THE NATIONAL MEASUREMENT STANDARDS AT CEM AND THEIR ROLE IN MRA AND EMRP PROJECTS

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Abstract- This paper presents a view about the role of the CEM national measurement standards in the framework of the Mutual Recognition Arrangement, MRA, of the International Committee for Weights and Measures, CIPM, and simultaneously as they used as a base in their participation in European Metrology Research Program, EMRP, projects. During last years the strategy of EURAMET and of its members National Metrology Institutes, NMIs, has been directing their efforts toward a joint participation in the EMRP. Centro Español de Metrología, CEM, is the organization responsible for the metrological infrastructure in Spain, and must establish and maintain the necessary technical-scientific infrastructure in order to reproduce the national standards of the measurement legal units in Spain. The EMRP allows at all NMIs, industrial organizations and academic bodies to collaborate on joint research projects within metrology specific fields. On the other hand, CEM realizes and promotes the research and development projects in the metrology field, as a necessary support in order to assure the quality of industry.

Keywords: National measurement standards, MRA, EMRP, EURAMET, NMIs, Key Comparisons, Degree of equivalence.

I. Introduction

Metrology is a horizontal scientific-technical field which underpins almost all subject fields in natural sciences and engineering. It is a technically wide and multidisciplinary field under a common methodology – characterized by the scientific treatment of measurement uncertainties, mathematical methods, principles of traceability, international metrological structures and organizations which cover the SI system such as the International Committee for Weights and Measures (CIPM) under the Meter Convention.

The CIPM Mutual Recognition Arrangement, MRA, which CEM is a signatory, has the following main objectives [1]:

- to establish the degree of equivalence of national measurement standards maintained by NMIs;
- to provide for the mutual recognition of calibration and measurement certificates issued by NMIs and
- to provide governments and other parties with a secure technical foundation for wider agreements related to international trade, commerce and regulatory affairs.

The process in order to get these objectives involves:

- international comparisons of standards, known as key comparisons;
- review of the technical competence of the participants based mainly on the results of comparisons; and
- the implementation and review of quality systems and demonstrations of competence by NMIs.

The European Metrology Research Program, EMRP, was implemented by EURAMET, which allows at NMIs, industrial organizations and academic bodies to collaborate on joint research projects within specific fields, including the electricity and magnetism field. The EMRP addresses metrological research activities at the frontiers of measurement science in order to meet the most urgent industrial and societal needs [2].

The program started in 2007 with iMERA-Plus, implementing Metrology in the European Research Area, as a pilot for implementation structure and procedures of the EMRP under Article 169 of the European Treaty. There were five calls and the last of them was opened on 31 January 2013 and it is running today.

Metrological research and development is usually addressed in a single-discipline approach along a scheme of technical fields given by the Consultative Committees of the CIPM and the Technical Committees of EURAMET. This approach is powerful in many cases, especially in the "classical" fields, and it is part of the EMRP. An increasing number of challenges, however, require a more multidisciplinary approach due to complexity of the topics. Thus coordination within the EMRP does not only mean coordination of national programmes in a specific field but also coordination of different research activities driven by a complex challenge.

Consequently, the activity areas of the EMRP are structured in:

- Grand challenges for multidiscipline metrology (health, energy, environment, new technologies)
- Grand challenges on fundamental metrology
- Focused single-discipline and applied metrology

The EMRP focuses on three key approaches:

- A new approach for the metrology research community in which "grand challenges" are addressed by bringing the various strands of measurement science to bear on issues of European and international relevance. The key challenges have been identified. They relate closely to the priority areas of the Seventh Framework Program, and will require input from the EMRP Research Council to focus resources in the most effective way on the appropriate metrology and measurement aspects.
- Developing cross-disciplinary solutions to solve direct challenges related to fundamental metrology, typically the fundamental constants and the redefinition of the SI units.
- Focused R&D within single metrology disciplines aimed at improving the accuracy of the realization and dissemination of the primary and secondary units of measurement.

The EMRP projects have impacted on metrology, industry and other research fields. EURAMET, together to the European Union and member states, is working in order to prepare a follow up new research program: EMPIR.

II. The national measurement standards at CEM as a basis for its participation in EMRP

CEM is the organization responsible for the metrological infrastructure in Spain. It is a young Institute what was created in 1985 as a consequence of the Law 3/1985, of Metrology.

The laboratories are at Tres Cantos, a city about 25 km from Madrid. They occupy an extension of 18 700 m^2, which 10 600 m^2 correspond to technical laboratories and the rest to general services.

The main functions of CEM are:

Establish, reproduce and maintain the units of the International System of Units, SI.
Disseminate them to the accredited laboratories in Spain, assuring their traceability to the National Standards
Establish and maintain the necessary technical-scientific infrastructure in order to reproduce the national standards of the measurement legal units in Spain
Advice and technical support to all economic sectors in Spain, in the metrology field, as a necessary support in order to assure the quality of production
Realize and promote the research and development projects in the metrology field, as a necessary support in order to assure the quality of industry.
Promote the knowledge and dissemination of the Metrology by the training activities of specialists and by the elaboration and diffusion of technical publications.

The main activities of CEM Electricity and Magnetism Division are directed to give fulfillment, among others, to the following fundamental objectives:

a) Establishment, maintenance, conservation, development and dissemination of the national standards of the measurement units corresponding to the electrical quantities in DC and LF. For it fulfillment to the requirements established in the Mutual Recognition Arrangement occurs:

- Participation on international Key Comparisons.
- Declaration of the Optimal Capabilities of Measurement and Calibration, CMC´s.
- Implantation in the Electricity Division Laboratories of a Quality System.

b) Execution of research, development and technological innovation projects: National and EMRP projects.

c) Search and optimization of methods for the improvement of the uncertainty values in the accomplishment of the standards, the extension of the already existing measurement ranges and the beginning of activities in new quantities.

The primary voltage standard is established in agreement with CIPM Recommendation 1 (CI-1988), which assigns the conventional value K_{J-90}=483 597.9 GHz/V to the Josephson constant. A measurement system allows comparing the DC voltage generated by 1 V or 10 V Josephson multi-junctions and a voltage standard materialized by an electronic Zener reference set.

The array Josephson junction consists in a thin insulating barrier separating two superconductors. When a microwave frequency is applied to the junction at cryogenic temperature, voltage steps are generated in the junction (1). Where V is the Josephson voltage, f is the microwave frequency applied, h is the Planck constant and e is the elemental electrical charge, i.e. the electron charge.

The voltage steps generated by the Josephson junction following the expression:

$$V = \frac{nh}{2e} f = \frac{nf}{K_J} \qquad (1)$$

The ratio 2 e / h is called Josephson constant, K_J.

The Josephson voltage standards are constituted by many junctions in series to generate a constant voltage. With an array of 1 000 or more junctions, a quantized voltage of 1 V is generated.

In this way, a DC voltage standard is obtained directly linked to physical fundamental constants, h and e.

A new system to compare conventional resistance standards with the Quantized Hall Resistance using our Programmable Josephson Standard as a Wheatstone bridge has been designed and developed at CEM (see figure 1). This method uses a Binary Junction Programmable Josephson Array Standard, BPJS, specifically designed to have a centre tap to simultaneously measure the voltage of the QHR and the test resistance [3].
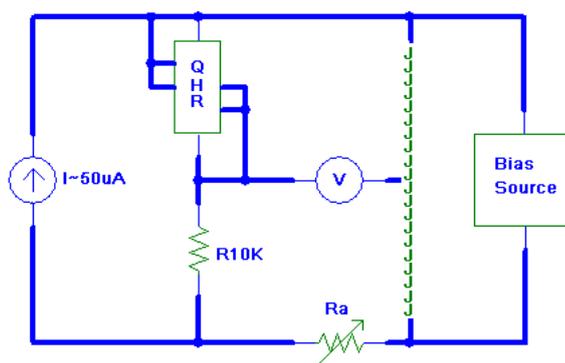

Figure.1. Wheatstone-Josephson bridge

Josephson binary arrays are normally used to synthesize AC signals or as multivalued DC voltage standards. However, a feature normally not considered of them is that could be extremely accurate voltage ratio standards, if two or more segments are simultaneously accessed. Another use of BPJS's is to stabilize DC current sources. CEM method combines both features of BPJS arrays to form a kind of "bridge". It's similar a Wheatstone bridge, with two segments of the array substituting the ratio arms. The estimated uncertainty is as lower as $3 \cdot 10^{-9}$.

The national resistance standard determines from the Quantum Hall effect, in agreement with CIPM Recommendation 2 (CI-1988) that assigns the conventional value R_{K-90} = 25 812.807 Ω to the von Klitzing constant.

The Hall sample consists of GaAs heterostructures measured as a function of a high magnetic field (10 T up to 12 T), at cryogenic temperature (T = 1.6 K). In these conditions, quantized plateaux are generated in the Hall sample and the quantum Hall resistance value is (2). This expression again directly linked to physical fundamental constants, h and e.

$$R_H = \frac{U_H}{I} = \frac{1}{i}\frac{h}{e^2} = \frac{1}{i}R_{K-90} \qquad (2)$$

The comparison system is based on a Josephson potentiometer which allows comparing directly the Hall resistance with a 10 kΩ ☐resistance standard, method completely developed in CEM. This method shows an agreement a level of relative uncertainty of $2 \cdot 10^{-8}$. The all measurement systems allow carrying out calibrations in the range from 1 mΩ up to 10 TΩ.

A novel and extremely simple resistive transfer standard to compare the Quantized Hall Resistance, QHR, with conventional 10 kΩ standard resistors has been developed at CEM. In this way, the potentiometric system has been complemented by this system based on a novel transfer resistance, which is made by different elements that, switching properly, can have a value equal to the ohmic nominal value of the QHR in a configuration and as a decimal multiple of the Ohm in another. The transfer resistance is divided into several sections, each of which can be compared directly against a resistance standard or against a conventional Hamon resistance and whose total value is nominally equal to the QHR (see scheme in fig.2).

Figure 2. Novel resistive transfer standard

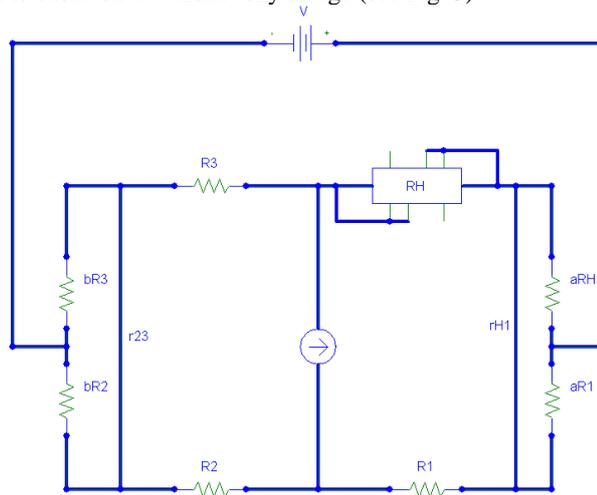The measurement system is based on a Warshawsky bridge (see Fig. 3).

Figure 3. Warshawsky bridge

An uncertainty analysis shows a potential to make ratio transfers with a relative uncertainty value near $1.3 \cdot 10^{-8}$ (k=2) [4].

During the last years the work of the AC laboratory has been mainly devoted to the establishment of a new AC reference based on Planar Multijuction Thermal Converters, PMJTCs from PTB.

For AC voltage the traceability comes from a 1.5 V thermal converters. From this and after several steps of comparisons a voltage reference system from 2 mV up to 1 000 V is obtained (see figure 4). At the higher levels, a set of CEM thin-film resistors has been used to obtain de voltage level dependence of the range resistor and correct the figures [5].

Figure 4. AC-DC voltage transfer difference system at CEM
up to 1 000 V

To obtain the reference from 2 mV to 100 mV a step-down procedure using resistive dividers has been used. The AC resistive divider has been calibrated by CEM using two known voltage reference at the input and output level.

A new national AC current reference has been obtained from 2 mA up to 100 A. The AC current reference has been recalibrated from 10 mA up to 20 A and from 10 Hz to 100 kHz by means of a step-up procedure starting by a PMJTC. A new reference chain has been obtained using a set of new resistors and PMJTCs. So a new national AC current reference has been obtained from 2 mA up to 100 A [6].

In conclusion, the AC laboratory has established a new AC voltage and current reference system based on a set of Planar Multijunction Thermal Converters (PMTC) from PTB-IPHT and new calibration services for AC-DC voltage and current transfer measurement have been approved in the last EURAMET CMC review processes.

The AC power and energy laboratory has established during last years a new national power standard by a digital sampling method. The measurement system is based on high precision coaxial current shunts designed by D.I. Mendeleyev, VNIIM, from Russia (see figure 5) and resistive dividers from SP, Sweden. This system is being able to get estimated uncertainty values about $40 \cdot 10^{-6}$ at rate ranges [7]. This project was carried out in collaboration with the Polithecnical University of Málaga.
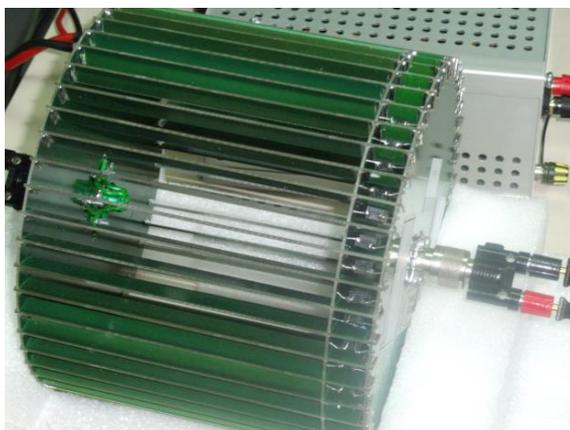

Figure 5. 5 A coaxial current shunt at CEM digital sampling power standard

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Regarding to impedance measurements, a new bridge for the comparison of like impedance standards defined to four terminal-pair has been developed. On the other hand, the development of a measurement system that has allowed establishing precise AC voltage ratios by means of inductive voltage dividers and the Straddling method has been carried out, obtaining uncertainty values of the order of some parts in 10^{-8}, (see key comparison CCEM-K7). The method "Straddling" consist in comparing the voltages of each transformer output with a similar reference ratio that must remain constant during the comparison process. With this method, the output voltages are obtained with the maximum precision available, mainly because to maintain a constant voltage ratio is easier that an absolute voltage value during the measurement process.

A Maxwell-Wien bridge has been designed for the realization of the inductance standard at CEM [8]. It allows the obtaining of a 10 mH inductance at the frequency of 1 kHz, in terms of resistance and capacitance. The different sources of uncertainty have been evaluated in detail and finally a relative expanded uncertainty from 20 μH/H up to 30 μH/H has been reached [9]. The results were presented in September 2012 in XX IMEKO World Congress in Busan, Korea and a new calibration service for inductance measurement has been approved in the last EURAMET CMC review process.

In relation with the AC resistance measurements, a new four-terminal coaxial-pair bridge has been developed for AC resistance measurement. Details of this system can be seen in figures 6 and 7. The system is referenced and based on two calculable resistances which values are well known in function of the frequency. At the moment, repeatability and uncertainty of the measurement system are being improved.
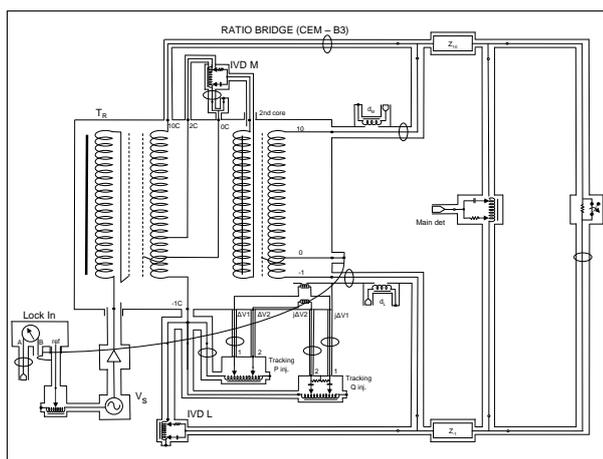

Figure 6. AC resistance measurement coaxial bridge

Figure 7. Photos of the CEM quadrifilar (on the left) and bifilar (on the right) calculable resistances

In line with this coaxial bridge, the laboratory is beginning to develop a sampling system for impedance measurement using high resolution analog-to-digital and digital-to-analog converters.

In the future, further efforts will be focused on the developing of the new systems and the improvement of the present system's accuracy.

III. The key comparisons as a guarantee in MRA

One of the main requirements established in MRA is the participation on international key comparisons.

Following the requirements established in CIPM MRA on the document CIPM MRA-D-05, the definitions considered are [10]:

1. The key comparison reference value, KCRV, is the reference value resulting from the measurements taken in a CIPM key comparison, together by its uncertainty (normally the standard uncertainty). The KCRV is interpreted as an estimate of the measurand on the basis of the measurements provided by the participating laboratories. The weighted mean of the Institutes measurements, where the weights are equal to the reciprocals of the squares of the associated standard uncertainties, should generally be taken as the KCRV. If some of the Institute measurements were inconsistent, they are not considered on the computation of the KCRV [11], [12].

2. Degrees of equivalence relative to the key comparison reference value of a national measurement standard or of a measurement result, x_i, is the degree to which the measured value is consistent with the key comparison reference value, x_{ref}. This is expressed quantitatively by two terms [12]:

   (a)   the deviation from the key comparison reference value, $D_i = x_i - x_{ref}$; and
   (b)   the expanded uncertainty of this deviation computed at a 95 % level of confidence (in practice, this is often approximated by using a coverage factor k equal to 2), $U_i = 2u_i$.

The "graph of equivalence" shows the degree of equivalence relative to the KCRV in a graphic way.

3. The degree of equivalence between pairs of national measurement standards is expressed quantitatively by two terms [12]:

   (a)   the difference of their deviations from the KCRV, $D_{ij} = D_i - D_j = x_i - x_j$; and
   (b)   the uncertainty of this difference at the 95 % level of confidence, $U_{ij} = 2u_{ij}$.

During last years CEM has been actively participating in the main key comparisons in order to guarantee its national measurement standards. The results of these participations on the DC and low frequency electricity field on international comparisons, as well as the bibliographical references for more complete information, are related in the BIPM Key Comparison Data Base, on Web page: http://kcdb.bipm.org/AppendixB/. The figures 8 to 11 show some examples.
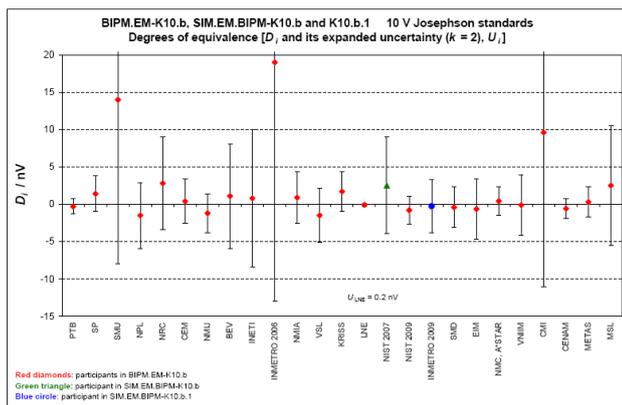

Figure. 8. BIPM.EM-K10.b. Key Comparison of 10 V Josephson Standards. (Source: The BIPM KCDB, November 2012)
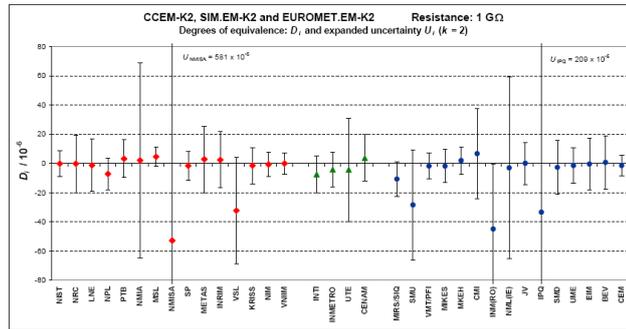
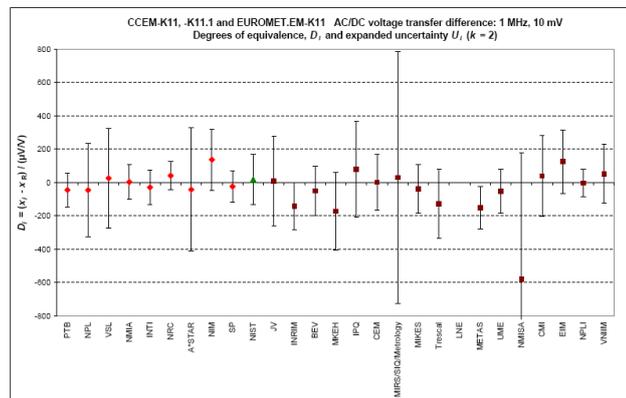Figure 9. EURAMET.EM-K2. Key Comparison of resistance standards 1 GΩ. (Source: The BIPM KCDB, May 2010)

Figure 10. EURAMET.EM-K11. Key Comparison of AC/DC voltage transfer difference at 1 MHz and 10 mV. (Source: The BIPM KCDB, November 2011)
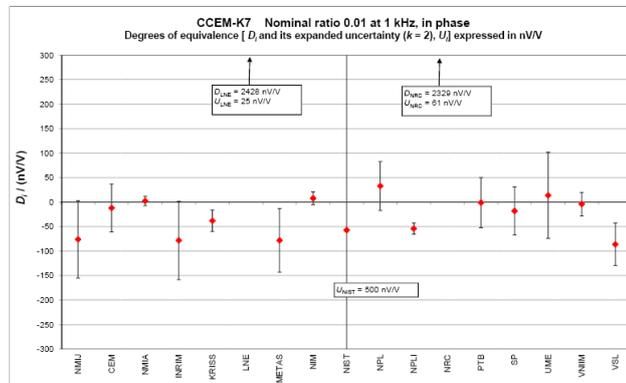

Figure 11. EURAMET.EM-K11. Key Comparison of AC voltage ratio at 1 kHz. (Source: The BIPM KCDB, June 2012)

IV. Participation of CEM in EMRP

In the electricity and magnetism field, CEM has participated or is participating on the following EMRP projects:

iMERA-Plus projects:

- T4.J01. Power & Energy. *Next generation of power and energy measuring techniques*.
- T4.J03. JOSY. *Next generation of quantum voltage systems for wide range applications*.
- T4.J04. ULQHE. *Enabling ultimate metrological Quantum Hall Effect (QHE) devices*.

EMRP Call 2009: ENG04. SmartGrid. *Metrology for Ssmart Grids.* This project was carried out in collaboration with CIRCE-University of Zaragoza.

EMRP Call 2012. SI Broader Scope. Its topics are: Development of the SI system and dissemination of the units through research and development for fundamental and applied metrology. They are:

- SIB53 AIM QuTE. *Automated impedance metrology extending the quantum toolbox for electricity*.
- SIB59 Q-Wave. *A quantum standard for sampled electrical measurements*.

A brief description of the projects currently in development or about to start is done here.

The Project Metrology for Smart Electrical Grids was a proposal for research under the "Energy Call 2009 for proposals" as part of the European Metrology Research Programme (EMRP see www.emrponline.eu).

The electricity grid is the backbone of our modern society. The increase of decentralised energy supply forces the network to become a 'smart grid', facilitating greater competition between providers, enabling greater use of renewable energy sources, and providing market forces with the tools to drive energy conservation.

In this project a metrological measurement infrastructure has been developed to support successful implementation of a Smart Electrical Grid in Europe in order to ensure security of electricity supply and grid stability, grid quality, and fair trade between commercial parties employing the grid. Portable systems and measurement routines for on-site power quality measurement have been developed dedicated to a series of specific applications.

CEM with CIRCE-University of Zaragoza were involved in different tasks related with "*portable and remote measurement of power quality*". To carry on this work, a test site, with renewable sources (wind turbines, solar plant and H_2 generation) was identified (WALQA Technology Park at Huesca, Spain). An innovative self-made hardware and software, including a system for GPS synchronization of the different measurement instruments, was developed along with new algorithms, according to the standards IEC 61000-4-30 and EN 50160, to measure PQ parameters. With these new instruments two measurement campaigns were carried out, storing a huge amount of data.

The main objective of the SIB 53 AIM QuTE project: *Automated impedance metrology extending the quantum toolbox for electricity* is the dissemination of impedance magnitudes. The technology used is based on Josephson bridges and digital measurement bridges. The operability and the uncertainty values currently achieved with the coaxial systems will be significantly improved. It will provide a measurement infrastructure which will improve substantially the scope of the current measures in the impedance field. CEM is collaborating, among others, on work packages WP1: Josephson bridges for impedance measurements and WP4: Dissemination and analysis of measurement methods.

The SIB59 Q-Wave project: *A quantum standard for sampled electrical measurement* trying to develop new quantum voltage references for no stationary signals based on the Josephson effect by using of analog to digital conversion techniques. The project deals with depth the new measurement digital techniques by using digital analog converters used in signal digital sampling. It comes to comply with the objective of dissemination of the AC measurement electrical quantities in the SI system. The phases of the SIB59 Q-Wave project are showed in figure 12. CEM is participating, among others, on work packages WP3: Transferring quantum referenced waveforms into practical sampled voltage measurements. Comparison and validation of sampling methods and WP4: Characterization of converters. Analysis and procedures.
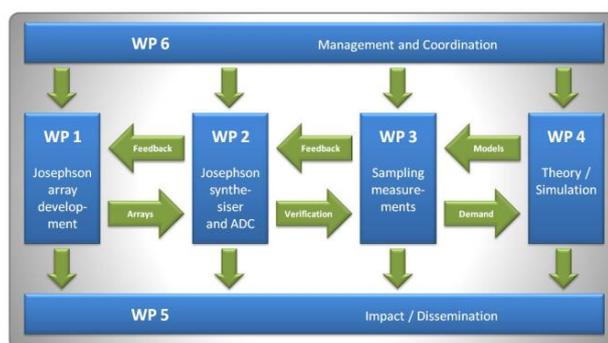

Figure12. Phases of the SIB59 Q-Wave project

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It can be stated that the standards and measurement systems described here in section II are the technical basis used by CEM in its participation in EMRP program.

V. Conclusion

CEM, as the organization responsible for the metrological infrastructure in Spain, establishes and maintains the necessary technical-scientific infrastructure in order to reproduce the national standards of the measurement legal units in Spain and on the other hand, CEM realizes and promotes the research and development projects in the metrology field, as a necessary support in order to assure the quality of industry.

To promote research and developing of new standards on this field of the metrology, together to the participation in high level comparisons are the key to ensure the maintenance of the national measurement standards and, therefore, guarantee compliance with the requirements established in MRA.

In conclusion, the participation of CEM in EMRP program is based on the new primary standards developed during last years and without them, this participation would not have been possible.

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