the connector supplying mains power to the EUT to output voltage at the connector for the measuring receiver). The input impedance must be within the tolerances defined by the CISPR committee of the International Electrotechnical Commission (IEC). The phase and magnitude tolerances are described by the CISPR 16-1-2 standard. For test laboratories it is of best interest to perform the LISN calibration with high accuracy because any calibration errors will affect conducted emission measurement results. On the other hand if the uncertainty due to the input impedance calibration is high; it is difficult to judge on the compliance of the LISN to the CISPR 16-1-2 standard. To measure the impedance at the EUT port and the insertion loss between 9 kHz to 30 MHz, a 50 Ω coaxial system is usually used: a Vector Network Analyzer (VNA) or an Impedance analyzer (IA). VNAs are equipped with coaxial connectors. In contrast, LISNs are equipped with a different type of connection that can be for instance a CEE 7/4 socket. The EUT plug is located on the front panel of the LISN: there is clear difference between VNA and LISN connectors. In consequence to improve the traceability of LISN impedance measurements and reduce the impact from adapters used by testing laboratories new coaxial-type to banana adapters as well as a correction method have been developed jointly by LNE and SIQ in this project.

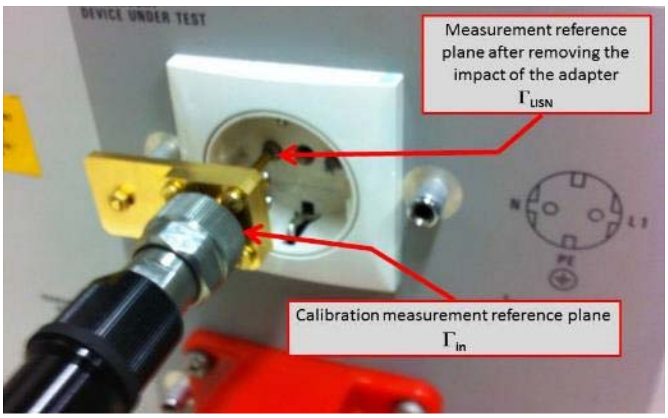


Fig. 12. Connection of the adapters to the LISN's socket. Γ_{in} is the uncorrected reflection coefficient of the LISN and Γ_{LISN} is the "true" reflection coefficient of the LISN.

The goal of the correction method is to assess the input impedance of the LISN by removing the impact of the adapter used during the measurement. After applying the correction, the measurement reference plane is located at the output of the adapter and the "true" Z_{in} input impedance of the LISN can finally be measured

(Fig. 12). The correction method is based on the S matrix of the adapter S adapter and on the input reflection coefficient Γ in measured at the input of the adapter. The matrix S of the adapter is derived from calculation. The “true” input reflection coefficient of the LISN (Γ_{LISN}) is calculated using:

$$\boldsymbol{\Gamma_{LISN}} = \frac{\boldsymbol{\Gamma_{in} - S_{11}}}{\boldsymbol{S_{22}(\Gamma_{in} - S_{11}) + S_{12}S_{21}}}$$

The “true” input impedance of the LISN is then finally calculated:

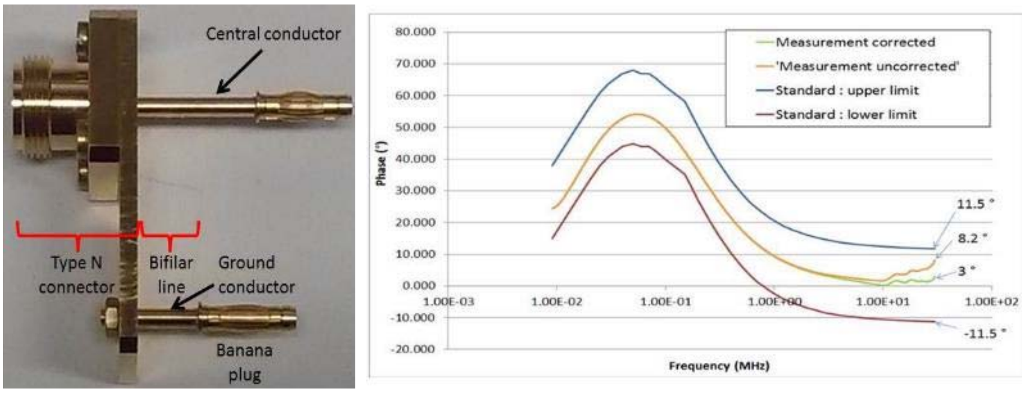
$$\boldsymbol{Z_{LISN} = Z_0 \frac{1 + \Gamma_{LISN}}{1 - \Gamma_{LISN}}}$$

Γ_{in}: input reflection measured by VNA

S_{11}, S_{12}, S_{21}, S_{22}: S parameters of the adapter

Z_{LISN}: LISN input impedance corrected after applying the correction method

These new coaxial-type to banana adapters jointly developed by LNE and SIQ improve the traceability of LISN impedance measurements. These adapters are fully calculable and their modelling is traceable to the International System of Units (SI) through dimensions and permittivity measurements. Using these adapters improves the measurement accuracy and traceability of LISN. The necessary correction applied to the measurement by using these adapters (up to 5° for the phase) is larger than uncertainties (2° for the phase) provided by test laboratories. For the first time, it has been clearly demonstrated that there is great importance of properly using these adapters in EMC test laboratories (see Fig.13).



(a) (b)

Fig. 13. New coaxial type to banana adaptors (a) photo, (b) results

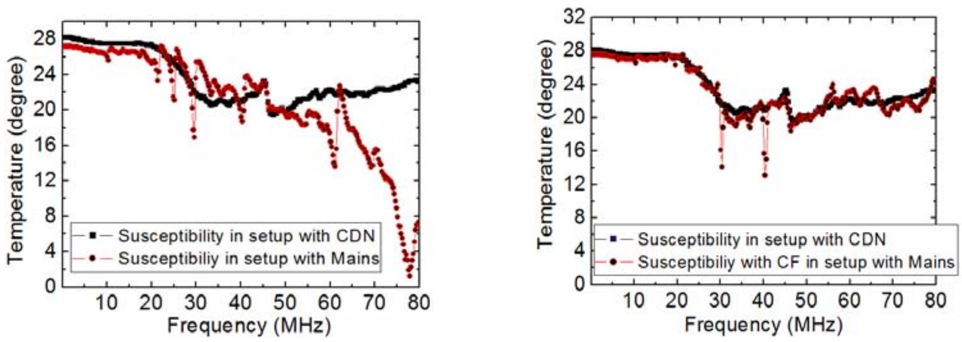
As there is a need for conducted measurements below 150 kHz, although not covered by standards yet, the widespread use of non-linear low power loads on the mains power network call for standardization of measurements in the frequency range of 2 to 150 kHz. These loads, although low power, produce synchronous load current spikes that tend to add up to serious waveform distortions at the locations of these synchronous spikes. These effects are most pronounced if many identical small loads are used like Compact Fluorescent and Light Emitting Diode Lamps (CFL and LED). A very useful device is the 1000:1 Mains Waveform Monitoring Probe, originally designed by Schaffner. The unit has two 1000:1 resistive dividers, one for the Line and one for the Neutral conductor (phase-)accurate from 0 to 100 kHz. For monitoring only, the -3 dB transfer point is approximetely 3 MHz. This device has also been built by REG(UTwente) for a three phase outlet. Both the units have been calibrated by VSL (see Fig.14).

Fig. 14. Mains waveform monitoring probes

Ultimately, a special filter has been designed by REG(UTwente) and built to be used in combination with this monitoring probe with a passband of 2 kHz to over 3 MHz to measure common-mode (CM) and differential mode (DM) noise on the mains lines. The passband attenuation is 34 dB. The waveform monitoring probe is used to trigger an oscilloscope that measures the CM and DM noise.

- <u>Conducted immunity tests</u>

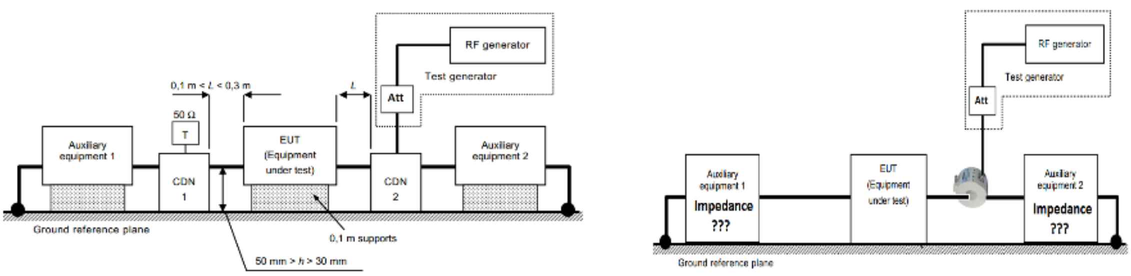
For conducted immunity tests, loop impedances on the standard conducted immunity setup and non-standard setups were measured and correction factors produced between the standard setup with CDNs and the alternative setups without CNDs like in industrial environment. Consequently, the first efficient link between the standard and alternative methods has been established collaboratively by TUBITAK and VSL for conducted immunity testing (see Fig.15). VSL also contributed to the research with the development of new impedance measurement methods.



(a) (b)

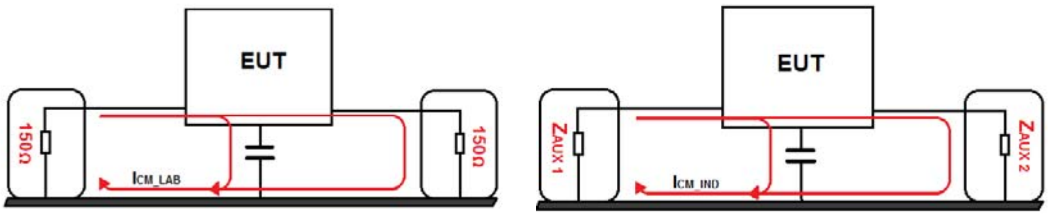
Fig 15. Susceptibility level of an example EUT, (a) without correction factors, (b) with correction factors

The alternative conducted immunity measurement methods in our research were completely based on the impedance measurements of loop impedances. This impedance measurement method uses a network analyzer, two current probes and one precision known impedance. It yields the value of the unknown target impedance as well as the impedance of used cables that include the effects of the used current probes and, if any, other measurement components. That means that we also took the induced impedances by the used injection clamp and receiving current clamp into account.



(a) (b)

Fig 16. Conducted immunity setups that have been linked (a) laboratory setup, (b) industrial setup



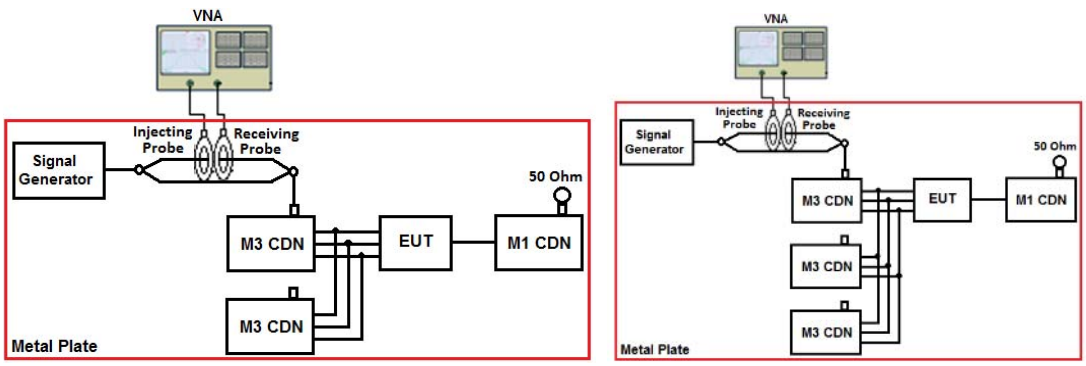
(a) (b)

Fig 17. Conducted immunity test setups (a) laboratory setup with CDNs, (b) industrial setup without CDNs

The standard EN61000-4-6 requires the setup presented in Fig. 16(a). On the other hand, the test setup commonly installed in industry is as depicted in Fig. 16(b). The conducted immunity test setup circuit models installed in laboratory and in industry are also shown in Fig. 17. As seen in Fig. 17(a), the standard loop impedance includes two 150 ohm impedances and EUT on the loop. On the other hand, the setup in industry includes two unknown impedances which are shown as Z_{AUX1} and Z_{AUX2} and EUT as seen in Fig.17(b). By using the loop impedances, the theoretical correction factors can be obtained as follows;

$$K = \frac{Z_{LOOP\_LABORATORY}}{Z_{LOOP\_INDUSTRY}} \qquad (6)$$

The impact of the induced impedance of the used current probes on the conducted immunity test results was also taken into account. In addition, the multi-CDN method has been developed by VSL and TUBITAK to allow the use of CDNs also for high-current EUTs. With the multi-CDN method, the high EUT current can be split into several parts that one CDN can handle and subsequently CDNs become available also for high-current EUTs (see Fig.18). A simple wire-winding for injection purposes was also investigated and it was shown that a simple wire can be reasonably used for frequencies up to 80 MHz in narrow places of industry and also on thick cables for which a commercial CDN or BCI probe is not available.



(a) (b)

Fig 18. Alternative Multi-CDN method, (a) with two CDNs, (b) with three CDNs

- Radiated emission tests

For radiated emission tests, a report on “how the Q value of the on-site facility can be increased and definition of related rules” has been prepared. The report summarizes the information from the literature study and experience from measurements in different environments. In addition, a report titled “Method for alternative radiated emission test involving changing Q value in the absence of OATS (Open Area Test Site) or anechoic chamber” was prepared to show how to determine the Q value when an industrial site environment has relevant similarities with a reverberation chamber (see Fig. 19). This excellent work has been jointly performed by SP, REG(UTwente) and INTA.

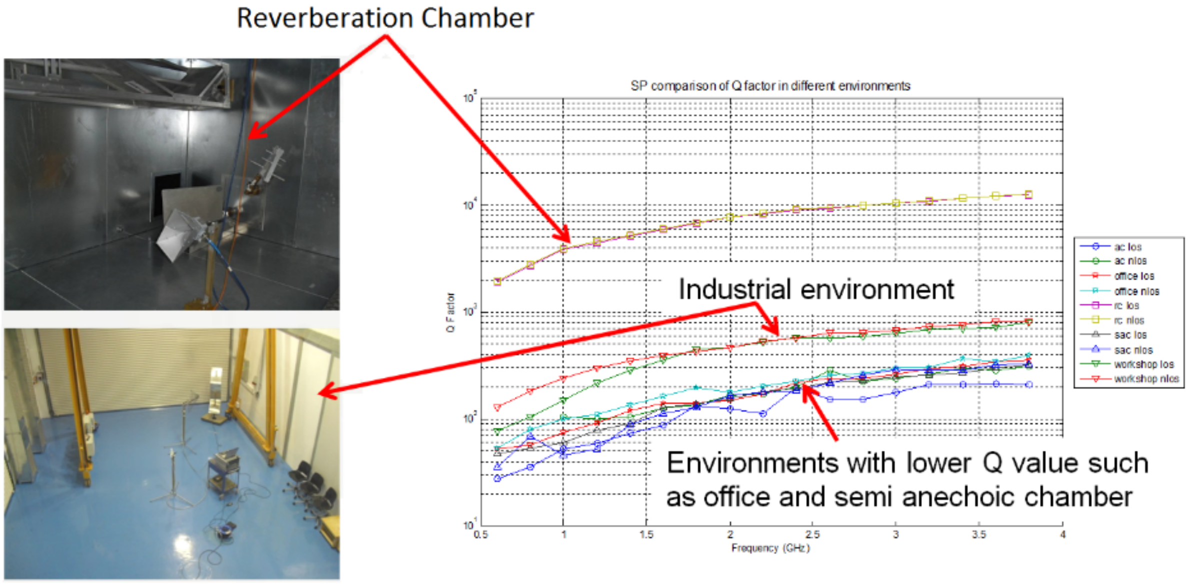
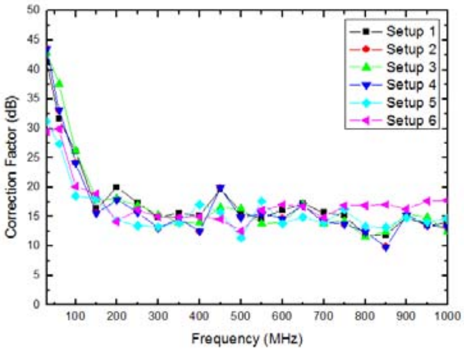


Fig. 19. Q factor results in different environments

The alternative close-distance radiated emission test method has been extensively investigated jointly by TUBITAK, SP, CMI, LNE, INTA and REG(UPC) in a very large scale under the leadership of REG(UTwente) and it has been concluded with promising results and an acceptable tolerance around 5 dB in most of the frequency range up to 1 GHz. As a consequence, an experimental link has been established between standard distance measurements and close-distance measurements by using a variety of EUT types and receiving antennas. The results obtained so far showed a similar tendency of the correction factor curves which depend on the size of EUTs and receiving antenna types. The research results also reveal that more stable and predictable results are obtained with the mini-biconical antenna (see Fig.20).

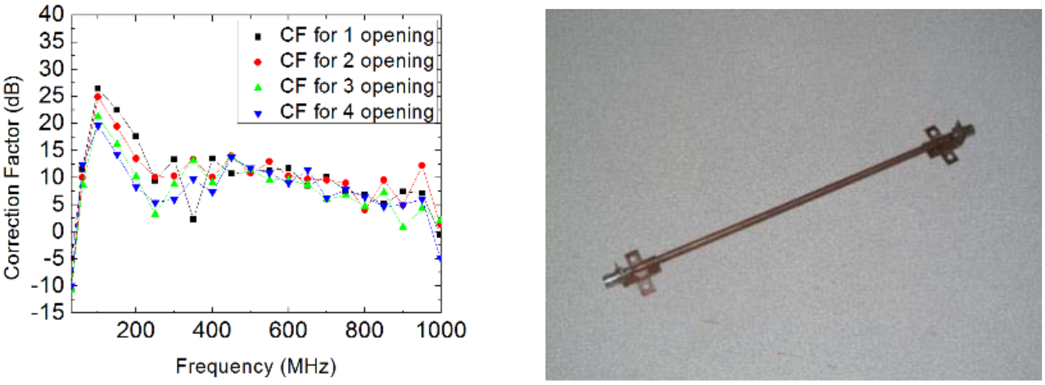


(a)

(b)

Fig. 20. Close-range radiated emission test method (a) results, (b) mini-biconical antenna used in research

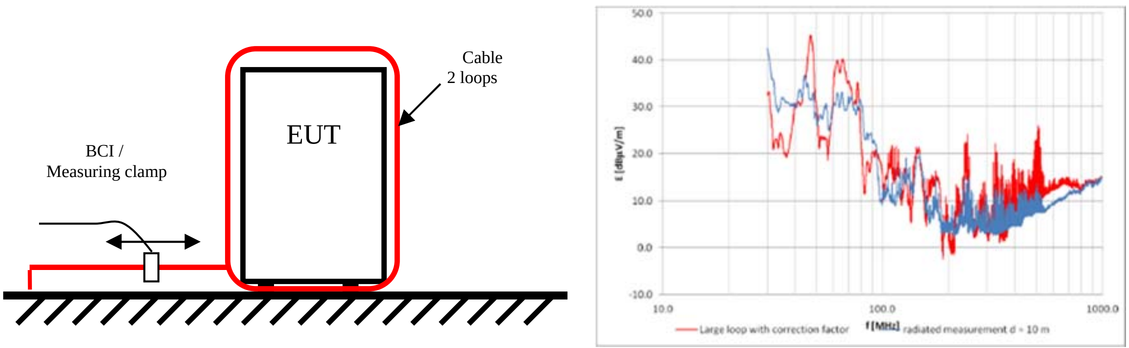
The state-of-art research results related to the surface wire test method were brought by TUBITAK with the contributions of SP, VSL, INTA and REG(UTwente) one more step further by investigating an experimental link between the alternative surface wire and the standard radiated emission test methods. The gained results in this work actually signal the presence of a correction factor between the alternative surface wire and the standard test methods. The surface wire test method looks more promising with 5 dB tolerance in most of the frequency range when it is applied to measure narrow slits by using maximum detection method and scanning the surface of the EUT (see Fig.21).



(a) (b)

Fig. 21. Surface wire method (a) example results, (b) surface sense wire used

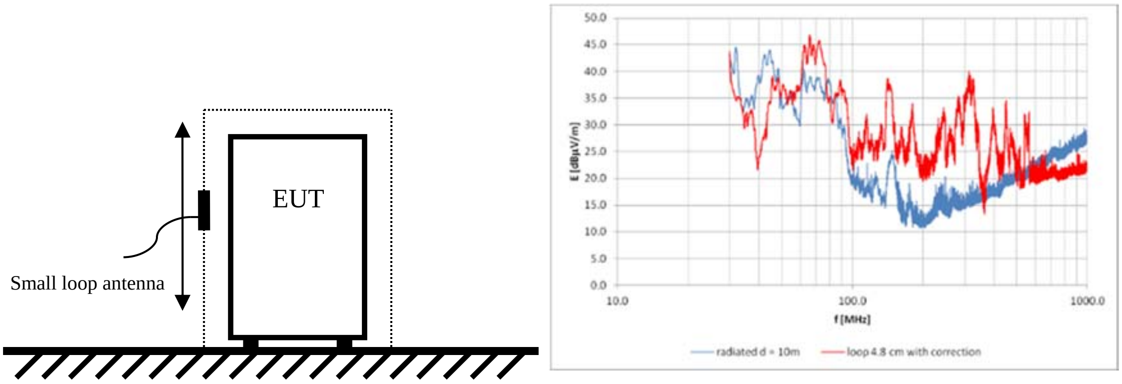
Regarding the usage of current probes and loop antennas in alternative radiated emission tests, four alternative radiated emission test methods were investigated by CMI supported by SP, TUBITAK and REG(UPC). The first one uses a BCI (Bulk Current Injection Clamp) current probe to measure current on the input/output wires of the tested device. This method has sufficient sensitivity to detect radiated fields but fundamentally corresponds to power measurements according to EN 55014. On the other hand, the results are not comparable to standard radiated emission limits due to different quantities. In order to overcome the impossibility of "setup calibration" of this method, three advanced methods were developed. Although the quantity measured in all these methods is different, all these methods use the same scheme of derivation of correction factors. First, a stable reference signal generator is measured using the standard method and the alternative method, thereafter the correction factor is derived from these measurement results and applied to alternative test method results of the unknown device. This makes the results comparable to the standard radiated emission limits. As EUT, a large AC power source was utilized in all the cases investigated. The first advanced method using the correction factor is based on measurement of currents of the large EUT induced into the large loop wound around the EUT (see Fig. 22). The large loop antenna collects radiation from the sample and current from the loop is measured by means of a current sensor or a BCI clamp.



a) b)

Fig.22. a) Test setup of large loop method b) Measurement results of large loop method

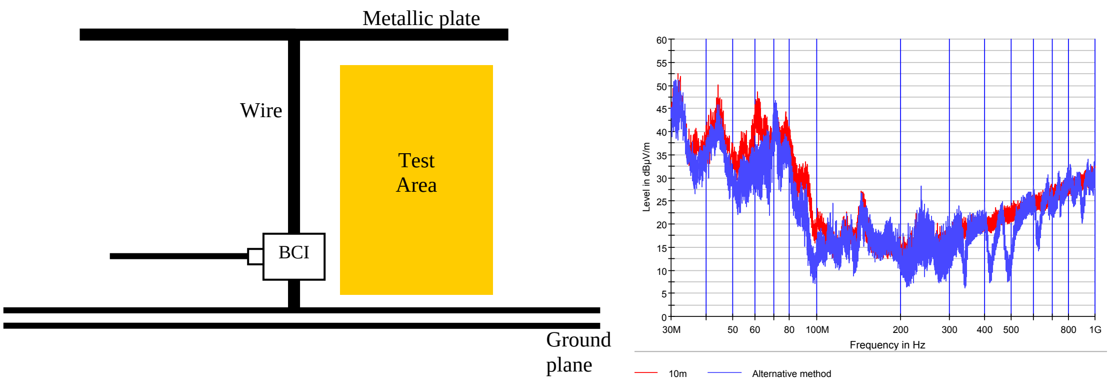
The second advanced method is based on the measurement of magnetic fields of a large EUT by means of a small shielded loop antenna. In order to ensure stable measuring conditions the loop antenna during the scan should have a constant distance from the EUT (see Fig. 23)



a) b)

Fig. 23. a) Test setup of magnetic field scanning b) measurement results of magnetic field scanning

The third advanced method uses a BCI clamp to measure radiated fields. The BCI clamp here is intended to measure the current on the cables going through them. To be used for radiated field measurements it is necessary to add a structure providing the coupling of radiated field to the wire. The test setup and the metallic structure used in this research are presented in Fig. 24. The metallic plate is positioned above the ground plane. The plate is connected to a ground plane with a wire and BCI clamp is placed on this wire. The output of the BCI clamp is connected to a measuring receiver. For all the stated alternative methods above, the uncertainty budgets were determined. As a result, the introduced methods that also contain calibration setups enable us to measure radiated EM fields from large devices especially for development and comparison measurements.



a) b)

Fig. 24. a) Test setup of “monopole construction” method b) measurement results of “monopole construction” method

A time domain electromagnetic interference (TDEMI) measurement system that employs an alternative approach and different algorithms in comparison to previously published works that address this subject, has been developed by REG(UPC). The experimental part of the research was supported by INTA with its extensive EMC test facilities. In order to keep the measurement setup as accessible and practical as possible, the direct measurements are recorded with a general purpose digital oscilloscope and processed with a commonly available personal computer. It is feasible to build it with a relatively small budget. One of the principal advantages of this TDEMI system is that it can be continuously improved through signal processing implemented via software. In addition, the measuring and processing time required by this TDEMI measurement system is much lower than the required by conventional EMI test receivers, Also, in this TDEMI measurement system the algorithms detect robustly the transient EMI pulses and automatically adjust the oscilloscope parameters and acquisition modes to capture only the pulse of interest with the optimal instrument configuration, thus the measuring system manages more effectively aspects such as the dynamic range and the ambient noise. These advantages make this system an attractive alternative for performing in-situ measurements in industrial environments or under situations where the equipment under test cannot be properly installed within a controlled measurement facility such as a semi-anechoic chamber (see Fig.25).

(a) (b)

Fig. 25. Time domain radiated emission method (a) software, (b) measurement with pico-scope

The TDEMI system developed by REG(UPC) can be employed for the measurement of either the radiated EMI or conducted EMI. For the measurement of radiated electromagnetic interference a broad-band antenna shall be used. The developed time domain methodology was applied to a real in-situ scenario providing a successful measurement campaign in huge automatic storage equipment (Fig. 26 and Fig.27).

Fig. 26. Measurements of a large fixed installation by applying the time-domain measurement system developed

The results obtained in these measurement campaigns conclude that the main troubles of in-situ measurements can be partially solved by using the time-domain approach. Furthermore, through the different comparisons done, it has been shown that it is also possible to obtain as good results in terms of accuracy as with an EMI receiver.

Fig. 27. Measurement setup for the measurement of the large fixed installation by applying the time-domain measurement system developed

Furthermore, multiple channel synchronous measurements open many possibilities that are particularly interesting for in-situ measurements, including advanced triggering capabilities and post-processing for ambient noise cancellation. The main benefits for in-situ measurements are described below.

- Reduction of the effective measurement time: the time-domain based systems are able to obtain the full spectrum information in milliseconds instead of several minutes when the EMI receiver is employed.
- Full spectrum real-time measurements: it is possible to obtain both the spectral and time domain information in real-time. This means that the user can view the entire spectrum and the time domain signal several times per second
- Transient interferences capture: Time-domain methodology allows us to capture extremely short duration interferences. These transient interferences are almost impossible to capture with the standard frequency sweep instrumentation.
- Background noise cancellation: It reduces the background noise employing post-processing techniques based on time domain captures.
- Time-domain data is available (APD): it is feasible to employ general purpose oscilloscopes to perform APD time-domain measurements in on-site tests. The TD APD measurement will permit to characterize properly the interferences and it will be possible to protect digital communication systems.
- Versatility of the measurement system: Full-TDEMI system can be USB powered and it has sufficient autonomy to be used in conjunction with a standard laptop. Therefore, this is a grateful advantage for in-situ measurements where it is difficult to power the measuring equipment.

As briefly emphasized above, one of the prominent advantages of multiple channel synchronous measurements is the background cancelation and this method is specially focused on by REG(UPC) in the project. This method is proposed to accomplish in-situ measurements in the presence of strong neighbour disturbance noise sources and back ground noise (BGN). In the approach, two additional channels are used to capture the background noise and the emission from the EUT in near field. Employing near-field triggering creates the possibility for identifying the emission of the EUT from the BGN and neighbour disturbances. The measurements are done in the time domain. This ensures the capture of the shortest transient signals, which is a significant improvement over traditional EMI measurement systems based on frequency sweeping (see Fig.28).

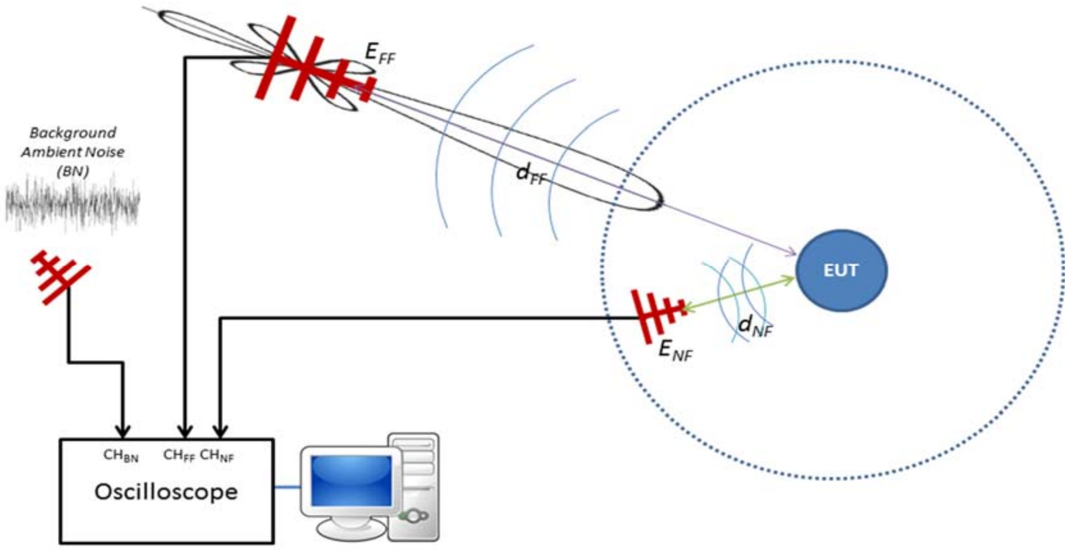
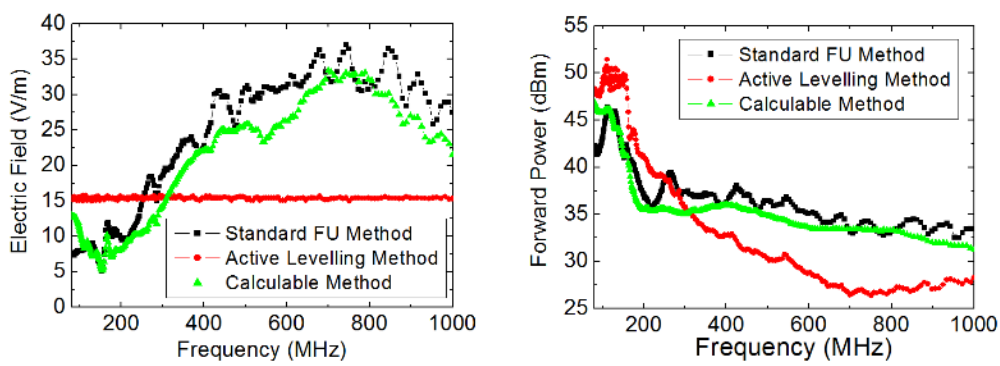


Fig. 28. Method proposed to mitigate background noise effects

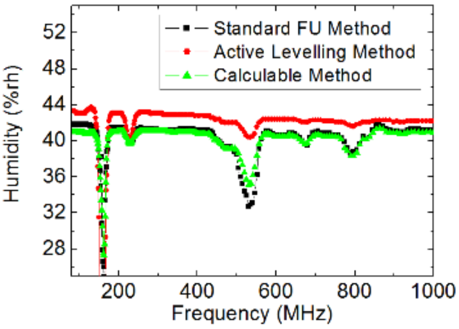
- Radiated immunity tests

For radiated immunity tests, an alternative test method with the use of BCI probes up to 1 GHz was developed jointly by CMI, INTA and REG(UTwente) and a report on “alternative radiated immunity tests with BCI” has been prepared. The critical items for further examination to extend the frequency range up to 1000 MHz for bulk current injection tests in industrial environment have been identified based on the literature study on the developments in bulk current injection testing and its challenges.

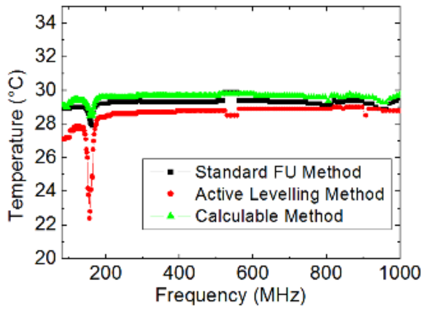
In addition, an alternative method for improved alternative on-site radiated immunity testing using antennas at close range to EUTs and effects of non-standard measurement distance and near-field effects on radiated immunity tests have been investigated collaboratively by TUBITAK and INTA under the leadership of REG(UTwente). In this context, TUBITAK and INTA supported by REG(UTwente) compared three radiated immunity test methods which are widely used in laboratories and in industry. The obtained comparison results show that they may lead to different test results in spite of the fact that all of them aim for the same field as a target on the EUT. On the other hand, the alternative calculable method was found more suitable in comparison to the alternative active levelling method as the active levelling method may cause severe overtesting or undertesting due to presence of the EUT and due to reflections caused by the EUT itself. (See Fig. 29)



(a) (b)



(c)



(d)

Fig. 29. Comparison of alternative test methods at 1m with standard method at 1m on an actual EUT; Thermo-hygrometer (a) injected power to antenna, (b) electrical field, (c) humidity susceptibility, (d) temperature susceptibility

Moreover, the radiation patterns of three different phones based on their 3D radiation pattern and 2D cross sections for alternative GSM immunity testing were investigated by TUBITAK and VSL. The behaviour of the mobile phones in vertical and horizontal polarizations were analysed and their radiated power and directivity values were compared by TUBITAK. In addition, VSL has developed a dummy mobile phone, which was also measured by TUBITAK, to be used in industry. It is concluded that the radiation pattern shape might be unexpected and the vertically polarized radiation may vary drastically from the horizontally polarized one. The results obtained in this research clearly emphasize the importance of the measurements of pattern and radiation parameters for more precise and more conscious alternative tests with the use of actual phones in industry (see Fig. 30).

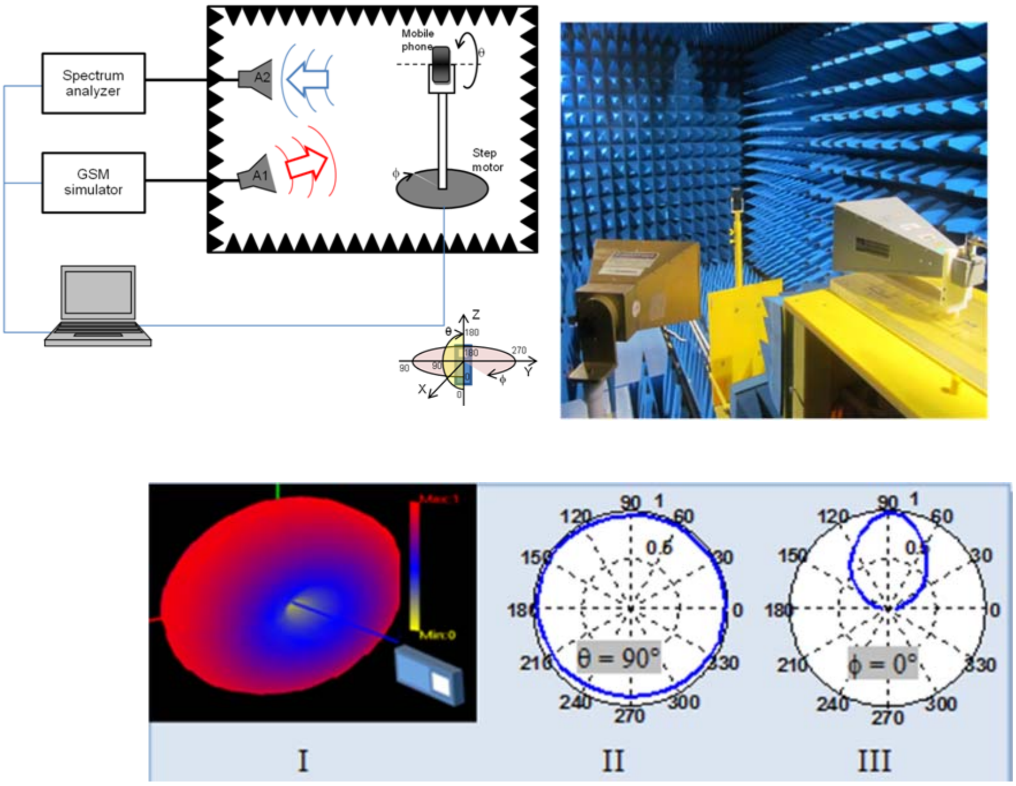


Fig. 30. GSM pattern measurement results on an example GSM phone (I) 3D pattern, (II) azimuth 2D pattern, (III) elevation 2D pattern

In the project, TUBITAK supported by SP, VSL and CMI also introduced a non-standard coil with a 3 dB uniform area which has a 3dB uniform magnetic field volume. It has been shown that by using a simple self made one turn coil a magnetic field uniform volume can be easily generated and hence complies with requirement of the standard (EN 61000-4-8). This means that as long as the field uniformity of a self-made coil is measured, it can be produced in any desired size and reliably used for testing of large devices in industry.

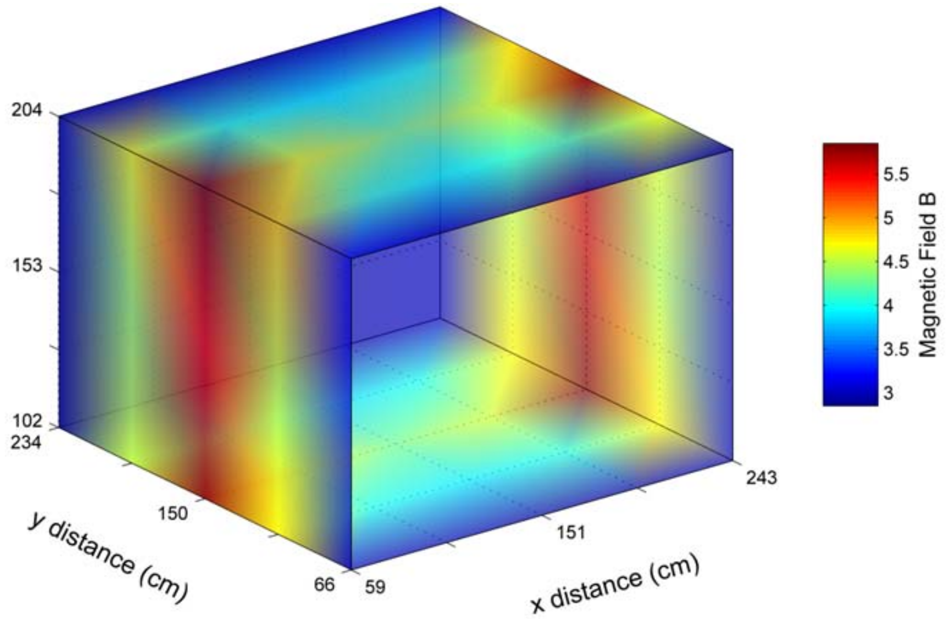


Figure 31. 3 dB uniform area for a self-made 3mx3m coil in a three-dimensional volume

In this project, TUBITAK supported by SP, VSL and CMI also investigated the method of using the surface wire method as an alternative method for radiated immunity tests. For investigating the feasibility of this method a metallic dummy EUT was built and a surface wire was placed on its surface as a radiating source. The surface wire was not optimized or designed with any criteria; it is rather a piece of wire with BNC connectors on both of the ends. The EUT was tested according to the standard method and also using the surface wire method, and the difference between the values obtained with both of the methods is considered as an indicator of the high efficiency in terms of injection. From the investigation it is concluded that the EUT plays a major role and might lead to reflections and resonances inside it. Also, a direct comparison is not easy due to the different way of wave propagation in both of the methods. It has been also concluded that it is more sensible to stress and express the high efficiency of the surface wire with respect to the standard method. In this context, any test with positive results obtained by the use of surface wire method with the same net power as the standard method may guarantee the positive results in the standard method.

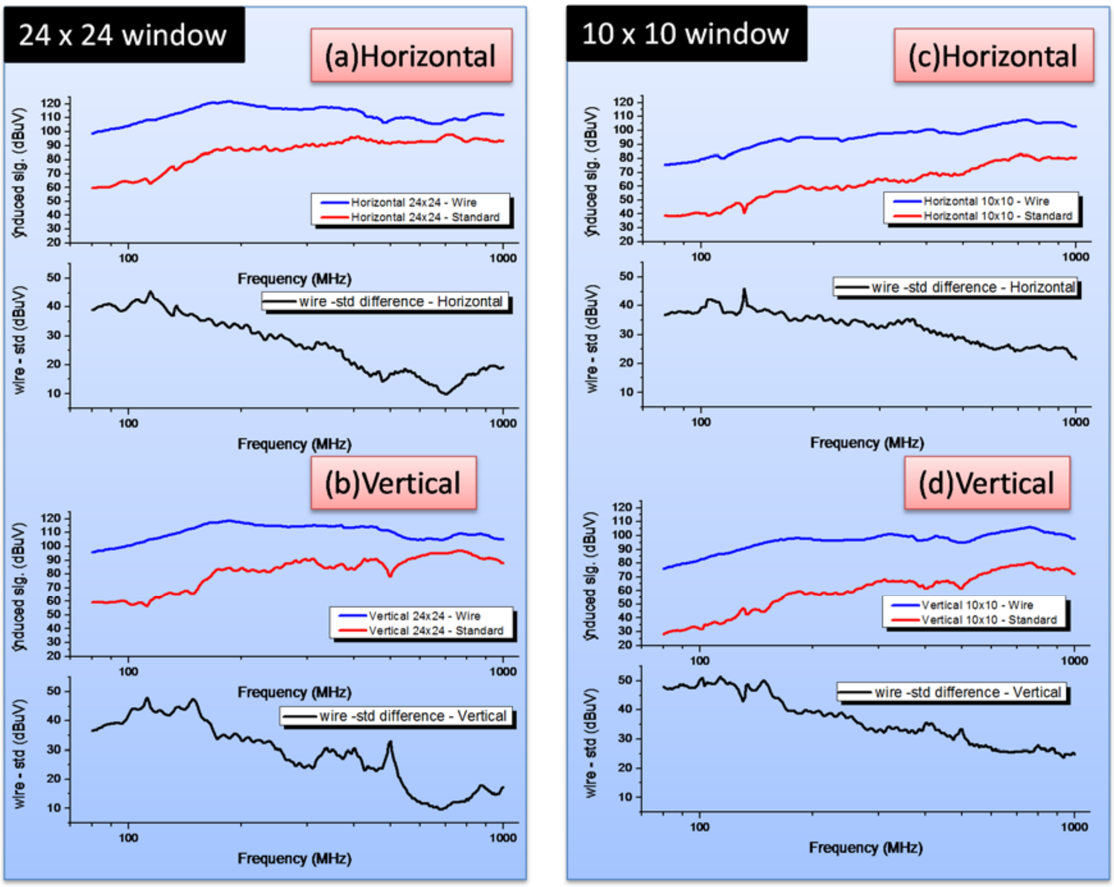
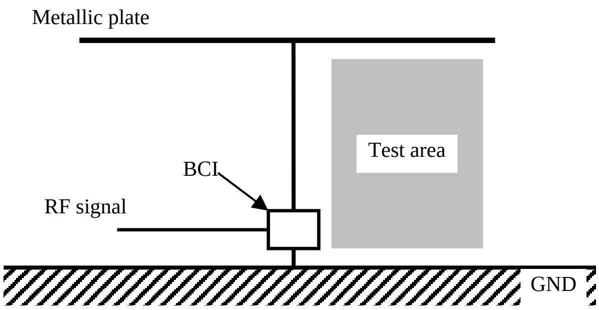
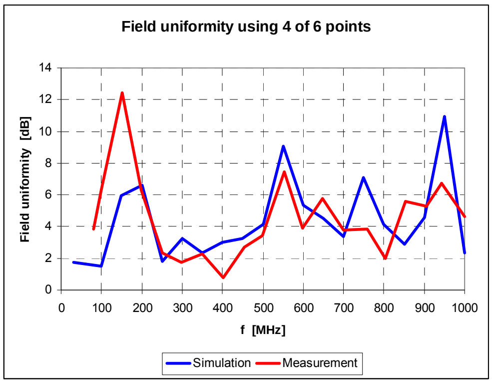


Fig. 32. (a) Radiated immunity measurement results (induced signal inside EUT) and correction factors of the EUT with (left graph) 24x24 cm^2 EUT window and (right graph) 10x10 cm^2 EUT window in (a) and (c) horizontal and (b) and (d) vertical antenna polarization (standard method) or surface wire placement (alternative method).

A complex study on the use of Bulk Current Injection clamps in immunity tests was performed jointly by CMI, INTA and REG(UTwente). The input impedance of the BCI is influenced with the load of the tested transmission line. This may be the first contributing effect to the inaccuracy of the open loop test method based on the calibration with well defined impedances. A typical automotive test setup for EN 61000-4-6 was used to analyze the influence of different load impedances and positions of the BCI clamp on the injected current. These tests showed the weakness of the open loop method, because the injected current is very sensitive to the change of the load impedance. The unknown input impedance of the EUT in the whole used frequency range leads to an unpredictable current level injected to the input of EUT. As a conclusion of this part, the closed loop method is proposed as an efficient method that should be preffered by industry. This method is more time consuming but the injected current is measured directly at the EUT and the impedance influence may be canceled by changing the power level of the amplifier. The BCI injection method using the closed loop was found as a usable alternative tool for immunity testing in the frequency range up to 1 GHz. Finally, the radiated immunity test method using BCI was developed. Additional construction, that can be excited by means of a BCI probe, is built around the EUT. This installed “Monopole” setup is shown in Fig. 33. The metallic plate is installed above the ground plane and connected to it with a wire or tube. The BCI probe is mounted on the vertical wire and connected to an RF amplifier. EUT is then placed to the area under the plate beside the wire. The calibration of the excited field was performed in the test area like in the standard calibration of the immunity test setup using a standart EMC antenna (EN 61000-4-3). This new alternative method enables us to perform immunity tests in industrial environments.





a) b)

Fig. 33. a) Test setup of “monopole construction“ method b) field uniformity of „monopole construction“ method

- <u>Reference devices and comparison measurements for emission and immunity tests</u>

For comparison measurements and reference devices, a report on “The analysis of the available validation methods and their use in the project” and a software solution to perform the comparison using the different measurement have been produced by REG(UPC). The key to this method lies in the idea of weighting the different indicators of the traditional feature selective validation (FSV) method. The weighting function may be changed to accomplish the application-specific needs of the case which is being validated (see Fig.34). The developed validation methods were utilized by all the project partners to validate the alternative methods developed in the project.

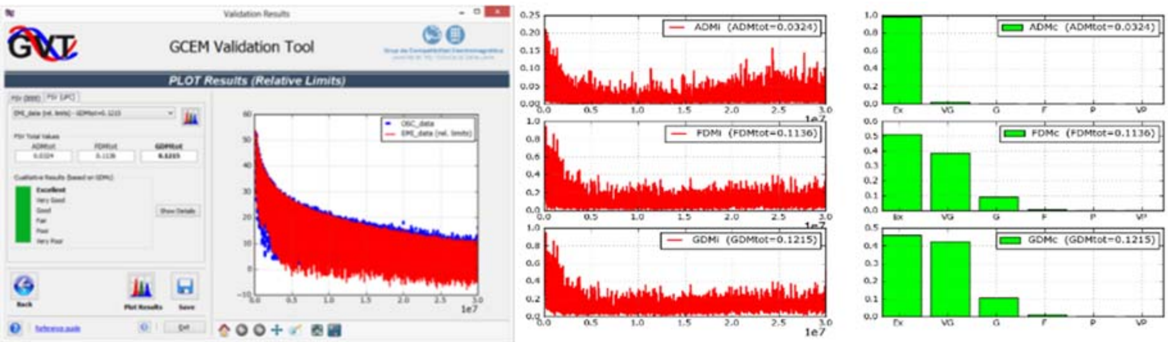


Fig. 34. Validation software

Inter-laboratory comparisons can be an important tool to evaluate the capabilities of EMC test laboratories. A prerequisite is the availability of a suitable test device. A new conducted immunity device has been developed jointly by METAS and VSL which is able to assess the immunity test capabilities of a laboratory according to the IEC 61000-4-6 standard. The device is intended to be tested as a normal EUT. It is equipped with appropriate detectors that record all important parameters associated with a chosen test set-up. The evaluation of the device performed shows that the device is able to identify a large set of faulty test procedures or mistakes in the setup.The concept and prototype for a conducted immunity reference source were completed and it is ready now for interlaboratory comparison conducted immunity tests. The comparison performed within this project could demonstrate how useful comparisons are performed in the field of EMC testing. Thanks to the comparisons performed among all the project partners within this project, we were able to identify faulty setups. This opens therefore a new area in the quality of EMC testing in Europe. The devices developed within this project can be used in the future to increase the quality of EMC testing of accredited labs (see Fig. 35).

.Fig. 35. Reference conducted immunity device developed within this project

Moreover, a conducted emission reference source used for RRT (Round Robin Test) were realized jointly by VSL and METAS in this project. The development of this source has also enabled a wide diversity of emission spectra and levels to be produced (see Fig.36). For measurements done above 30 MHz, the results show the correlation between the results of using CDNE (coupling/decoupling network for emission measurement) method and the LISN method. The device has been circulated around Europe for interlaboratory comparison tests. The comparison serves to either identify the source of an actually unperformed correction, or to validate the uncertainty budget.

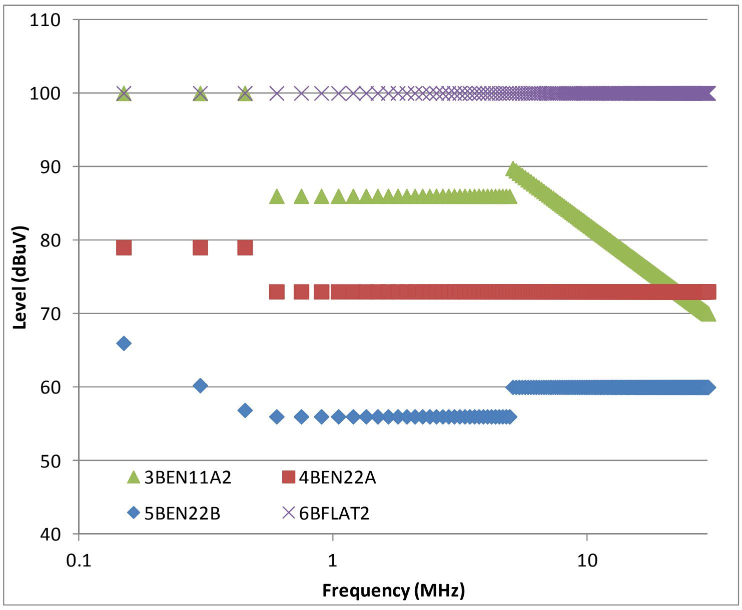
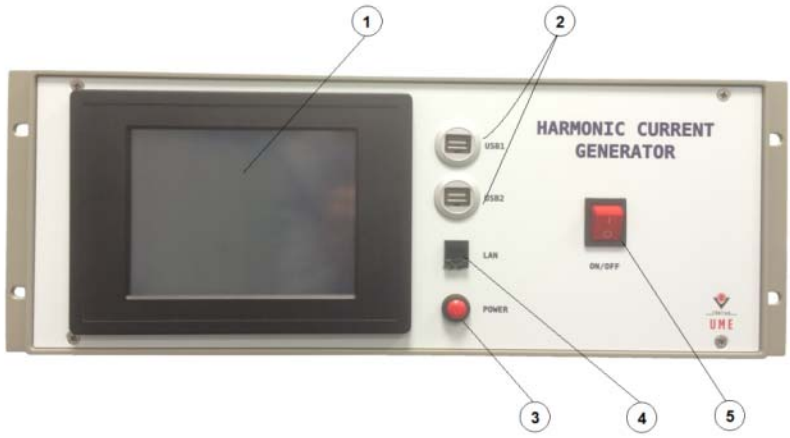


Fig. 36. The emission levels in Band B generated by VSL_CE_RRT corresponding to the limitation lines of selected standards

Finally, a frequency adaptive harmonic current generator has been designed collaboratively by TUBITAK and VSL for the purpose of generation and measurement of defined harmonics. The view of the device and installed components on the front and rear panels are given in Fig. 37 & 38.



Panel PC screen

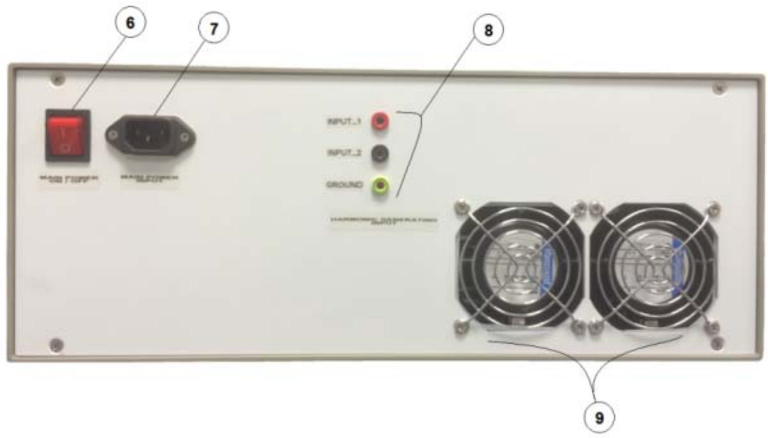
USB connectors

Power button for panel PC

Network connector

Harmonics On / Off switch

Fig. 37. Front Panel of the Harmonic Current Generator.



Main power On / Off switch

Main power input

Harmonics input

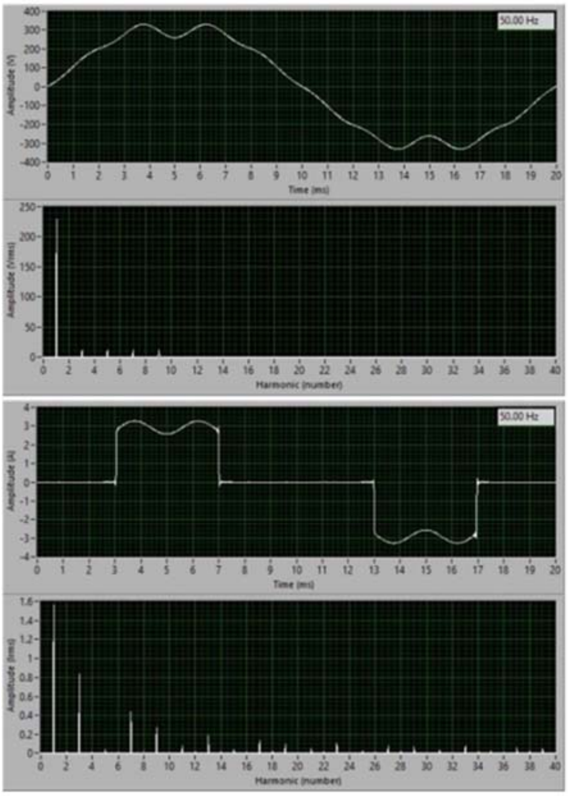
System cooling fans

Fig. 38. Rear Panel of the Harmonic Current Generator

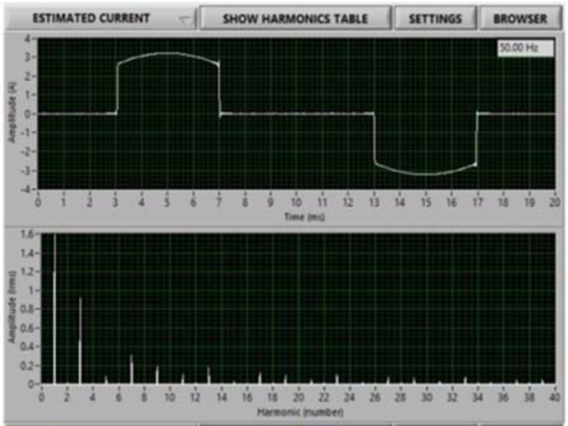
The device is suitable for being used as a transfer device for harmonic measurement and interlaboratory comparison harmonic tests. The device has novel features as follows. It is capable of both generating and measuring harmonics, hence a user can observe the generated harmonic values in real time graphs and tables. Also the recording of the measurements as an excel file is possible. It has two power inputs; one for the main power input of system blocks and one for harmonics generated. This feature increases the quality of the generation and the measurement of stable harmonics. Additionally, second input is allowing the user to apply different voltage levels, base frequencies and voltage harmonics while the main power input of the system is stable at the mains line.

Another novel feature of the device is frequency adaptiveness. Traditional harmonic generators in the market could work at only an exact mains frequency (e.g. 50 Hz). This device can be used between 45 - 65 Hz frequency interval for both harmonics generation and measurement. Generated harmonics are stable in this frequency interval. The device has another unique feature of estimation of drawn current harmonics as if the applied voltage signal was purely sinusoidal. This feature is very useful and facilitates measurements under polluted mains when a voltage source has harmonics (see Fig. 39).

TUBITAK has applied for a patent for this device.



(a)



Harmonic	Mag. (Irms)	Mag. (%)	Phase (deg)	Harmonic	Mag. (Irms)	Mag. (%)	Phase (deg)
1	1.5871	100.00	0.0	21	0.0478	3.01	-0.4
2	0.0130	0.82	179.9	22	0.0121	0.76	179.2
3	0.9076	57.18	-180.0	23	0.1010	6.36	179.7
4	0.0084	0.53	1.4	24	0.0098	0.62	0.8
5	0.0877	5.52	0.4	25	0.0194	1.22	-0.6
6	0.0076	0.48	-3.1	26	0.0058	0.37	-4.4
7	0.3090	19.47	-0.1	27	0.0741	4.67	-0.4
8	0.0132	0.83	-179.2	28	0.0135	0.85	-179.9
9	0.1860	11.72	180.0	29	0.0608	3.83	179.7
10	0.0010	0.07	17.3	30	0.0029	0.19	5.1
11	0.1003	6.32	179.8	31	0.0278	1.75	179.9
12	0.0126	0.79	-1.2	32	0.0116	0.73	-1.7
13	0.1796	11.32	-0.2	33	0.0699	4.40	-0.5
14	0.0091	0.57	-177.9	34	0.0104	0.65	-178.8
15	0.0245	1.54	-179.7	35	0.0178	1.12	179.5
16	0.0067	0.42	177.6	36	0.0049	0.31	176.4
17	0.1229	7.74	179.8	37	0.0512	3.22	179.7
18	0.0134	0.85	-0.3	38	0.0135	0.85	-0.8
19	0.0890	5.61	-0.3	39	0.0470	2.96	-0.7
20	0.0020	0.13	-167.2	40	0.0038	0.24	-174.4

(b)

Fig. 39. (a) Operation under polluted power supply, (b) estimation of real harmonics.

Key results and conclusions

Conducted Emission Test:

For conducted emission tests, correction factors that will link industry to the test laboratory were successfully obtained for equipment such as a drill and a UPS (Uninterruptible Power Supply), which is based on impedance measurements of the equipment under test (EUT) and the power supply.

A Line Impedance Stabilisation Network (LISN) is a device used in conducted emission tests to isolate the equipment from the power source or provide a known impedance value, which cannot be used for high current EUTs under normal circumstances. It was demonstrated that the simple dummy LISN, alias LISN simulation, which has been developed in the project can be used together with a voltage probe as an alternative conducted emission test method in circumstances with high current.

Several conducted emission alternative test methods (such as current and voltages probes) were evaluated and the benefits and constraints of each method were assessed. In addition, a new time-domain conducted emission alternative test method based on an oscilloscope was successfully developed and tested. This new testing method is fast and reliable.

Time domain emissions measurements allow the reduction in the time needed to cover all the frequency range required by the standards. The one shot oscilloscope measurement is very useful in difficult measuring scenarios, for example industrial in situ measurements. Also, new impedance measurement methods have been developed to be used in industry to assist in evaluation of conducted emissions. Uncertainty calculations have been completed for the improved and developed conducted emission test methods. Finally, new coaxial-type to banana adaptors for precise LISN calibrations to obtain traceability have been developed and successfully tested in LISN calibrations.

Conducted Immunity Tests:

For conducted immunity tests, loop impedance values on the standard conducted immunity setup and non-standard setups were measured and correction factors were produced between the standard setup with CDNs (Coupling Decoupling Network) and the alternative setups without CDNs like in industrial environment. Consequently, the first efficient link between the standard and alternative methods has been established for conducted immunity testing. The impact of the induced impedance of the used current probes on the conducted immunity test results was also taken into account. In addition, the multi-CDN method has been developed to allow the use of CDNs also for high-current EUTs. With the multi-CDN method, the high EUT current can be split into several parts that one CDN can handle and subsequently CDNs become available also for high-current EUTs.

Radiated Emission Test:

For radiated emission tests, a report on "*How the Q value of the on-site facility can be increased and definition of related rules*" has been prepared. The report summarises the information from the literature study and experience from measurements in different environments. In addition, a report "Method for alternative radiated emission test involving changing Q value in the absence of OATS (Open Area Test Site) or anechoic chamber" was developed to show how to determine the Q value when an industrial site environment has relevant similarities with a reverberation chamber. Furthermore, the alternative close-distance radiated emission test method and the surface sense wire methods have been extensively investigated and they have been concluded with promising results and an acceptable tolerance of around 5 dB in most of the frequency range up to 1 GHz. The time domain measurement system developed in the project was also employed for the measurement of the radiated EMI. For the measurement of radiated electromagnetic interference a broad-band antenna was used. The developed time domain methodology was applied to a real in-situ scenario providing a successful measurement campaign in a huge automatic storage. Finally, a background cancellation method was proposed to accomplish in-situ measurements in the presence of strong neighbour disturbance noise sources and background noise (BGN). BCI probes along with loop antennas have been efficiently integrated into alternative radiated emission test methods and three novel-type alternative radiated emission test methods which include the use of BCI probes have been developed.

Radiated Immunity Test:

For radiated immunity tests, BCI probes have been efficiently investigated with a conclusion that the closed loop method is proposed as an efficient method that should be adopted by industry and finally alternative test methods with the use of BCI probes up to 1 GHz were developed. In addition, construction that includes a metallic monopole structure which facilitates field uniformity with the aid of a BCI probe has been developed and verified for alternative radiated immunity testing. In addition, an alternative method for improved alternative on-site radiated immunity testing using antennas at close range to EUTs and research on effects of non-standard measurement distance and near-field effects on radiated immunity tests have been finalised. In this context, the project compared three radiated immunity test methods which are widely used in laboratories and in industry. Also, in an extensive scale, the 3D balloon patterns and the 2D patterns of several actual mobile phones have been experimentally measured along with some useful extra information such as directivity and radiation power, for the purpose of alternative EMC testing. The project consortium has also introduced a non-standard coil with a 3 dB uniform area which has a 3dB uniform magnetic field volume. It has been shown that by using a simple self made one turn coil a magnetic field uniform volume can be easily generated and hence complies with requirement of the standard (EN 61000-4-8). Ultimately, the method of using the surface wire was investigated as an alternative method for radiated immunity tests and high efficieny of surface wires in terms of electromagnetic injection was shown in comparison to the standard field uniformity method.

General conclusion for emission and immunity tests:

The existing testing methods were characterised and improved. New methods were also developed. This means that all large or high power equipment can now be tested with confidence, to ensure compliance with the EMC directive. Correlations were made between the alternative test methods and the standard test methods. The traceability of these existing and newly developed alternative EMC test methods was evaluated. Test specimens and tools were developed for the EMC tests which can be used in inter-laboratory comparisons for both emission and immunity tests. Guidance documents were developed for the application of improved and newly developed alternative EMC tests in industry, including calculations of uncertainty and usage of correlation data.

Tools and concepts for EMC test devices to be used in inter-laboratory comparisons:

For the comparison measurements and reference devices, a report "*The analysis of the available validation methods and their use in the project*" and a piece of software to perform the comparison using the different measurement have been produced. In addition, the concept and prototype for a conducted immunity reference source were completed and the first inter-laboratory conducted immunity comparison tests have been performed with the participation of 8 laboratories. A concept and a prototype for a conducted emission reference source with a wide diversity of emission spectra and levels were also designed. Finally, a frequency adaptive harmonic current generator with many novel features has been designed for the purpose of generation and measurement of defined harmonics. All the developed reference sources were measured by the project partners in three inter-laboratory comparison tests held internally.

4 Actual and potential impact

4.1 Dissemination Activities

4.2.1 Scientific publications

The project outputs have been shared widely with the metrology, instrumentation and industrial communities. Workshops disseminated the project outputs and liaised with stakeholders in the industrial, standards and research communities. Around 50 papers reflecting the project were presented at a variety of prestigious EMC conferences and journals. The work contributed to the standardisation activities of CISPR meetings, and the time domain measurements, in particular, were taken up by industry.

4.2.2 Stakeholder Engagement

In the scope of the project, the first workshop was held at the EMC Europe 2013 conference on 2 September in 2013 in Brugge, Belgium in order to gather information on the needs of industry and also existing non-standard alternative methods used in industry. Stakeholders had been informed about the workshop via emails and invitation letters before the workshop.

On 13 October, 2015, the consortium delivered three presentations in the yearly EMC Symposium for Developers of Large Installations and Machines in the Leusden, Netherlands.

On 20 May 2016, in Shenzhen Convention & Exhibition Center, the venue of International APEMC 2016 Conference in China, the project consortium successfully organized a workshop to disseminate the project outputs. The workshop was one of the initiative activities of this European joint research project in the area of EMC. There were totally 6 talks and 4 speakers in this workshop. It attracted more than 50 participants. The talks were followed by interactive questions and comments.

Ultimately, the final workshop was successfully held at VSL on 03 June 2016 with the participation of all partners and around 20 stakeholders and a one-day tutorial session was successfully organized at the EMC Europe 2016 conference in Wroclaw, Poland on 09 September 2016 with the participation of around 20 attendees.

In all the workshops, the prepared newsletters were distributed to the participants of the workshops with a questionnaire and very affirmative opinions of the participants about the project outputs were collected.

4.2.3 Standards

CISPR is a part of the International Electrotechnical Commission (IEC) which sets standards for controlling electromagnetic interference, or EMC, in electrical and electronic devices. The project results were presented in the meeting of the subcommittee CISPR/I/WG2 which oversees the important CISPR standards that are relevant to large, distributed or high current equipment, as in the scope of the project. There was also interest from the subcommittee CISPR/A/WG1/A (on measurement of radio interference and statistical methods) which has decided to create a working group to work on LISN calibration issues. Subsequently LNE has become a member of this working group.

The time-domain methodology developed by Universitat Politècnica de Catalunya has been included in Annex B of IEC 62920 standard. This is one of the most important outputs of the project because IEC 62920 covers EMC requirements for solar photovoltaic energy systems that are usually large and distributed, and especially need improved or developed EMC test methods. The standardisation activities will continue with the support of the IEC members, and will try to incorporate the new time-domain methodologies into the new edition of CISPR 11. The project covered test methods which are jointly utilised by several EMC standards, and the testing methodology is similar and common to most of EMC standards. Therefore contributing to EMC standards via CISPR/A and CISPR/I will mean that in due course the project's contributions will be disseminated to the other subcommittees and put into other relevant standards. This means that the project will have an impact on all the other EMC standards which are likely to be applied large and high-current EUTs.

Most of these international standards produced by CISPR are then adapted for European (EN) standards by one of recognised European standardization organizations: CEN, CENELEC or ETSI for the targeted directive such as the European EMC directive. Therefore these standards are key to complying with the EMC Directive.

4.2 Examples of early impact

4.3.1 Standards and regulation:

The consortium gave an extensive presentation on project results in the CISPR/I/WG2 meeting and received good interest from IEC members.

The subcommittee CISPR/WG1/A has decided to create a working group to work on LISN calibration issues as a result of the related project outputs and of the presentation given in the IEC meetings, subsequently LNE has become a member of this working group.

The time-domain methodology developed by REG(UPC) has been included in Annex B of IEC 62920 standard, which is one of the most excellent outputs of the project.

On April 2016 one of the project partners had the opportunity to hold a meeting with an IEC member, Dr. Eng. Yasutoshi Yoshioka, from Fuji Electric (Japan). The IEC member proposed the meeting as he was interested in the time-domain measurement research carried out in the IND60 project. Mr Yoshioka has strong participation in many standardization technical committees at the International Electrotechnical Commission (www.iec.ch). One of the main meeting outputs was to go ahead with standardization activities with the support of Mr Yasutoshi Yoshioka and to try incorporating the new time-domain methodologies into the new edition of CISPR 11 and also maybe other standards.

4.4.2 User Uptake

LISN manufacturers and laboratories such as a manufacturer from France and a company from Turkey have shown great interest in LISN adaptors produced during the project and would like to purchase adaptors. Laboratories and manufacturers also have been showing great interest in the conducted immunity round robin device and harmonic reference device which have been developed in the project.

Many laboratories were keen to purchase the conducted immunity devices and to participate in conducted immunity inter-laboratory comparison tests, because there had been no opportunity for this in the past.

The alternative conducted emission test methods improved in the scope of the project have been evaluated and employed by one of the stakeholders in Turkey and found very efficient.

Finally, the time-domain measurement method developed in the project was successfully utilised in in-situ emission measurements of a large fixed installation in the premises of one of the company Mecalux S.A. The excellent results achieved at the in-situ measurements highlight the benefits of this novel time-domain measurement method.

4.3 Potential impact

The results of this project will have an impact directly on industrial manufacturers who need on-site EMC testing due to the size of their products and/or high currents, and also on EMC testing laboratories which often have to perform non-standard EMC tests on site. It will help industry, especially SMEs, to evaluate their products during the design stage. This will ultimately allow companies to have confidence that their products conform to the EMC directive and can enter the marketplace.

5 Website address and contact details

The address of the project public website, if applicable, as well as relevant contact details. The web site will continue to be online till 2018 after the project.

Project Web Site: http://www.emc-industry.com/

6 List of publications

- M. Pous, F. Silva, “Prediction of the impact of transient disturbances in real-time digital wireless communication systems”, IEEE Electromagnetic Compatibility Magazine, 2014, Vol. 3, no: 3, pp. 76-83.
- M. Pous, F. Silva, “Full-Spectrum APD Measurement of Transient Interferences in Time Domain”, IEEE Transactions on Electromagnetic Compatibility, 2014, Vol. 56, no: 6, pp. 1352 - 1360.
- M. Kokalj, B. Pinter, M. Lindic and F. Ziade, “Development of coaxial adapter for calibration of EMC devices”, in Proc. 2014 Precision Electromagnetic Measurements Conf., 2014, pp. 586-587.
- G. Costa, M. Pous, A. Atienza and F. Silva, “Time-Domain Electromagnetic Interference Measurement System for intermittent disturbances”, in Proc. 2014 International Symposium on Electromagnetic Compatibility (EMC Europe), 2014, pp.833-837
- R. Jauregui, M. Pous and F. Silva, “Use of reference limits in the Feature Selective Validation (FSV) method”, in Proc. 2014 International Symposium on Electromagnetic Compatibility (EMC Europe), 2014, pp. 1031-1036.
- M. Pous and F. Silva, “APD radiated transient measurements produced by electric sparks employing time-domain captures”, in Proc. 2014 International Symposium on Electromagnetic Compatibility (EMC Europe), 2014, pp. 813-817.
- S. Cakir, O. Sen, M. Cinar and M. Cetintas, “Alternative conducted emission measurements for industry”, in Proc. 2014 International Symposium on Electromagnetic Compatibility (EMC Europe), 2014, pp. 1037-1042.
- D. Zhao; G. Teunisse and F. Leferink, “Design and implementation of conducted emission reference source”, in Proc. 2014 IEEE International Symposium on Electromagnetic Compatibility, 2014, pp.12-17.
- B.J.A.M. van Leersum, R.B.Timens, F.J.K. Buesink and F.B.J. Leferink, “Time domain methods for the analysis of conducted interference on the power supply network of complex installations”, in Proc. 2014 International Symposium on Electromagnetic Compatibility (EMC Europe), 2014, pp. 605-610.
- C. Keyer, Timens, R.B.Timens and F.B.J. Leferink, “In-situ measurement of high frequency emission caused by photo voltaic inverters”, in Proc. 2014 International Symposium on Electromagnetic Compatibility (EMC Europe), 2014, pp. 74-78.
- R.A. Vogt-Ardatjew, G.S. van de Beek and F.B.J. Leferink, “Experimental extreme field strength investigation in reverberant enclosures”, in Proc. 2014 International Symposium on Electromagnetic Compatibility (EMC Europe), 2014, pp. 332-336.
- M. A. Azpúrua, M. Pous and F. Silva, “Decomposition of Electromagnetic Interferences in Time Domain”, IEEE Transactions On Electromagnetic Compatibility, Vol. 58, No. 2, April 2016
- M.A. Azpurua, M. Pous, S. Cakir, M. Cetinta and F. Silva, “Improving time-domain EMI measurements through digital signal processing”, IEEE Electromagnetic Compatibility Magazine, vol. 4, no. 2, pp. 82-91, 2015.
- Sen, O., Cakir, S., Cinar, M., Pous, M., Silva, F., Cetintas, M., "Alternative Conducted Emission Measurements On Mains Without LISNs", IEEE, Electromagnetic Compatibility Magazine, 4:4 (2015) : 58-65
- F. Ziade, M. Kokalj, M. Ouameur, B. Pinter, D. Belieres, A. Poletaeff, D. Allal, “Improvement of LISN Measurement Accuracy Based on Calculable Adapters”, IEEE Transactions on Instrumentation & Measurement, Vol. 65, pp. 365 - 377, Feb 2016.
- J. Tan, D. Zhao and J.A. Ferreira, “A method for in-situ measurement of grid impedance and load impedance at 2 k - 150 kHz”, in Proc. 9th International Conf. on Power Electronics and ECCE Asia (ICPE 2015-ECCE Asia), 2015, pp. 443-448.

- M.Kokalj, B.Pinter, M. Lindič, B. Voljč, Z. Svetik, R. Lapuh, “Numerical method for calculation of transfer matrix for non typical adapters used for calibration of EMC devices”, Proceedings of the 24th International Electrotechnical and Computer Science Conference
- O. Sen, S. Cakir, S. Acak and M. Cetintas, “Alternative Conducted Emission Measurements with LISN Simulation & CISPR16 probe”, in Proc. IEEE International Symposium on Electromagnetic compatibility and EMC Europe, 2015, pp. 1243-1247.
- S. Cakir, O. Sen, S. Acak and M. Cetintas, “Alternative Conducted Immunity Testing with Multiple CDNs and Wire Winding”, in Proc. IEEE International Symposium on Electromagnetic compatibility and EMC Europe, 2015, pp. 1060-1065.
- E. Tas and F. Pythoud, “A new Conducted Immunity Test Device for Inter-laboratory Comparisons”, in Proc. IEEE International Symposium on Electromagnetic compatibility and EMC Europe, 2015, pp.855-860.
- M. Pous, M.A. Azpurua and F. Silva, “Radiated Transient Interferences Measurement Procedure to Evaluate Digital Communication Systems”, in Proc. IEEE International Symposium on Electromagnetic compatibility and EMC Europe, 2015, pp.456-461.
- M.A. Azpurua, M. Pous and F. Silva, “A Measurement System for Radiated Transient Electromagnetic Interference Based on General Purpose Instruments”, in Proc. IEEE International Symposium on Electromagnetic compatibility and EMC Europe, 2015, pp.1189-1194.
- R.A. Vogt-Ardatjew, A.E. Sowa and F.B.J. Leferink, “The effect of magnetic dielectric absorbing coating on unsymmetrical antenna cables”, in Proc. 2015 Asia-Pacific Symposium on Electromagnetic Compatibility (APEMC), 2015, pp.624-627.
- B.J.A.M. van Leersum, F.J.K. Buesink and F.B.J. Leferink, “Quantification of minimal needed cable terminations”, in Proc. 2015 Asia-Pacific Symposium on Electromagnetic Compatibility (APEMC), 2015, pp.470-473.
- A. Ubin, R.A. Vogt-Ardatjew, F.B.J. Leferink, M.Z.M. Jenu and G.S. Van De Beek, “Statistical analysis of three different stirrer designs in a reverberation chamber”, in Proc. 2015 Asia-Pacific Symposium on Electromagnetic Compatibility (APEMC), 2015, pp.604-607.
- R.A. Vogt-Ardatjew and A.E. Sowa, “Accurate Experimental Field Mapping in the Close Vicinity of a Pyramidal Absorber Using the Monostatic Optically Modulated Scatterer Technique”, IEEE Transactions on Electromagnetic Compatibility, vol. PP, no. 99, pp. 1-7, 2015.
- F. Ziadé, M. Ouameur, D. Bélières, A. Polétaeff, D. Allal, M. Kokalj and B. Pinter, “Adapter and method for improving the LISN input impedance measurement accuracy”, in Proc. IEEE International Symposium on Electromagnetic compatibility and EMC Europe, 2015, pp. 1254-1259.
- Azpurua, M.A.; Pous, M.; Silva, F., “On the Statistical Properties of the Peak Detection for Time-Domain EMI Measurements, IEEE Transactions on Electromagnetic Compatibility”, Vol. 57, Issue. 6, 2015, 1374 - 1381
- Pous, M.; Azpurua, M.A.; Silva, F., “Measurement and Evaluation Techniques to Estimate the Degradation Produced by the Radiated Transients Interference to the GSM System”, IEEE Transactions on Electromagnetic Compatibility”, Vol. 57, Issue. 6, 2015, 1382 – 1390
- B. van Leersum, J.K. vd Ven, F. Buesink and F. Leferink, “Protection against common-mode currents on exposed cables”, in Proc. IEEE International Symposium on Electromagnetic compatibility and EMC Europe, 2015, pp. 1478-1483
- R.A. Vogt-Ardatjew and F.B.J. Leferink, “Experimental plane wave and random field coupling to uniform and non-uniform transmission lines”, in Proc. IEEE International Symposium on Electromagnetic compatibility and EMC Europe, 2015, pp. 767-772
- Osman Şen, Soydan Çakır, Murat Celep, Mehmet Çınar, Ramiz Hamid, Mustafa Çetintaş, “Influence of Dielectric Support on Military Radiated Emission Tests Above 30 MHz”, in Proc. APEMC 2016 Conference, Shenzhen, China
- Dongsheng Zhao ; S. Cakir ; O. Sen, “Uncertainty Evaluation of an Alternative Conducted Emission Test Method”, in Proc. APEMC 2016 Conference, Shenzhen, China
- Sen, O., Tektas, C.B., Cakir, S., Cetintas, M., "Alternative Radiated Emission Measurements at Close Distance in Industry", International Journal of RF and Microwave Computer-Aided Engineering, 26:4 (2016) : 294-303
- Azpurua, M.A.; Pous, M.; Silva, F, “On-board compact system for full time-domain electromagnetic interference measurements”, in Proc. 2016 ESA Workshop on Aerospace EMC (Aerospace EMC), 2016.
- Bahadır Tektaş, Osman Şen, Soydan Çakır, Mustafa Çetintaş, “Improvements in Alternative Radiated Emission Test Methods With Surface Wire”, in Proc. EMC Europe 2016 Conference, Wroclaw, Poland

- Mohammed A. Salhi, Soydan Çakır, Mehmet Çinar, Bahadir Tektaş, and Mustafa Çetintaş, "GTEM cell as an Alternative Method for Radiated Immunity Tests", in Proc. EMC Europe 2016 Conference, Wroclaw, Poland
- Mohammed A. Salhi, Osman Şen, Soydan Çakır, and Mustafa Çetintaş, "3D/2D Radiation Pattern Measurement of Different GSM Phones for EMC Applications", in Proc. EMC Europe 2016 Conference, Wroclaw, Poland
- Tas, Emrah; Cakir, Soydan; Cetintas, Mustafa; Hamouz, Pavel; Isbring, Thomas; Kokalj, Miha; Lopez, Daniel; Lundgren, Urban; Mandaris, Dwi; Pinter, Borut; Poriz, Martin; Pous, Marc; Pythoud, Frederic; Sen, Osman; Silva, Ferran; Svoboda, Marek; Trincaz, Braise; Zhao, Dongsheng, "Proficiency Testing for Conducted Immunity with a new Round Robin Test", in Proc. EMC Europe 2016 Conference, Wroclaw, Poland
- Azpurua, M.A.; Pous, M.; Silva, F, "On-board compact system for full time-domain electromagnetic interference measurements", in Proc. 2016 ESA Workshop on Aerospace EMC (Aerospace EMC), 2016.
- Azpurua, M.A.; Pous, M.; Silva, F, "On-board compact system for full time-domain electromagnetic interference measurements", 2016 ESA Workshop on aerospace EMC
- Bart van Leersum, Jan-Kees van der Ven, Hans Bergsma, Frits Buesink,Frank Leferink, "Protection Against Common Mode Currents on Cables Exposed to HIRF or NEMP", IEEE Transactions on EMC
- Robert Vogt-Ardatjew, Stefan van de Beek, Frank Leferink "Influence of reverberation chamber loading on extreme field strength", Proceedings of the 2014 International Symposium on Electromagnetic Compatibility, EMC 2014, Tokyo, Japan
- C. Keyer, I. Setiawan, F. Leferink "Drawbacks of a medium sized, grid coupled Photo Voltaic Array", Proceedings of the International Conference on Renewable Energy And Power Quality (ICREPQ) Madrid
- Dwi Mandaris, Niek Moonen, Stefan Van de Beek, Frits Buesink, Frank Leferink, "Validation of a Fully Anechoic Chamber", Proceding of the 7th Asia Pacific International Symposium on EMC
- I. Setiawan, C.H. Keyer, M. Azpurua, F. Silva, F.B.J. Leferink, "Time-domain Measurement Technique to Analyze Cyclic Short-Time Interference in Power Supply Networks", Proceding of the 7th Asia Pacific International Symposium on EMC