FINAL PUBLISHABLE JRP REPORT

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JRP-Coordinator:

Name, title, organisation:	Dr. Paul Wright, National Physical Laboratory, UK.
Tel.: E-mail:	+44 208 943 6367; paul.wright@npl.co.uk
JRP website address:	http://projects.npl.co.uk/power_energy/

Other JRP partners:

Long name, (Short name), country:

BEV, Austria,

CEM, Spain,

CMI, Czech Republic,

Trescal, Denmark,

BRML - INM, Romania,

INRiM, Italy,

JV, Norway,

LNE, France,

EJPD, Switzerland,

MIKES, Finland,

MIRS/SIQ, Slovenia,

PTB, Germany,

SMU, Slovakia,

SP, Sweden,

VSL, Netherlands.

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1. EXECUTIVE SUMMARY

This three-year metrology research project was a response to the changing nature of electricity generation, transmission and distribution that has been brought about due to the need to develop and integrate renewable energy sources. The project concentrates on electrical measurements and their role in supporting industry in the significant challenges of remodelling electricity networks. Further it has implemented a harmonized measurement infrastructure to underpin the EU regulations for electrical goods and electricity revenue metering.

The project was formed of a consortium of ac electrical measurement experts from 16 National Metrology Institutes. Prior to the project much of the expertise in ac measurements at the highest level related to laboratory based measurements using well-conditioned sinusoidal waveforms. The challenge for this project was to develop the capability to make measurements of a similar quality at generation and distribution sites involving the accurate measurement and analysis of complex wave shapes.

To ensure the projects aims were focused on the needs of industry a User Committee of industrial representatives were given access to the project as it was planned and implemented. These representatives attended the project meetings and have offered facilities and staff time to help test the resulting measurement systems on-site.

In order to build this capability, the problem was subdivided into a set of work packages that mirrored the measurement process; firstly the high current and high voltage levels that are prevalent at electricity distribution/generation sites must be transformed to lower measureable levels. This transformation must be made with a known, measureable and stable division factor whilst maintaining the shape of the ac waveforms to a known level. This entailed the development and characterization of lab-use and portable transducers to cover a wide range of currents and for voltages up to 33 kV.

These transducers have the added requirement of being capable of being connected to the electricity system without interrupting the supply (not a popular proposition for network operators or their customers).

The lab-use transducers are of the highest accuracy and will be used for lab-based power and power quality in support of revenue metering, power quality and efficiency measurements as required by product developers.

Having transformed the signal levels the electrical measurement of the ac waveforms is made by digitizing signals into data that can be processed by computers. This is achieved using analogue to digital convertors that must operated at high data output rates continuously converting the waveform with known fidelity. Six channel systems were required for the current and voltage measurements required in the three phase systems used by electricity companies. The resulting system is portable, robust and has a wide temperature range. They are characterized for a wide range of parameters.

The resulting data is processed using algorithms which result in the complex range of power quality metrics that are used by industry. As the waveforms of interest are continuously changing in amplitude, phase and frequency (for example as the electricity demand changes), the mathematical transformation of these so-called non-stationary waveforms is non-trivial and this has resulted in the development of new waveform transforms to analyse these waveforms accounting for possible high noise conditions.

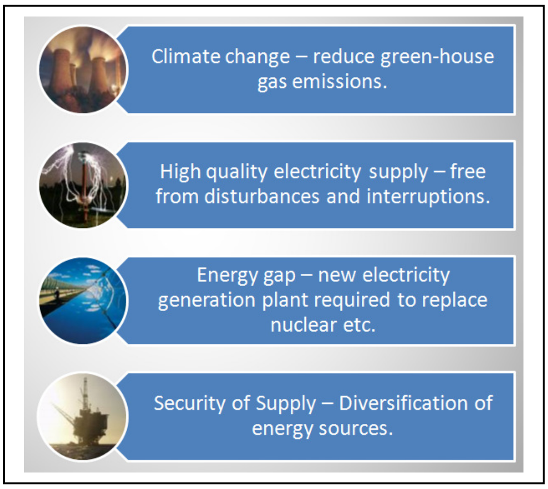
Finally all the strands of the project were brought together and demonstrated in a series of seven on-site measurements at electricity distribution sites which included medium voltage (33kV), high current (kA), power loss measurements at low power factor and power quality at a substation.

Providing this infrastructure has been a significant technical challenge; designers of new technology such as wind-turbines or low-loss transmission equipment will benefit from in-situ power loss and generation efficiency measurements. Complex, non-stationary waveforms are implicit to present and future power quality normative standards and new techniques developed here are required to underpin a EU regulatory framework that oversees the multi-billion Euro markets for electrical goods and power generation, transmission and distribution.

2. PROJECT CONTEXT, RATIONALE AND OBJECTIVES

2.1 THE CONTEXT AND RATIONALE OF THE POWER AND ENERGY PROJECT

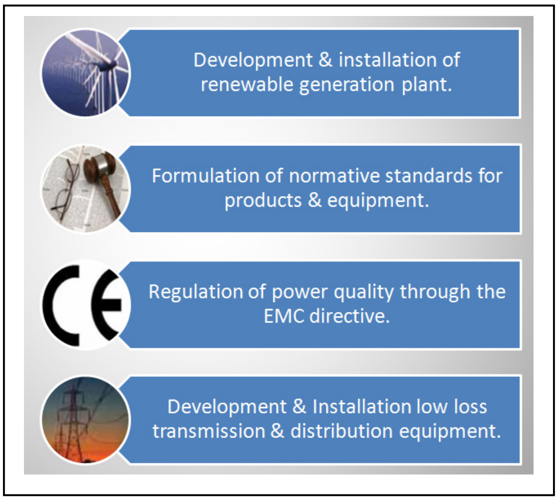
Society demands energy supplies that are secure, sustainable and of high quality. In the next decade, Europe is facing potential energy shortages as oil and gas supplies run down and nuclear power facilities age. Pressure to reduce the green house gas emissions will lead to a requirement for more renewable energy generation, efficient appliances, energy management and improved electricity distribution efficiencies. Commerce will demand an electricity supply of the highest quality, free from momentary voltage interruptions or interference sources.



To meet these pan-European challenges, Governments are focusing regulation and policy on reduced energy consumption, improved efficiency and power quality. These challenges will be a catalyst for new technology that will require new measurement infrastructure. In contrast to the existing state-of-the-art consisting of lab-based measurements of sinusoidal ac signals, the next generation of power and energy measurements will be made directly at generation and distribution sites and will involve the accurate measurement and analysis of complex wave shapes.

Providing this infrastructure has been a significant technical challenge; designers of new technology such as wind-turbines or low-loss transmission equipment require *in-situ* power loss and generation efficiency measurements. Complex, non-stationary waveforms are implicit to present and future power quality normative standards and new techniques have addressed a EU regulatory framework which oversees the multi-billion Euro markets for electrical goods and power generation. These developments are a radical departure for ac power metrology involving measurement and signal analysis challenges and have required novel solutions within a metrology framework.

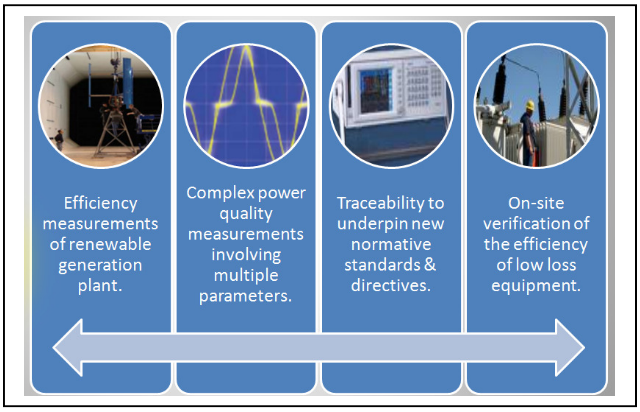
These challenges are pan-European and have required a coordinated European response in the form of this JRP to deliver a harmonized solution. The sixteen national Governments identified in this project have tailored their national metrology programmes with the aim of answering the needs of the energy industry. Acting alone, NMIs can only address parts of the problem and will inevitably deliver conflicting solutions, particularly in developing methodologies for such complex measurements. Acting together in this project, a critical mass has been achieved that can deliver a more complete and – more importantly – harmonized solution to develop enhanced measuring capabilities for the assessment of the quality and efficiency of electrical power, and for the monitoring and protection of power grids and apparatus.



During the project period, significant further investment in the electricity network has been envisaged through a new paradigm for electricity distribution, the SmartGrid. It is particularly gratifying to the formulators of this project that the work programme that was devised back in 2007 has turned out to be in the centre of a technical revolution in electricity networks. Indeed, the outputs from this project have spawned two new EMRPs which will provide the metrological infrastructure to support SmartGrids and High Voltage DC transmission.

2.2 THE OBJECTIVES OF THE POWER AND ENERGY PROJECT

Electricity network operators are faced with significant challenges by the increase of electronic based products that present a non-linear load to the power grid, and by the planned increases in renewable generation. Both factors have the potential to induce poor power quality, which in-turn could cause widespread power failures if left unchecked.



As a result, an evolving regulatory system enforces the requirement that all new electrical products must be type tested to ensure that their detrimental effect on power quality is minimized. These measurements are complex and involve the measurement of a number of different power quality parameters on distorted and fluctuating waveforms. Failure of these tests prevent the products from sale in the EU. Furthermore, efficiency measurements on renewable energy generators and low loss transmission equipment are required at high grid voltages. As this equipment is in fixed installations, these measurements must be made in-situ.

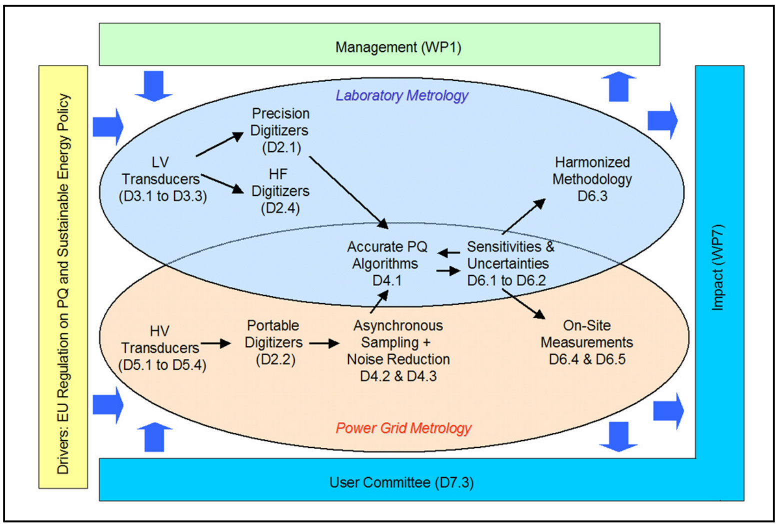
The state-of-the-art in AC power metrology as existed at the start of this JRP, was lab-based involving sinewave signals and is not adequately equipped to underpin this regulatory system. As disputes between test laboratories, manufacturers and electricity suppliers grew, the demand for a response from the metrology community led to the following technological objectives:

- To accurately measure ac waveforms that are high distorted, contain discontinuities and are non-stationary.
- To develop mathematical transforms to accurately analyze these waveforms and determine power quality parameters.
- To accurately measure power loss on fixed installation at high voltage under hostile electrical conditions.
- To determine the propagation of uncertainties from measurements, through the complex mathematics to the final power quality parameters.

This leads to the following socio economic objectives:

- To support power quality regulations and international standardization through sound measurement protocol and appropriate traceability.
- To underpin the introduction of renewable generation capacity through the understanding and management of power quality on power grids.
- To provide a level-playfield for the testing of electrical goods through the provision of traceable calibrations for testing apparatus.
- To support the measurement of the efficiency of electrical goods and generation plant such that reductions in electrical energy demand can be quantified and improved.

These objectives represented a significant R&D effort, which during the duration of the JRP advanced power and energy metrology beyond the state-of-the-art. This was only achieved by pooling the resources of NMIs who specialize in different aspects of the problem. Some NMIs excel in signal processing algorithms, others in transducers, or digitiser technology. Smaller but highly focused contributions from labs in areas such as modelling, grid level working and specialist transducers were all essential in bringing together a pan-European response to EU regulation and the Energy Grand Challenge set out in EMRP2007.



A response to these technical objectives was achieved through five technical work packages. The relation between these work packages is schematically indicated in the figure which shows the flow of the measurement starting with signal conversion (WP3 and WP5), to measurement by use of digitisers (WP2), through to data analysis and signal processing (WP4) culminating in an integrated system and methodology including on-site measurements (WP6).

The first challenge tackled by the JRP was to build new transducers. WP3 concentrated on voltage and current transducers with accurate phase and amplitude characteristics for laboratory metrology of power quality. WP5 developed and characterized non-conventional current and voltage transducers to enable traceable measurements over the necessary ranges suitable for on-site measurements on the medium voltage grid. In both work packages, modelling and measurement methods were developed to fully characterize this hardware to a level well beyond the state-of-the-art.

The second challenge was to make accurate measurements of the voltage signals arising from the transducers. This was the subject of WP2, where three types of metrological grade digitising hardware were developed capable of performing three phase, wide band, and on-site grid measurements respectively.

Digitisers and transducers can produce sample measurements with excellent accuracy, however this performance is meaningless unless the sampled data can be assembled in a well-formulated manner and can be correctly processed by validated algorithms. This was the task of WP4 that developed novel waveform analysis techniques and signal processing algorithms to enable meaningful sample based measurements of arbitrary, fluctuating signals under noisy, asynchronous conditions.

All this technology has been brought together in WP6 which implemented a harmonized metrology infrastructure to underpin EU regulation. This was achieved by the development of a methodology and an agreed measurement protocol, for the verification and calibration of the equipment used to assess power quality. On-site power loss and power quality measurements were developed and trialled at network sites, and in the future this infrastructure will provide manufacturers and operators of network equipment access to accurate information to improve energy efficiency and operational performance.

3. SCIENTIFIC AND TECHNOLOGICAL RESULTS AND FOREGROUND

3.1 METROLOGY GRADE DIGITISING TECHNOLOGY FOR POWER QUALITY MEASUREMENTS

Digitisers are at the heart of power measurement and power quality (PQ) equipment and are used to convert analogue input signals from transducers (see Sections 3.2 and 3.4) to digital samples for subsequent analyses (Sections 3.3 and 3.5).

High quality digitisers are fundamental to determine the various PQ parameters required by regulation. This Section describes the development of high-grade linear, high impedance digitizers for laboratory and field use for data acquisition of complex waveforms (also non-repetitive) via synchronous and asynchronous sampling. Methods for the characterization of these digitizers and some of the results obtained are also described.

3.1.1 COMPACT THREE PHASE VOLTAGE DIGITISER WITH A FREQUENCY RANGE UP TO THE 50TH HARMONIC OF THE MAINS

A high-grade voltage digitizer for laboratory applications, where sampling accuracy was the main issue, was developed by PTB. Whilst compact, the system allows multi-phase measurements with integral nonlinearities of the order of some µV/V at sampling rates as high as 128 kilo samples per second (kSPS), corresponding to a maximum bandwidth of 64 kHz. At power frequencies, the attainable measurement uncertainties are comparable to those of the PTB ac primary power sampling standard.

Clock timing of the internal analog-to-digital converter (ADC) is built with direct digital synthesizers (DDS), which operating in cascade allow extremely high sampling frequency resolution and low jitter to be attained, enabling the digitizer to be used either in synchronous or asynchronous sampling modes. The ADC sampling rates can be adjusted by the synchronizer with resolutions of some parts in 10^{+9} Hz or even lower at a selection of ADC decimation factors. Special PC software employs synchronization algorithms (patent pending, application DE 10 2007 043 927 A1). Data are gathered via a USB port and further processed for user's visualization and interpretation. Synchronization hardware and PC software allows also the use of a commercial sampling digital voltmeter (like the Agilent A3458A) if desired. Routines for uncertainty analyses are also embedded in software and are based on a general mathematical description model for ADCs, providing the user with uncertainty evaluations (type A and B).

The sampling system constitutes a valuable device for ac Metrology in general (referred to as "universal sampling system"). Besides root-mean-square, phase and ac power, ratio measurements can easily be done for both in-phase and in-quadrature quantities (i.e., complex quantities) within some µV/V uncertainty for amplitudes and µrad for phase even at 128 kSPS sampling rate.

The three-phase sampling system prototype mounted in a 19-inch case. This instrument allows measurement uncertainties comparable to those of the PTB ac primary sampling standard to be attained.

The digitizer may thus be operated as a high-resolution vector sampling voltmeter (or locked-in voltmeter). Its usefulness is thus extended towards other applications (e.g., impedance and phase measurements and transducer characterization as well). The system can easily be calibrated with minor effort by calibrating an internal direct voltage reference (also embedded in the hardware and accessible to the user). The ADC and its input amplifiers are then calibrated automatically by the control software.

3.1.2 PORTABLE THREE PHASE DIGITIZER FOR ON-SITE MEASUREMENT OF THE HIGH VOLTAGE GRID

For on-site measurements a portable and reasonably rugged digitizer is required. As the instrument maybe required to verify/calibrate regulatory and revenue instruments on the electricity network, the device should be of a high accuracy of the order of 10 µV/V per channel. At least six channels are required to enable voltage and current measurements on all three phases of the network.

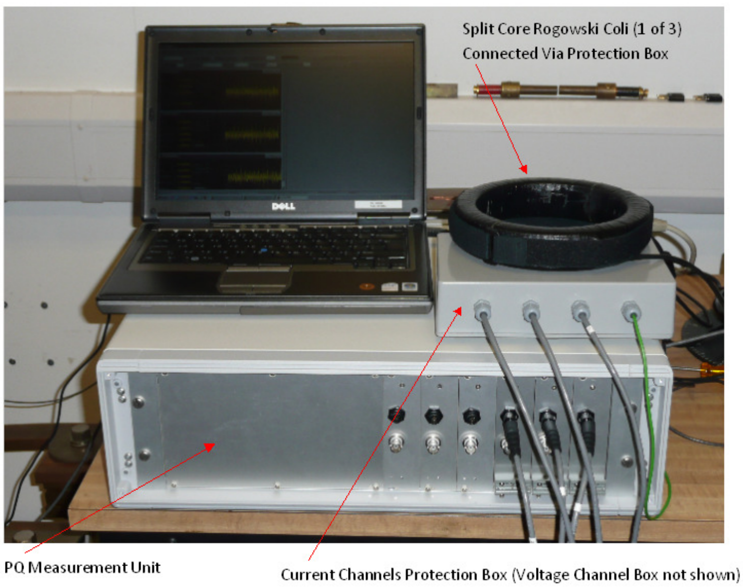
Two separate approaches have been developed in this task, the first (MIKES) employed a commercial high-grade digitizer system and the second (NPL) developed a system based on a new sampling ADC chip.

MIKES developed a power quality measurement system based on commercial digitizer cards. The 8-channel system consists of two four-channel samplers in a PXI-rack. Their maximum sampling rate is 204.8 kS/s, and the resolution 24 bits. The rack accepts both ac and dc power, and the system is controlled by a remote computer via a fibre-optic link.

A compensation scheme was developed to cancel temperature related effects on the system. The scheme bypasses the automatic calibration procedure provided by the manufacturer, and relies on the temperature sensors and voltage references on the digitizer board. After calibration of the onboard references and using the compensation scheme 100 µV/V overall uncertainty was reached for the 10 V input range of the digitizers.

The control software relies on synchronizing the sampling with the input signal. The synchronizing is implemented by feedback to the sampling clock. The frequency of the input signal is detected from each record, and the sampling clock on the digitizer board is adjusted to sample integer number of cycles for the next record. This process is running continuously, so the system tracks the fundamental frequency of the input signal. MIKES's three-phase routines implementing evaluation of non-balanced, non-sinusoidal power according to DIN 40110 and IEEE 1459 are embedded into the controlling software. The first routine implements a time domain power analysis, whereas the latter one is a frequency domain approach using FFT which leads to spectral and harmonic analysis of the input signals.

The system can measure sinusoidal three phase power with an overall uncertainty of few µW/W, when used with well behaving converting devices for current and voltage scaling.



NPL Six Channel Digitizer ready for on-site measurements.

In addition to the commercial approach described above, NPL have developed a new digitizer system based on a new commercial 128 kSPS, 24 bit successive approximation ADC. The digitizer has capacity for six fully isolated channels, each consisting of a PCB housed in a shielded plug-in module. The channels plug into a backplane which routes the signals back to a field programmable gate array (FPGA) PCB which controls timing and marshals the data which is passed on to a digital signal processing (DSP) PCB for processing. The DSP uses a real time operating system for data handling and analysis as required. Data is then passed to a standard PC/laptop using Ethernet, which can be wireless, thus ensuring safety isolation from HV systems. An external sampling clock of any frequency up to the maximum sampling rate can be connected via optical fibre.

One of the design objectives of this digitizer system is to process long term (months) of real-time data continuously with no “gaps” in the incoming data stream. This is important for the measurement of fluctuating signals, for example modulated harmonics. Missing sections of data or gaps will distort the results, for example spectrograms will not represent the true evolution of the signals.

Handling and processing high data rates in real time with six channels is a considerable challenge and careful software design is required. The DSP firmware and PC software in this system both use a multi-threaded approach to achieve this aim. Threads can be considered the fundamental components of multi-tasking software, with each thread appearing to run in parallel. This multi-threaded system allows for continuous real-time measurements on six digitizer channels at the 32 kHz sampling rate, which requires a bit transfer rate of 6.144 M bits per second.

As the digitizer is intended for site use where the temperature can have wide variations, good temperature performance is of the utmost importance. The worst temperature coefficient observed on any channel was of the order 2 ppm/^{o}C over the 10^{o}C to 40^{o}C range measured.

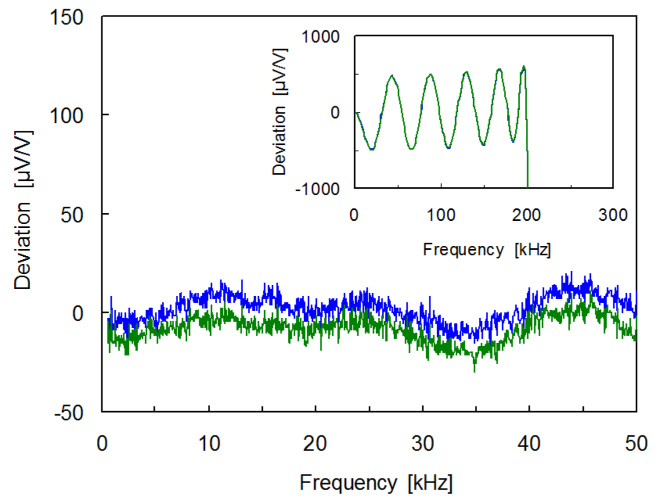
The dc linearity of the channels was approximately ± 3 ppm and the ac linearity at power frequencies ± 1 ppm. The noise floor was measured at to be some –140 dB over the Nyquist bandwidth. The gain stability was measured at <0.1 μV/hour and within ± 10 μV/V over 40 days. The interchannel phase was stable to the micro radian level at power frequency. Accounting for these and other factors the measurement uncertainty of the instrument is of the order ± 10 μV/V. Further characterization was carried out by METAS and is reported below.

For on-site measurements, a software selectable ranging capability was added giving ranges of 415V, 230V, 110V, 70V, 22V, 10V and 1V inputs for the three voltage channels. Current ranging has been achieved using a Rogowski coil input integrator PCB fitted to the three current channels. This is designed to work with the Rogowski coils recommended by MIKES - several software selectable sensitivities available.

3.1.3 WIDE BAND DIGITISERS FOR TRANSIENT AND IMPULSE MEASUREMENTS

The project has also addressed the emerging requirement for power measurement traceability at higher frequencies, driven by applications such as energy saving lighting and switched power supplies where higher frequencies are used in order to achieve better efficiency and lower energy losses. The heart of wideband commercial power meters consists of a fast digitizer combined with wideband voltage dividers and current shunts, used to convert the input voltage and current signals to the input voltage levels of the digitizer. For calibration of such power meters, a reference system is needed where again a digitizer plays an important role.

VSL and Trescal together have characterized a commercial two-channel high-speed digitizer for possible use in a reference system for power measurements up to 1 MHz. The characterization of the digitizer system included frequency flatness, phase, stability, linearity, temperature effects, and self-calibration effects.



Measured frequency response of the 2 Vpp range of both digitizer input channels expressed as a relative deviation from unity gain at a sampling rate of 500 kSPS, when a compensation filter is applied. The inset gives the original frequency response, which shows deviations from flat response that are 25 times larger than the corrected response.

The inset of the Figure shows a typical result of the frequency response of the 2 V peak to peak (Vpp) ranges of both digitizer inputs, obtained at 500 kSPS. The large 'ripple' seen in the data below 200 kHz is caused by the digital filter used by the digitizer firmware. The 500 µV/V relative deviation from flat frequency response is too large for accurate power measurements. Therefore a compensating, inverse, filter was designed and implemented in the measurement software, so that the raw data received from the digitizer are immediately corrected for the non-flat response. The main part of the Figure shows that with this compensating filter the maximum residual deviation from a flat response is only 20 µV/V. This is an improvement with a factor 25 with respect to the original response.

A perfect digitizer should show zero phase difference between its two channels. In the characterisation, there appeared to be a small but detectable phase error between the digitiser channels which increased linearly with signal frequency over the complete frequency range up to 1 MHz, independent of sampling rate, and not affected by the "flatness compensating filter". This behaviour could be explained by a constant time delay of (250 ± 30) ps between the two digitizer channels. It is relatively easy to mathematically correct the digitizer measurement data for this delay.

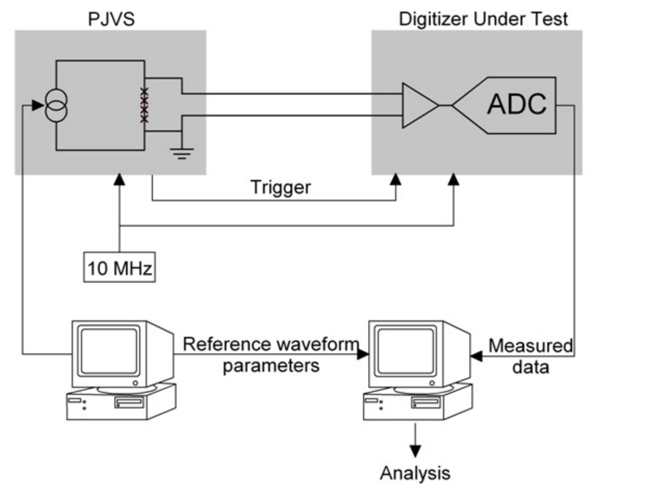
The overall results of the digitizer characterization indicates that under practical circumstances it has an overall uncertainty contribution in power measurements at 10 kHz up to 1 MHz of better than 70 µW/VA and 400 µW/VA respectively. This excludes loading effects, which are significant at higher frequencies, especially above 100 kHz. At low frequencies up to three times lower uncertainties are achieved when the digitizer is calibrated at the correct signal level after each self-calibration, and subsequently used in an environment with a constant temperature.

3.1.4 DIGITIZER CHARATERIZATION TECHNIQUES – NOISE AND LINEARITY

In order to use digitizers for regulatory or revenue calibrations and verification, traceability and associated uncertainly budgets are required. The digitizers described above each required separate characterization to be carried out in a traceable and rigorous manner. This Section describes the development and application of some of the methods used in the JRP.

Test methods for digitizers were developed many years ago and are today fully normalised in standards such as IEEE Std. 1241-2000 and IEEE Std. 1057-2007. But the steady improvement of the analogue-to-digital converters has led to the apparition of commercial devices with 24 bits of resolution that are well suited for metrological applications.

3.1.4.1 Characterization of Digitizers Using Programmable Josephson Voltage Systems

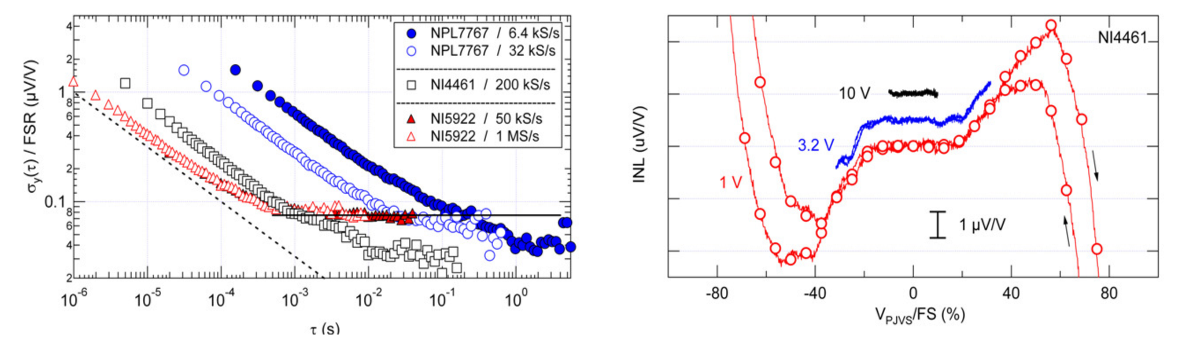


METAS ADC Characterization System.

Standard tests are not well suited for these high resolution digitizers because of the accuracy constraints they place on the reference source applied to the digitizers. The use of a programmable Josephson voltage standard (PJVS) permits to overcome this limitation and enables the development of new methods for the characterisation of digitisers with the highest level of accuracy. In addition the PJVS intrinsically ensures the traceability of the measurements.

To this end, a test bench for the DC and AC characterization of metrological grade ADCs has been developed at METAS based around a 1 V PJVS. The diagram on the left shows the test system. Two types of characterization have been carried out: DC characterization where a DC Josephson signal is applied to the input of the ADC and quasi-dynamic characterization where a stepwise triangular Josephson signal is applies to the input of the ADC. The term quasi-dynamic refers to the fact that signals are made up by successive steps as opposed to continuously varying. The intrinsic noise of the digitizer can also be characterized with the Allan deviation. For this test, a 50 ohm termination is placed at the input of the digitizer.

One of the key parameters in characterizing an ADC is the integral nonlinearity (INL). For this measurement, a triangular stepwise reference waveform, synthesized by the PJVS, is digitized by the unit under test. The reference voltage being accurately known, the error of the digitizer is simply given by the difference between the ADC’s output and the Josephson voltage. The INL is the deviation of this voltage difference from linear normalized to the full scale of the converter. The two graphs below show an example of noise measurements and INL made on some 24 bits ADCs including the NPL system described in 3.2.1.



3.1.4.2 Phase and the dynamic linearity characterization of the digitizers

Phase and the dynamic linearity characterization of the digitizers were investigated by INRIM. A two output generator, based on an open platform commercial board, with high speed (1Gsamples/s for channel) and high resolution (16 bits). It is mainly intended to generate signals with a sharp time definition and, consequently, a good phase definition of the different harmonic components of the waveforms.

There are two main blocks:

- a high performance FPGA board based on the VirtexV having 64 MB DDR2 SDRAM and 16 MB flash memory;

- an auxiliary board based on a double channel DAC and a high frequency phase-locked loop (PLL).

The high frequency clock is provided by a voltage controller crystal oscillator controlled by means of a high performance PLL clock synchronizer. FPGA makes possible the accurate synchronization of digital devices, by using internal distribute clock architecture.

INRIM's Two Output Generator for ADC Phase characterization

Different test functions can be implemented by means of this generator, as for example:

- sinusoidal signals with programmed characteristics (amplitude and phase) at the two outputs;

- multitone signal generation at the same output;

- signals with a programmed time jitter or phase shift variations.

For ac linearity characterizations of ADCs, a wideband inductive divider with guard and cable connections was developed by INRIM. The guard circuit is based on a twin-divider and allows the connection to the outputs of a digitizer reducing the influence of the capacitive load of the cable and, consequently the errors of the main divider. The operative conditions are: voltage up to 10 V, frequency from 500 Hz to 50 kHz. The errors in the operative frequency band, computed by a circuital model, are less than 3 parts in 10^6 for the ratio and less than 3 µrad for the phase.

3.1.4.3 Characterization of a Commercial Digitizers Against Thermal Convertors

Thermal convertors are used to measure the heating effect of ac signals which is proportional to the RMS value of the waveform. Direct comparison to stable dc standards or other ac standards can then be made.

LNE studied the performance of a commercial voltmeter widely in ac measurements when used in sampling mode for measurement of various low frequency signals. In particular the influence of aperture time and sampling frequency has been investigated. It has been shown that aperture times ranging between 50 µs and 100 µs or larger than 250 µs lead to the lowest measurements errors.

The error of the voltmeter for RMS voltage measurement has been measured by comparison with thermal converters. An agreement of the order of 2 µV/V between both techniques has been found for sinewaves at frequency ranging between 20 Hz and 400 Hz sampled with a frequency of 2.2 kHz with aperture times between 150 µs and 400 µs. At higher frequencies (up to 10 kHz) the observed error is generally larger and depends on measurement conditions (aperture time and sampling frequency). For such signals, a sampling frequency of 50 kHz and an aperture time of 10 µs, lead to errors that remain always smaller than 25 µV/V.

Performance of the voltmeter was also investigated for distorted waveforms with a fundamental component at 50 Hz and a spectral content limited to 50 stationary harmonics with total harmonic distortion (THD) up to 85 %. The agreement with thermal converters has generally been found better than 5 µV/V but can reach 15 µV/V for high THDs when THD is mainly due to highest order harmonics.

The work was extended to the characterization of the type of commercially available PXI digitizer used in Section 3.1.2. Stability test performed on constant AC voltage at constant temperature and constant humidity showed variations of measured value characterized by a standard deviation of 16 µV/V. Performance of the card for RMS voltage measurement at frequencies from 100 Hz up to 40 kHz has then been established again by comparison with thermal converters. The error of the card for signals at frequencies lower than 10 kHz is generally between 200 µV/V and 400 µV/V depending on measurement conditions, but can reach about 1000 µV/V at 40 kHz. Nevertheless, taking into account the stability of the card and calibration uncertainty, this card could be calibrated with an uncertainty of about 30 µV/V.

3.2 PRECISION TRANSDUCERS FOR LABORATORY MEASUREMENTS OF POWER AND POWER QUALITY

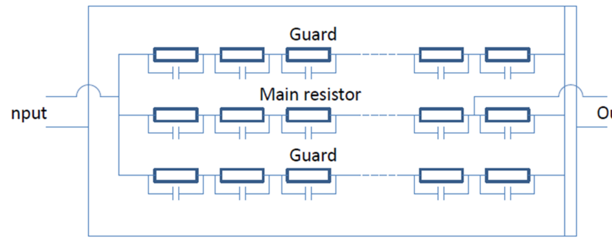
In order to measure electrical ac power it is necessary to measure voltage (V), current (I) and the phase displacement (φ) between the voltage and current. The power is defined as $P = V \cdot I \cdot \cos(\varphi)$. For high accuracy measurements, this is usually accomplished using a voltage divider, a current shunt and an accurate two channel phase sensitive voltmeter operating at a voltage level around 1 V.

The purpose of the voltage divider is to transform the voltage signal from a high level to a level suitable for the voltmeter and the current shunt to transform the current signal to a voltage signal. Ideally the output from the voltage divider should just be a perfect scaled down copy of the input signal, and the current shunt should act as a perfect resistor, but inevitably the devices will introduce errors, such as frequency dependent scale factor, phase displacement and distortion.

An objective for this JRP was to develop and fully characterise the transducers to a level well beyond the state-of-the-art. During the whole project, at least two rounds of simulation, modelling, prototyping and testing of the transducers are undertaken.

We have also chosen not to decide on one single design for the three groups of transducers (i.e. voltage dividers, shunts up to 20 A and current shunts up to 100 A), but to pursue various routes. In this way we could make use of the powerful experience and competence existing in the participating institutes and explore a broad range of options. The overall targets for the three types of transducers have been met.

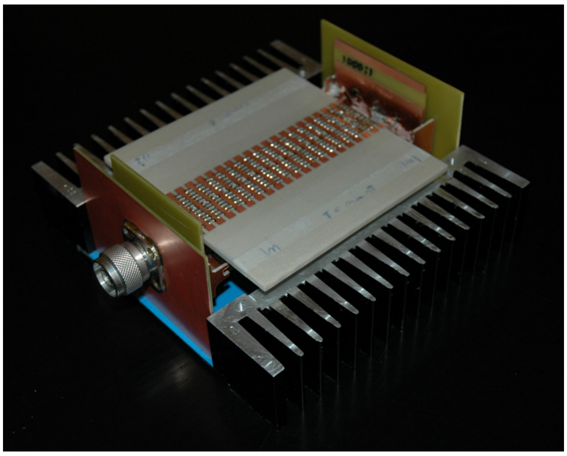
3.2.1 DEVELOPMENT AND CHARACTERISATION OF TRANSDUCERS FOR WIDEBAND VOLTAGE MEASUREMENTS UP TO 1000 V



JV Voltage Transducer

At JV voltage dividers for wide band use have been developed for the division ratios 10 V : 1 V; 400 V : 1 V and 1000 V : 1 V, covering the frequency range from DC to 100 kHz. The target is to provide the division with minimal frequency dependency, temperature dependence, voltage dependence and phase shift. A design employing a resistive ladder, made of surface mounted resistors on a board, and two guard boards above and below the resistive ladder, is used (the figure shows the equivalent diagram of the divider).

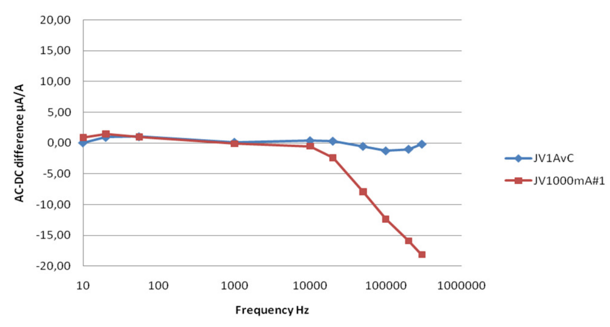
For the higher voltages (i.e the 400 V and 1000 V dividers), the power dissipated becomes more significant, and the thermal conductivity of the divider board and divider overall must be as high as possible. For these, the boards are made of AlN (Aluminium Nitride), instead of the fibre glass epoxy used for 10 V. Also forced air cooling is employed. In addition, an important aspect is the loading effect of the measuring instrument connected, which has an important effect on the phase and frequency response of the divider system. Therefore, the impedance must be matched or compensated according to the load in question. The photograph (right) shows one divider of AlN partly assembled, the white AlN main board with the ladder, below it sits one guard card, and one more is mounted above the main board.


Photograph of the JV Voltage Divider

New voltage dividers were constructed by MIRS/SIQ for 10 V / 0.8 V and 100 V / 0.8 V voltage ratios. They were used primarily to set-up and study models developed for these voltage dividers. By characterising voltage dividers and comparing them with the models, a satisfactory agreement was found, which enabled us to calculate the necessary additional elements and their placement for compensation of the expected frequency roll-off at higher frequencies. Results confirmed the model used. The modelling approach could therefore be used also for other voltage dividers, developed within the project.

3.2.1 *DEVELOPMENT AND CHARACTERISATION OF WIDEBAND TRANSDUCERS FOR CURRENT MEASUREMENTS UP TO 20 A*

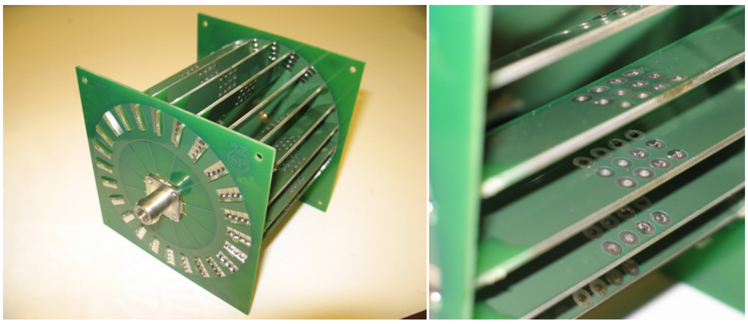
DC measurements of 4 cage shunts (developed at JV, SIQ and CMI) were performed at CMI using its measurement set up, which was developed mainly for characterization of high current shunts and its detailed description is given in the chapter related to high current shunts. The worst measured temperature coefficient (TC) was 4.0 ppm/K, the best measured TC was -0.8 ppm/K. The worst calculated power coefficient (PC) was 5.7 ppm/W and the best measured PC was -1.5 ppm/W.



Previous and New (JV1AvC) Shunt Design at 1A

Similarly an extensive range of tests of the DC characteristics of the original JV shunts developed prior to this project has been performed by VSL. In addition to TC and PC determination, the long term drift rates of the shunts were assessed. Originally, the JV shunts were designed to accommodate optimal frequency response, low AC/DC difference, low phase shift and low component cost. For the purpose of this project, also the mentioned DC parameters are important. Results from VSL give TCs ranging typically from 1 to 3 µΩ/Ω per K for most devices, and all were below 10 µΩ/Ω per K, PC typically from 2 to 4 µΩ/Ω per W and the drift rates are typically below 10 µΩ/Ω per year.

AC/DC current shunts were developed at JV for the following range: 100 mA to 20 A, covering the frequency range from DC to 1 MHz. The design is a development of the former JV devices. The shunts are modelled, and the response is calculable from geometry and component and material characteristics. Components used are low cost surface mounted resistors on a cage structure. The frequency response is exceptionally flat, and represents state of the art today. As an example, the graph above shows the response of the latest JV 1 A shunt, compared to the former JV design.



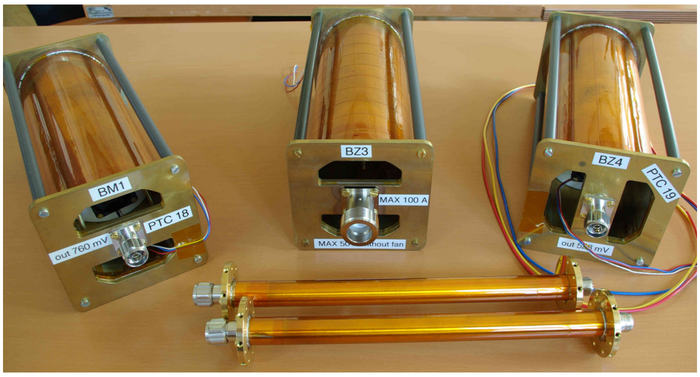
The prototype 10 A shunt constructed at SP. By soldering chip resistors through the PCB, the inductance is minimised. The previous design had through-hole resistors, and the inductance of the component legs dominated the phase response of the shunt. The chip resistor elements are of a newly developed type with very low temperature coefficient.

SP has designed a set of new shunts with improved characteristics compared to previous designs, notably the phase response and the power dependence. The base design is a cage geometry originally invented at JEMIC in Japan, and further developed by several metrology labs. This geometry gives a low inductance which means a small phase response.

When resistors are mounted in the cage structure the parasitic inductance of the resistors adds to the cage inductance, mainly because of their connection wires. Therefore the new design includes chip resistors which are mounted through the printed circuit board. This way the added inductance is minimised and the phase response of the shunt is tiny, e.g. for a 10 A shunt the phase angle of the output voltage relative the input current is less than 100 µrad at 100 kHz.

When measuring current the temperature of the resistors rise because of resistive heating, and this changes the resistance value. It is particularly noticeable for large current shunts (10 A and up). In order to minimise this change we have chosen a newly developed type of resistor (called Z-foil, from Vishay) which has very low temperature and power dependence. The result is a tenfold decrease of the power dependence of the shunt.

3.2.1 *DEVELOPMENT AND CHARACTERISATION OF TRANSDUCERS FOR CURRENT MEASUREMENTS RANGING FROM 10 A TO 20 A*



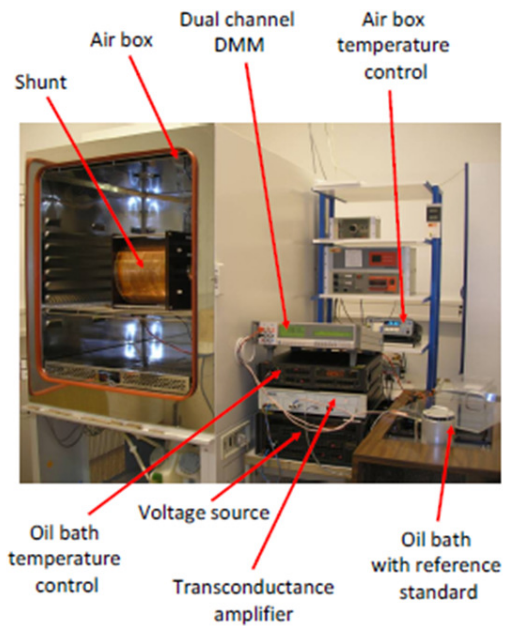
BEV Shunts

Based on a former construction of shunts for ac-dc measurements a new design of coaxial shunts for the measurement of electric power and power quality in a wide frequency range was developed at BEV. These units use resistive foils to transform currents up to 100 A to voltages which can be handled by electronic sampling devices. In principle the construction combines 3 cylinders made of brass, copper and Manganin with thicknesses down to 20 µm to a 4 terminal resistor with an inductance in the pH range.

Due to forced air cooling the size of the shunts could be significantly reduced, the use for absolute ac-measurements improved and the warm up time shortened.

In addition to an excellent frequency behaviour the shunts are also optimized for a small change of the dc resistance with temperature and power and a very low phase angle error. These three properties make the shunts very suitable devices for the measurement of electric power.

Constructed and manufactured at BEV, Austria, continuous measurements performed at CMI, Czech Republic, INRIM, Italy and SP, Sweden contributed to iterative improvements during the 3 years duration in this European research project.



CMI Characterization System

The current shunts are usually employed in a broad current range, therefore it is necessary to know their current (resp. power) level dependence. The change of resistance in a power interval is represented by the power coefficient of resistance (in ppm/W). Next, the resistance of all resistors (as well as current shunts) varies with temperature. This variation is characterized by temperature coefficient of resistance (in ppm/K). Characterization of the shunts at direct resistance temperature and power coefficient was performed mainly at CMI.

The measurement set up used the measurement of the ratio of output voltages of the tested shunt and the reference standard by a dual channel multi meter as the basic measurement method.

For the characterization of shunts in a wide current and temperature range a set of oil filled resistance standards placed in the oil bath (with stability ±0.02°C) was used. The power coefficient PC = $\Delta R/\Delta W$ was measured and calculated in the current range of 50% - 100% of nominal current. The temperature coefficient TC = $\Delta R/\Delta T$ was measured in the temperature range from 18 °C up to 28(30) °C at 1/10 of nominal current. The uncertainty of the calculated PC was less than 3.5 ppm and of TC less than 2.5 ppm

13 current shunts of two types of construction (foil and cage) with nominal current from 20 A up to 100 A and two testing foils were measured.

From 9 characterized foil shunts the worst measured TC was 8.0 ppm/K, the best measured TC was 0.5 ppm/K. The worst calculated PC was -3.97 ppm/W and the best measured PC was 0.51 ppm/W.

From 4 characterized cage shunts the worst measured TC was 1.7 ppm/K, the best measured TC was 1.2 ppm/K. The worst measured PC was -0.25 ppm/W and the best measured PC was -0.06 ppm/W.

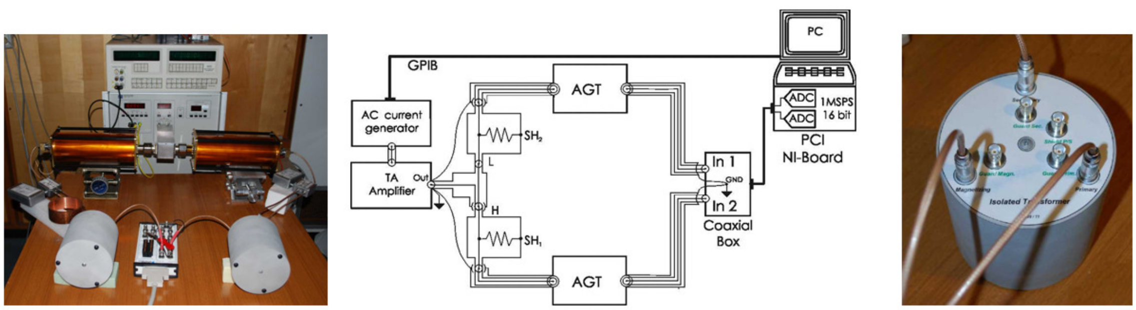
Next, a measurement method for shunt impedance measurement was developed at CMI. A step down method from 1 Ω calculable impedance standard down to 0.005 Ω shunt was performed. The current was applied through in-series connected reference and tested shunt and their output voltages were sampled by two digital sampling multimeters synchronized by trigger. The resulting uncertainty for a 0.0005 Ω shunt was 500 ppm at 100 kHz.

4 shunts were characterized and their AC-DC difference of impedance was calculated. Gathered results met the AC-DC difference of the shunts measured at JV, SP or BEV.

A new type of phase comparator has been built by INRIM for comparing the phase of shunts for currents between 10 A and 100 A and frequencies from 500 Hz to 100 kHz. It consists of a system for current generation and another for detecting phase differences. The ac current is produced at the output of a transconductance amplifier, whose input is driven by a calibrator, automatically set to the proper voltages and frequencies directly by the computer via IEEE-488 bus. By means of suitable current nodes, the ac current is supplied to the two shunts under comparison connected electrically in series.

In the system for detection of the phase difference two active guarded transformers (AGTs) are employed to transmit the voltage between the output of the shunts and the inputs of the phase detector. They are identical and made as a special type of double stage transformers, where one of the core acts as the magnetizing element and the winding is driven by a buffer. In this way, the primary winding only requires a negligible current. Their outputs are sent to a digital phase detector built by means of a commercial acquisition board put inside the controlling computer. A software program for acquiring and processing the samples, developed in MATLAB, can evaluate the phase difference. With a proper measurement procedure where the shunts are exchanged at the T-connector most of the errors are cancelled and the difference between the phases of the two shunts under comparison can be evaluated.

Tests performed on different elements of the comparator showed that, even if the constitutive elements (digital phase comparator – AGTs) have non-negligible phase shift, their stability and the compensation of the procedure improve the accuracy of the phase determination by at least an order of magnitude.



Phase comparator: a) setting b) basic circuit c) an active guarded transformers (AGTs)

A large set of comparisons on the shunts existing before the project for current up to 100 A and for frequency up to 100 kHz has been performed at INRIM by means of a step-up procedure starting from 0.5 A. The differences of the phases between two shunts are the starting point for the data processing and the additional constraints set by the measurements' coherency allowed us to adjust the resulting values by means of a optimization performed by a best fit, for each frequency and current value. The evaluation of the uncertainty was made a priori from the standard deviations and the degrees of freedom. A successive evaluation was made *a posteriori* from the standard deviation of the displacements. For linking the phase differences of the shunts with different nominal current a typical step-up procedure was utilized.

At the end of the project the phase characteristic as a function of the frequency (from 500Hz to 100 kHz) of the new shunts of 100 A built by BEV for the project has been measured.

The absolute phases of the shunt, taken as a reference, was evaluated at INRIM by using a step-down procedure for the steps 5 A, 2 A, 1 A and 0.5 A. The determination of the absolute value of the reference was accomplished by considering three types of shunts of identical structure (resistance respectively of 0.5 Ω, 1 Ω, 2 Ω).

From the identical internal construction the same value of the inductance L was assumed, even if the contribution of the inductance of the resistive elements is not negligible. The reference value was computed by supposing that, for all couple of shunts of this type and with different resistances, the absolute values are obtained from the relative ones, considering their time constants proportional to 1/R.

3.2.2 CHARACTERIZATION SYSTEMS FOR SHUNTS AND DIVIDERS

SP has developed a characterisation system for the phase displacement of both voltage dividers and current shunts. The basic principle is to supply the same signal (voltage or current) to two devices (voltage dividers or current shunts) and measuring the output signals with two synchronised high frequency sampling channels (for current shunts we actually use four channels to get two differential voltage channels). We can then determine the relative phase displacement between the two devices.

In order to determine the absolute phase displacement we also need an absolute phase reference. For voltage dividers we can use a low ratio divider (e.g. 5:1) and directly compare the input and output signals with good accuracy. We can then use the relative phase between this reference and a second higher ratio divider to determine the absolute phase displacement of the second divider, then use the second divider to determine a third divider and so on.

For current shunts we determine the absolute phase by measuring the inductance of one shunt. We have developed a method to measure inductance with an accuracy of about 10 pH using specially designed circuit boards with a well known inductance, in combination with a voltage divider. We can then calibrate an inductance meter at the pH level and use it to measure the very low equivalent inductance (L_{eq}) of a current shunt. The equivalent inductance is defined as $L_{eq} = L - R^2C$, where L, R and C are the shunt inductance, resistance and capacitance respectively. Once we know this inductance we can calculate the phase displacement using the formula $\varphi = 2\pi \cdot f \cdot L_{eq} / R$, where f is the frequency. As with the voltage dividers, we can then determine the phase displacement of other shunts from the relative measurements.

The uncertainty is frequency and level dependent. Below are the project targets and the achieved results at 100 kHz

Level	Device	Target	Achieved
240 V	Divider	200 µrad	40 µrad
5 A	Shunt	100 µrad	50 µrad
100 A	Shunt	500 µrad	100 µrad

3.3 THE DEVELOPMENT OF ACCURATE SAMPLING TECHNIQUES AND ANALYSIS ALGORITHMS IN SUPPORT OF POWER QUALITY

The aim of this Work Package is to develop digital signal processing algorithms to traceably measure a range of parameters defined by power quality standards, which are in place to ensure a reliable and efficient electricity supply. Due to the nature of the large number of non-linear time-varying loads that are present on the network at any particular time, the measured waveforms are complex and non-stationary. Further, the electricity grid is a noisy environment where the sampling frequency cannot be readily synchronized due to the frequency variation of the supply. As such the development of asynchronous sampling techniques and noise reduction algorithms with an associated uncertainty analysis are required.

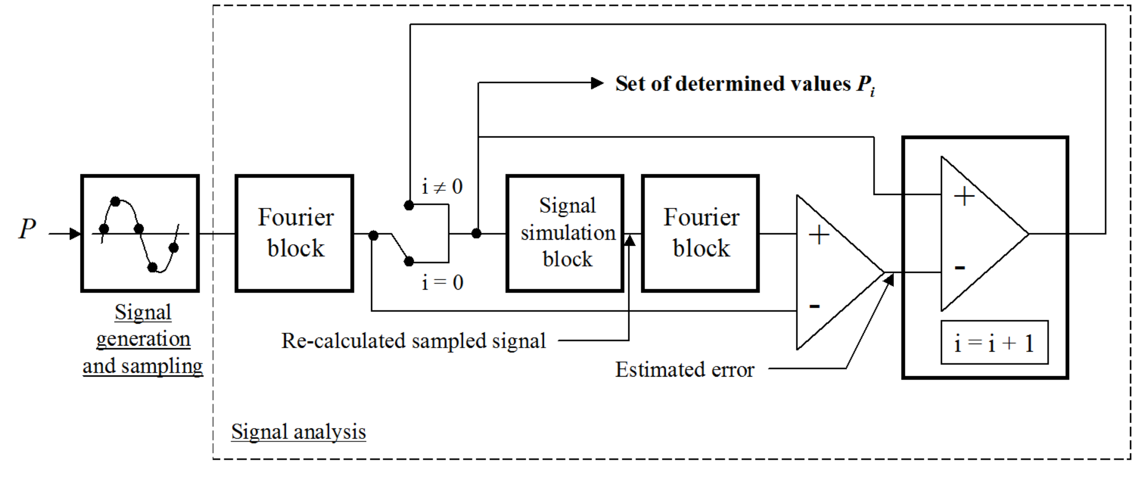
3.3.1 DEVELOP/ADAPT ANALYSIS ALGORITHMS FOR THE ACCURATE DETERMINATION OF POWER QUALITY PARAMETERS

One of the most difficult problems when using digital sampling techniques in power quality measurement is dealing with signals that vary with time. Traditional digital signal processing techniques to recover harmonics for example, rely on the periodicity of the analysed waveforms and errors such as spectral leakage occur if the signal amplitude or phase changes with time. A number of different techniques for correcting such errors were investigated as part of this work.

The first of these is the use of windowing in Fourier transforms. This important technique is widely used to correct errors due to spectral leakage and can be seen as a benchmark for all frequency domain analysis.

The purpose of the work was the determination of the amplitude and the modulation depth of fluctuating harmonics contained in a low frequency (typically 50 Hz) sampled signal. The Fourier-based method requires prior knowledge of the orders, modulation frequencies and shapes of the modulating waveforms of the harmonic components. As such, it cannot be used for the characterisation of totally unknown signals but can be applied for the calibration of programmable sources that provide reference signals containing fluctuating harmonics.

The Fourier transform is used to recover the amplitude of the harmonics. It can also be used to give the amplitude of modulation components in the case of simple modulation functions such as square and sine waves. The modulation depth of each fluctuating harmonic can be deduced from the amplitude of adjacent frequency bins known as sidebands.



Synoptic diagram of the iterative process

However, such signals often contain high frequency components. All components having a frequency higher than half the sampling frequency "wrap" or "fold" around the spectrum and can overlap the components of interest giving rise to significant errors. Moreover, some modulation components arising from one fluctuating harmonic can directly overlap components resulting from other harmonics leading to significant errors. Finally, the period of the fluctuations may not be known and so the signal to characterise generally cannot be observed over an integer number of periods leading to errors in the Fourier analysis.

In order to reduce all these errors, an iterative process has been developed, intended to estimate and correct them (see the figure above).

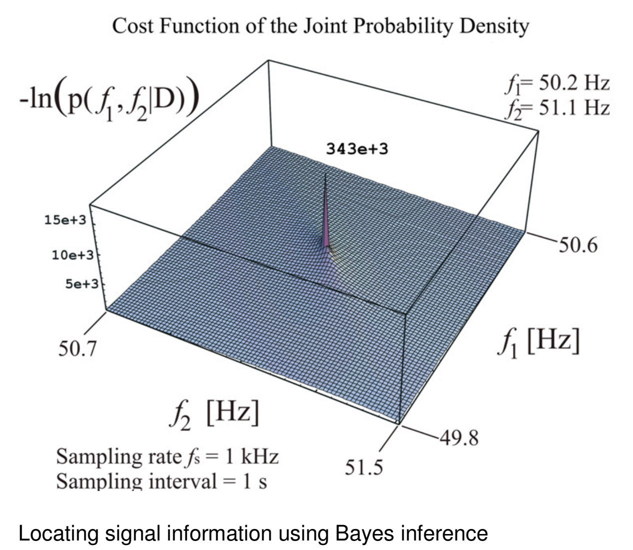
Simulations were performed with signals consisting of a fundamental component at 50 Hz and two fluctuating harmonics. In low noise conditions the remaining error after 10 iterations using a Blackman-Harris observation window with 7 terms can be of the order of a few parts in 10^{15} and rarely larger than 10^{10} under certain conditions. I.e. the signal must be observed over a time interval larger than 6 periods of the modulating waveforms and the ratios between amplitudes and modulation depths of fluctuating harmonics should not exceed 10. Such errors can be considered as negligible compared to errors that would arise from the measurement instrument (of the order of a few parts in 10^6 in best cases).

Although this method can be used to give high accuracy results and can be successfully applied to laboratory based calibration, it relies on a certain amount of prior knowledge of the signal under analysis and so is not generally applicable to the type of waveform that can occur on the electricity supply network.

As such PTB has concentrated on applying a broader technique known as Bayesian Inference on sampled data. This powerful method is underpinned by the theory of probability and allows pre-knowledge or prior information from an observer to be accounted for in the analyses. It is a powerful mathematical instrument has been employed in investigations of many natural phenomena. Bayes inference is controversial and is still object of study in the field of Mathematics in most renowned universities. It was re-discovered and further refined in the 1960s and 1980s.

Bayesian Inference is fundamentally a regression analysis, where a functional is searched, which "best" explains the phenomenon under investigation. The challenge thus relies on finding maxima of very complex multi-dimensional probability density functions (the so called "joint-posterior" probabilities or "cost" functions) and from these maxima, to extract parameters of a model equation (with the help of "likelihood" functions) using any pre-knowledge or prior probabilities that may be known (in most cases even not known). As important as the estimation of parameters in a functional is the evaluation of their uncertainties, which can be obtained by integrating such probability functions within a confidence interval. Employing Bayesian inference can only be done numerically with the help of considerable computer power. Any waveform (including fluctuating quantities) can be investigated with Bayesian Inference. There is no restriction on whether sampled data were obtained either by asynchronous or synchronous sampling methods.

Complex signals consisting of multiple frequency components result in multi-dimensional probability functions. Those with a dimension greater than two cannot be represented straightforwardly on a three-dimension graphic. Therefore, to illustrate the method in question, the figure on the right depicts the cost function (the negative of the natural logarithm of the posterior probability density function) over 80 points on an interval where two frequencies f_1 and f_2 are estimated, which result from asynchronous sampling of two non-harmonic signals at 50.2 Hz and 51.1 Hz at a rate of 1 kHz over a sampling interval of 1 s. The peak of it is found by search algorithms. It is located exactly at those values and their magnitudes can be found with high accuracy. Noisy data display a broadened joint probability density function.



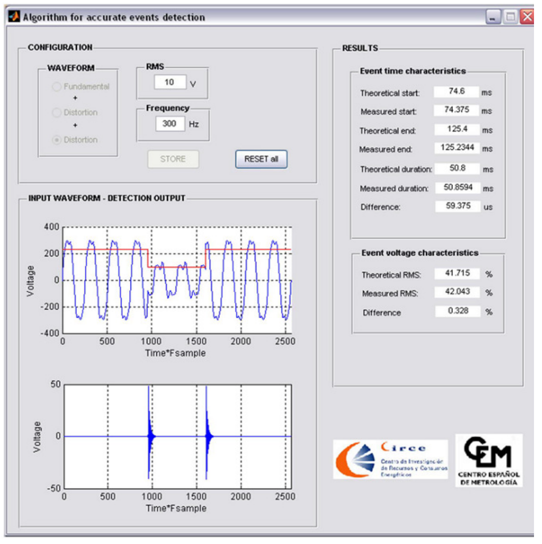
Locating signal information using Bayes inference

Bayesian techniques have been shown to be accurate and flexible, but they can be complex and difficult to implement without considerable expertise. Therefore a further signal processing technique, wavelet theory was investigated, which lends itself well to the analysis of time varying signals. The main benefits of the Wavelet Transform over the Fourier transforms for the applications required by this work are:

1. Localisation in time of transient phenomena and presence of specific frequencies content
2. Accurate edge detection for events

For these two important reasons, this theory was chosen for power quality measurements (harmonics and event detection and characterisation).

To test 53 different digital filters, an automatic system based on dyadic filter banks to choose the most suitable wavelet filter (digital filter) was developed. For harmonic evaluations (stationary and non-stationary input waveforms) with the appropriate filter, wavelet decomposition was shown to provide a significant improvement in recovering frequency components of fluctuating signals when compared with traditional transforms (STFT).

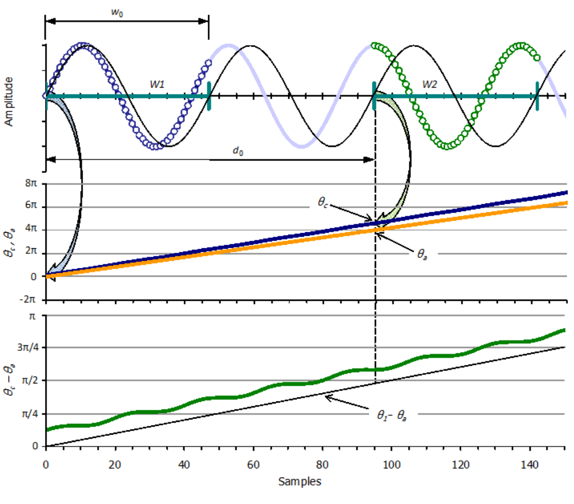


CEM Wavelet analysis software

Further research was carried out in the event detection field through the partial use of the previously developed wavelet decomposition banks. With the information extracted from the first level of decomposition, time and amplitude were measured accurately. In order to perform a complete set of tests, a Matlab-based interface was designed. This tool allows the user to construct any waveform for testing the detection algorithm under specific boundary conditions, such as phase jumps, noise or varying harmonic content during the event, a screenshot is shown in the above figure.

3.3.2 DEVELOP ASYNCHRONOUS SAMPLING TECHNIQUES SUITABLE FOR APPLICATION TO POWER QUALITY MEASUREMENTS

Asynchronously sampled signals are common to all measurements where an appropriate synchronization between signal source and sampling device is not available or practical. This spans from on-site and industrial measurements over data converter testing to specific precision calibrations in metrology laboratories. This is especially true for power quality signals which are sampled directly from the mains, for which exact synchronisation with the measuring instrument is practically impossible.



PSFE algorithm developed at SIQ

For that reason, algorithms capable of accurately estimating the frequency and amplitude of the sampled waveform were required. These algorithms should further perform well under all perturbations that are common to mains borne signals. This includes flicker, dips, swells, harmonic distortions and their modulation and relatively high levels of noise. Three new algorithms were developed and compared against other published methods.

The first of these was a new phase sensitive frequency estimation algorithm (PSFE), developed at SIQ to provide for accurate estimation of frequency, amplitude and phase of such signals. The algorithm estimates the signal parameters by detecting phase difference between a signal model and the actual sampled signal. This detection is extremely accurate when the two windows are positioned at the distance covering approximately the whole number of cycles. This enables the PSFE to accurately estimate all signal parameters in only a few iterations. This new technique practically resolves the problem of sensitivity to harmonic distortions, which is now smaller by three orders of magnitude compared to the standardised iterative procedure, described in the IEEE Standard 1057-2007.

The PSFE algorithm was further compared to other state-of-the-art algorithms where it performed close to the theoretical limits and outperformed all other algorithms in its speed class for harmonic distortion insensitivity.

The PSFE algorithm was thoroughly tested on power quality signals together with the Time Domain Interpolation and Scanning Algorithm (TDIS) which was developed at NPL. This method uses cubic spline interpolation to effectively adjust the sampling rate of the signal in software, allowing synchronisation with the analysed signal using an estimate of its frequency. It allows traditional signal processing techniques (e.g. Fourier analysis) to be used on non-periodic signals with greatly reduced errors.

Both algorithms showed predictable behaviour even at very high signal perturbations and thus proved their suitability for estimating power quality signal parameters. Both have now been implemented in software and applied to on-site measurements. The PSFE also has the advantage that it has relatively low computational requirements, which allows it to be used in embedded real-time measuring systems for power line signals.

As the PSFE algorithm is a general solution for signal parameter estimation, it was also used in improving a calibration capability for digital sampling oscilloscopes (DSOs). It was shown that DSOs can benefit greatly by using such an algorithm when measuring amplitude and frequency of captured signals.

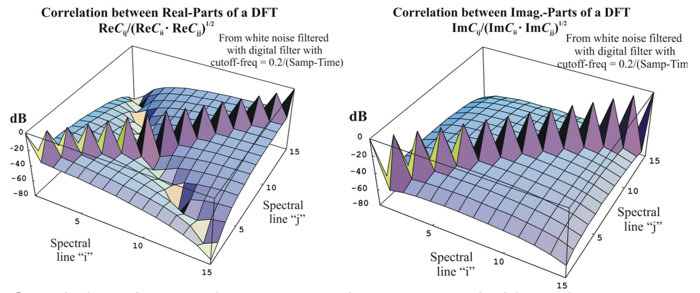
A further algorithm was developed by INRIM, which although less accurate at recovering frequency from larger waveforms, has the advantage that it can process signals only one half-cycle in length (as opposed to 2 cycles or more for the PSFE and TDIS techniques), allowing signals with rapidly changing frequency to be analysed.

This algorithm can operate for partially distorted waveform (< 30%), and it is based on least square adjustment. The procedure is non-linear and so the determination of the harmonic components is based on a successive approximation procedure, with the harmonics and the frequency difference employed as parameters in the best fit. This algorithm can reach high accuracies in the determination of frequency, but only if the frequency is constant throughout the analysed signal. As such the technique was expanded so that the fitting procedure allows the harmonic amplitudes and frequencies to be time-varying functions and only one half-cycle is required for a frequency estimate. This is now ready for use in the primary power measurement capability at INRIM.

3.3.3 DEVELOP NOISE MITIGATION TECHNIQUES/ALGORITHMS TO IMPROVE POWER QUALITY MEASUREMENTS

When making on-site grid-based measurements it is often necessary to utilize existing transformers and associated circuits, which were never intended for measurement purposes, for example protection transformers on the MV grid. As such these installations are not always best configured to reject interference, whilst being subject to relatively high levels of noise. This interference is due to extraneous factors and not part of the underlying signal of interest.

In order to reduce the influence of noise and interference on sampled data from on-site measurements, in-depth investigations into the nature of noise processes and noise mitigation techniques were carried out. This included a study at PTB on the effect of noise and interference on traditional signal processing techniques such as the discrete Fourier transform (DFT), Hilbert and Wavelet transforms, which are used to determine spectral components. Depending on the noise spectral density over frequency, non-white noise may produce strong correlation between spectral



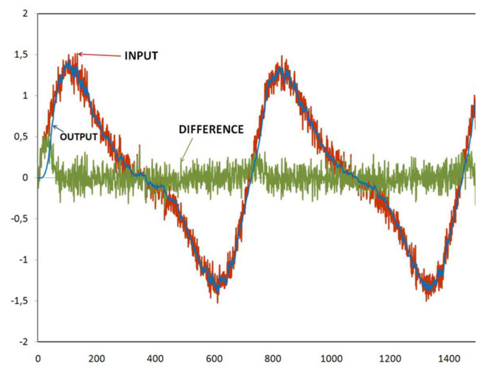
Correlation of spectral components in presence of white noise

components (or coefficients). This means that the determination of spectral components depend mutually on whether other higher or lower components are present or not in the signal. Such correlations make uncertainty analysis of digital sampling systems extensive, time-consuming and difficult. The figure shows correlations among spectral components for the real and imaginary parts of a DFT.

Laboratory-based metrology typically involves the measurement of synthesized ac signals. For these types of signal, a wide palette of random (non-synchronous or non-coherent) and non-random (synchronous) signals arises, which may be considered superimposed on the signal of interest. Synchronous noise components (for example: glitches and spikes) may be well distributed over frequency and are always coherent to the internal time-base clock of signal synthesizers. Although of deterministic nature, synchronous components do cause systematic deviations which are usually not readily perceived by the user. These can, however, be filtered with conventional (analog- or digital) filters, which are the state of the art in the practice.

The last category of noise is related to those signals that are not of random nature and asynchronous to the sampler time base, as may be found on signals measured on the electricity grid. These may be intermittent (i.e., non-stationary) affecting sampling systems in very particular ways. The mitigation of noise effects is not 100 % possible. However, this type of noise can be considerably reduced by adaptive filtering (learning filters).

A wide range of these filters were studied and implemented in software for on-site measurements. These have been applied in mains-beat cancellation and cancellation of magnetically coupled interference using pick-up coils to estimate the level of interference.



Application of 13-pole LMS filter to sampled data

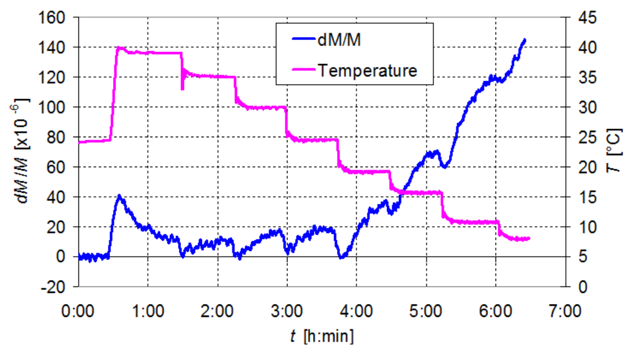
Examples of the filters studied include “Wiener” filters, Kalman filters, Least Mean Square (LMS) and Recursive Least Squares (RLS) filters. These filters can be applied prior to any power quality transform and can be shown to reduce the noise level by an order of magnitude or more. On a frequency range, the response of filters may be corrected by calculating their inverse transfer function (e.g. cosine for adaptive LMS filters that result in a finite-impulse-response (FIR) filter). The figure shows an example of filtering a signal (red) with a signal noise ratio of 20 dB employing a 13-pole LMS filter. Denoising is readily apparent as shown by the output of the filter (blue). The instantaneous error is shown in green.

3.4 THE DEVELOPMENT AND CHARACTERIZATION OF HIGH CURRENT AND HIGH VOLTAGE TRANSDUCERS

The need for accurate, traceable energy and power measurements and for a better power quality assessment at medium (MV) and high voltage (HV) level calls for the use of reference current and voltage transducers with improved and metrologically validated on-site performances. Specific required features are enhanced measurement uncertainty, close to that obtainable in laboratory measurements, optimised behaviour in a quite wide frequency range, reduced dimensions and weight, insulation, toughness and portability. To meet these demands, non-conventional transducers for on-site use in the medium voltage grid have been developed and experimented, and their achievable laboratory and on-site uncertainties have been assessed within three complementary tasks, respectively focused on the measurement of high currents at power frequency and harmonics, impulse and fast transient currents, and high voltages at power frequency and harmonics.

3.4.1 ON-SITE, HIGH CURRENT MEASURING SYSTEMS

Two measurement systems have been developed, both based on Rogowski coil sensors of different type, whose specific features include galvanic separation from the current conductor, linearity and flexibility of use.



Rogowski coil mutual inductance compensation against changes in temperature.

MIKES has studied the characteristics of a commercial split-core Rogowski coil to qualify it for high accuracy on-site measurements and calibrations of power frequency currents up to 5 kA. The main advantage of using a Rogowski coil is its inherent linearity, since it has no ferromagnetic material in the core and thus cannot be saturated.

The output voltage u of a Rogowski coil is proportional to the mutual inductance M between coil and current conductor and to the derivative of current di/dt.

The coil was used with temperature compensation. With suitable resistive loading the temperature effects due to thermal expansion of the coil former and resistance change of the coil winding will cancel each other. In this case adding an 11.2 kΩ compensation resistor leads to less than 60 ppm change in mutual inductance in the temperature range from 16 °C to 40 °C. A test in a temperature chamber confirmed the performance of the compensation method (see above figure).

The linearity of the coil was measured from 12 A to 5600 A in two steps. First, the test current (0.3 A to 9 A) was measured using a calibrated shunt and fed through a 39 turn coil. Effective current through the split-core Rogowski coil under study was from 12 A to 350 A. As a second step, the test current (200 A to 560 A) through a 10 turn coil was measured by an auxiliary coil characterized during the previous step. The effective current through the split-core Rogowski coil under study ranged in this case from 200 A to 5600 A. The coil was found to be linear within 20 ppm from 40 A to 5600 A. The same trend continued down to minimum measured, 12 A, but with increased uncertainty due to the low signal (some millivolts) from the coil.

An ideal Rogowski coil is not influenced by the position of the current conductor through the coil. However, due to imperfections of the Rogowski coil windings, this is not true. For the investigated coil, the difference between the worst case (conductor touching the coil) and the reference one (conductor in the centre of the coil) was found to be less than 200 ppm.

The frequency response of the coil was checked up to 2000 Hz. The resistor added for temperature compensation acts as resistive load to the coil, leading to decrease in effective mutual inductance with increasing frequency. This effect was measured to be about 3000 ppm at 2000 Hz. This systematic influence can be software compensated.

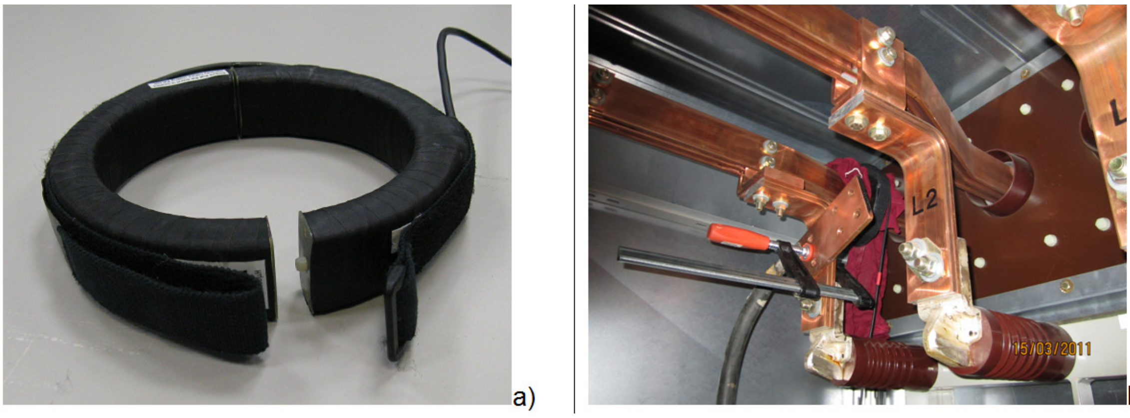
To study the immunity to external magnetic fields, a known current was fed through a straight conductor. By keeping the distance from adjacent current conductors larger than 30 cm, the coupling is less than 100 ppm.

From the investigations performed on the major uncertainty sources of a split-core Rogowski coil, the overall measurement uncertainty is estimated to be 300 µA/A. Lower uncertainties can be reached if the coil is calibrated in the setup, relying on the linearity and low temperature dependence of the coil. As soon as data about long term stability of the sensor becomes available, the interval between successive calibrations of the mutual inductance can be extended, and the uncertainty value probably lowered.

The split-core Rogowski coil can be used for on-site high current calibration up to several kiloamperes with uncertainty which is low enough for the needs of industry. Two on-site calibrations were performed using the Rogowski coil studied in this project.

During these on-site measurements, the Rogowski coil was calibrated against a shunt on the actual setup. The 0.026 Ω and 0.1 Ω shunts used for the purpose are constructed from a set of 1 Ω metal foil resistors connected in parallel. Drift of the resistance value is less than 20 ppm per year. Their measured temperature coefficient is about 4 ppm/K.

Two commercial digitizing voltmeters are used to sample voltage signals from the Rogowski coil and from the shunt or device under calibration. External trigger is generated by a signal generator for simultaneous triggering of the voltmeters and all instruments are controlled by computer. Sampling frequency is continuously adjusted according to the frequency of the measured signals. Measured signals are transformed into frequency domain by FTT, and only the fundamental component is picked out for further analysis. Ratio of the transformer under calibration and its phase displacement are evaluated for the fundamental frequency. No integration is performed for the Rogowski coil signal.



a) b)

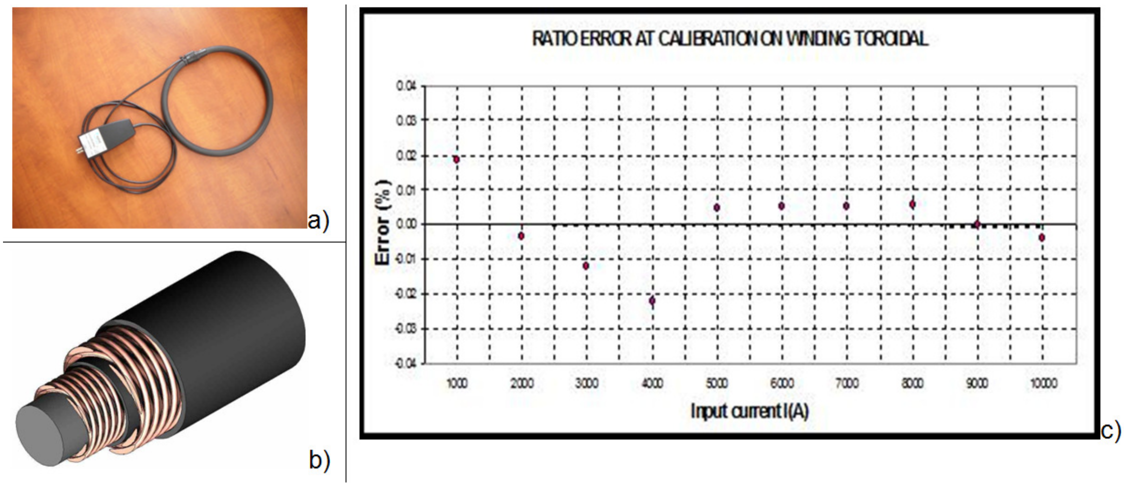
a) Split core Rogowski coil (ID 150 mm); b) Coil installed on a busbar of a medium voltage switchgear.

The above figure shows a detail of the on-site installation during calibration of a current transformer on a medium voltage switchgear where, as often on these installations, there is not much space for connection of additional equipment. The split-core Rogowski coil is installed on a short section of the busbar and is centred onto it as well as possible. An external power source was used to feed the current.

Results obtained show that the split-core Rogowski coil can be used for characterization of current transformers in testing laboratory environment with an overall uncertainty lower than 0.03 % for ratio error, and less than 1’ for phase displacement. Power frequency pick-up from mains was found to cause systematic errors when working on mains frequency. That is, together with difficultly to maintain large enough free distances, the main limiting factor for precise on-site measurements. Uncertainties below 0.01 % and 0.3’ can be reached in laboratory conditions using frequencies other than 50 Hz, when required clearances are met.

The system investigated by SMU is based on an openable and flexible commercial Rogowski coil. The choice of a flexible coil, even if characterised by a lower uncertainty with respect to the rigid one, can otherwise enable its easier positioning on the conductors, when operating in narrow on-site conditions.

The solution studied by SMU makes use of electro-optical transfer of the measured signal and supply, to get galvanic separation of the coil from the measurement unit. The HV current sensor (see (a) in figure below) is based on patented multi-winding technique of Rogowski coil; the sensing coil consists of two wire groups wound in opposite directions on the same supporting core. The shielding wires are individually isolated and interconnected in one single point; this shielding construction eliminates the circular current affecting the sensing coil functionality, but maintains the low impedance needed for shielding functionality.



a) Commercial Rogowski coil; b) coil structure; c) ratio error linearity under calibration with toroidal winding.

Linearity was measured in the current range from 1 kA to 10 kA at 50 Hz. The coil behaviour was investigated by generating homogeneous circular magnetic fields, which simulate the field of an ideal infinite wire, by a toroidal air-core coil. A power source and a standard power and energy meter, were respectively used to supply the toroidal coil and measure the Rogowski coil system output.

Under this configuration the linearity of the system ratio error was found within 0.02 % (see (c) above) and that of the phase error was lower than 0.05°

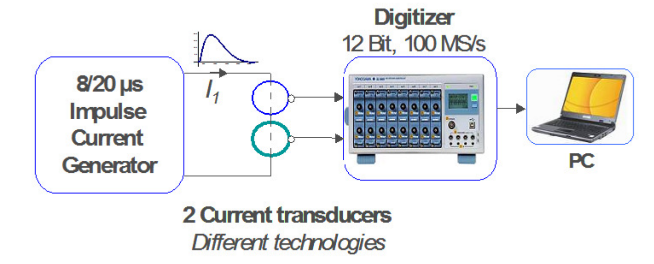
Linearity measurements were repeated by centring the coil on a busbar conductor supplied with a high current source and verifying the measuring system output by comparison with a standard voltage transformer. Higher errors, up to the part per thousand for the ratio error, were found in this condition, because of the perturbing effect due to the current-carrying conductors.

Finally, since in many practical situations the Rogowski coil directly hangs on the busbar conductor, influence of this positioning condition was quantified by rotating the coil over 360°. As expected, the overall accuracy was significantly affected when the coil closing connector was directly touching the busbar, with increase of the ratio errors up to some part in 10^3.

3.4.2 IMPULSE CURRENT AND SHORT-CIRCUIT CURRENT MEASUREMENTS

Developing and characterising measurement setups for high transient and impulse currents at the part per thousand level is very challenging, since there is no reference for the impulse current generator and no continuous characterization of the frequency response of current transducers over a quite extended frequency range can be easily performed. In addition, a number of difficulties arise when generating large currents at high frequencies.

Metrology grade, commercial current transducers have been characterised by LNE for the on-site traceable measurements of 8/20 µs (rise/fall time) impulse currents up to 60 kA peak value, with a target uncertainty of 0.1 %. The combination of high peak values and relatively fast rise times of such currents requires transducers of sufficient dynamic performance, so as not to degrade the shape of the impulse. Among the analyzed current transducers, two of them were chosen, a Pearson current transformer and a Rogowski coil, for their large bandwidth (4 MHz and 1 MHz respectively), rated current range (50 kA) and linearity.



Impulse measurement principle

LNE has chosen to implement a comparison method which relies on the use of two current transducers that detect simultaneously the same impulse current (see figure). This method has the advantage of using different technologies, which do not disturb neither the measurement dynamics due to the transducer principle (inductive transducers), nor the arrangement of the circuit due to the non-invasive connection. In addition, it allows passing over the common factors like impulse generator fluctuations that might considerably increase the expanded uncertainty.

The characterization of the measurement set-up was made according to the recommendations of EN 60060 standard. The dynamic response of the measurement chain was obtained by means of a home-designed current step generator, while the digitizer characterization was performed according to EN 61083 standard. Various aspects related to the influence of the transducer positions in the circuit were measured.

The main challenge was to determine the value or function of the transfer constant of Pearson and Rogowski transducers to be used for impulse current measurement at a certain level and with the target uncertainty of 0.1% for the peak value. To this end, a connection between the dynamic gain and the gain measured at 50 Hz (calibration point) of a transducer was established taking into account the results obtained during the characterisation of transducers, digitizer and measurement set-up, according to the following approach. The transfer constant of the Rogowski coil in a sinusoidal regime and at high level of current (minimum value 5 kA), which approaches the impulse current peak value), is determined by traceable calibration.

The same value is considered for the Rogowski dynamic gain (the transfer constant for impulse currents). Measurements of 8/20 µs impulse currents are performed by using simultaneously Rogowski and Pearson transducers. Once the corrections related to the digitizer frequency response by the bias of a Fast Fourier Transform analysis are applied, the dynamic gain of Pearson transducer is obtained and compared with the value of its transfer constant provided by 50 Hz calibration. The results indicate a dynamic gain of Pearson transducer which is constant within 0.05 % for currents with peak values between 5 kA and 50 kA (nominal range of transducers). The difference between the Pearson dynamic gain obtained by this approach and the value at 50 Hz was 0.08 %.

The characterisation activity performed indicates that the quality of analysed commercial current transducers (commercial ones) allows their use as 8/20 µs impulse standards for measurements up to 60 kA (peak value) with an uncertainty of 0.1 %.

Design and optimization of Rogowski coil for impulse and transient current measurements and improvement of calibration methods have been carried out by CMI.

Software for optimised Rogowski coil design for various cross-sections of core (rectangular, circular and oval) was developed. Based on the design specifications obtained by the developed software, two prototypes of Rogowski coils for measurement of harmonic signals with turn effect correction by return conductor were designed. Measurement at 50 Hz frequency of the coil constant of the built Rogowski coil agreed with values predicted by the design software.


Current loop for the calibration of Rogowski coil up to 30 kA

In the following step, design and realization of a reference Rogowski coil for measurement of 8/20 µs impulses with peak value 2 kA was accomplished and parameters of the reference Rogowski coil were measured in a wider frequency band.

As to the characterisation of Rogowski coil based high current measuring systems, a calibration method was developed which makes use of a current loop up to 30 kA (see the above figure).

Calibration has been performed at 50 Hz by using a commercial current comparator with a standard resistor 0.1 Ω connected in its secondary circuit and two sampling voltmeters simultaneously triggered. Using the current loop shown in the figure, expanded uncertainties from 0.02 % up to 0.034 % were achieved.

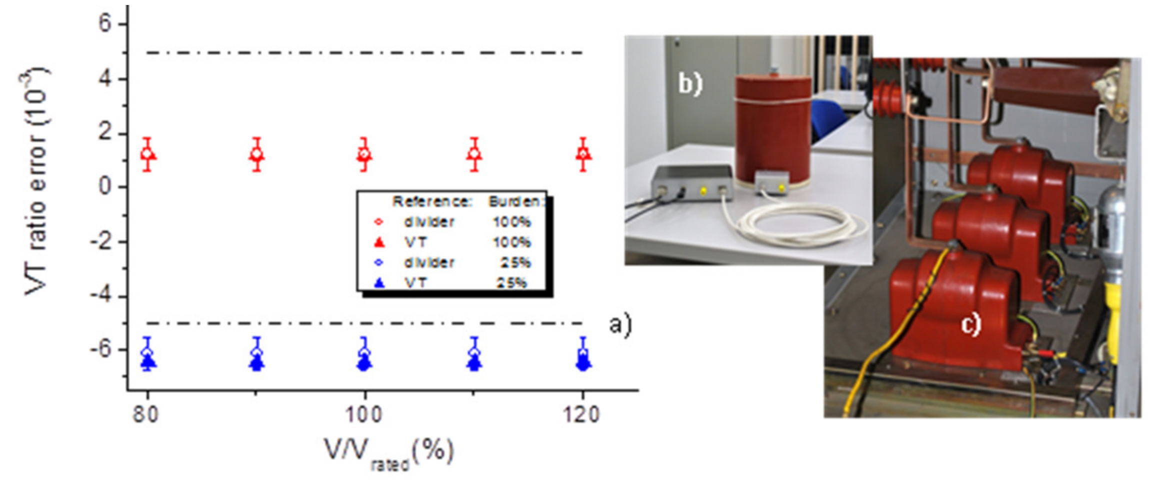
3.4.3 VOLTAGE TRANSDUCERS FOR ON-SITE CALIBRATION

Traceability of MV voltage measurements should be ensured by carrying out on-site calibrations and checks of the measurement transducers over the range of amplitudes and frequencies of interest.

A MV divider has been developed by INRIM as an alternative to the use of voltage transformers (VTs) as measurement standards. It is intended for usage in indoor environment and is specifically aimed at power frequency calibration of substations measurement transformers (typically class 0.2 and 0.5 VTs). The developed transducer is a resistive-capacitive divider, equipped with a two sections cylindrical shield, which allows the control of the capacitive coupling due to the surrounding components and the mitigation of the environmental electromagnetic fields. A circuital model was extensively used in the divider design phase to optimise its dynamic behaviour, taking into account both the component stray parameters and the numerically evaluated capacitive couplings with the divider shield.

The rated transformation ratio of the divider is 30 kV/100 V; the adoption of suitably developed external matching stages allows the further reduction of the overall ratio to levels directly compatible with digitiser inputs (e.g. 30 kV/1 V). With respect to conventional VTs, the divider is characterised by reduced dimensions and weight (less than 10 kg), which make it easily moveable, extended linearity and larger frequency bandwidth.

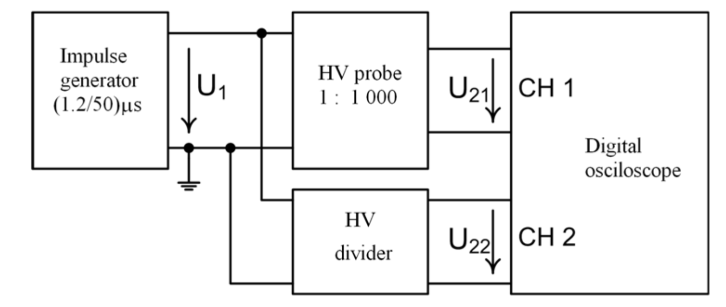
The uncertainty associated with the on-site use of the divider with measurement chain (digitiser and control, acquisition and analysis software) has been evaluated by carrying out characterisation measurements at low and medium voltage. The frequency behaviour was investigated at low voltage up to 10 kHz. Temperature dependence was also investigated in thermal cell over the temperature range 5°C to 35 °C. With the adoption of suitable correction for temperature and linearity, the uncertainties achievable in the on-site calibration of VTs with rated primary voltages ranging from 3.5 kV to 22 kV were found within 0.055% for the measurement of the ratio error and 0.31 mrad for the phase displacement.



a) On-site calibration results: measured ratio errors; b) MV divider and matching stage;
c) 6.3 kV/√3/100 V/√3 VT under calibration.

On-site experimentation of the divider as a reference standard in the calibration of VTs was successfully performed. Two medium voltage inductive 0.5 class VTs, with rated primary voltage 6/√3 kV and 22/√3 3 kV, located in different indoor MV/LV substations, were calibrated according to the procedure indicated by EN 60044-2 standard, generating the needed primary voltage levels by a suitable VT used as a step-up transformer. Both the divider and the VT under calibration outputs were acquired by software controlled commercial digital sampling multimeters. The above figure (a) shows the ratio errors and phase displacements of the 6/√3 kV / 100√3 V VT under calibration (Fig. (c) above), measured by making use of the MV divider (Fig. (b) above). Equivalence is found with the results obtained when repeating the measurements using an INRIM standard VT as a reference. The calibration results highlighted in particular, that, in the lower burden conditions (25 % of the rated one), the VT was no longer compliant with the performance specification relevant to its rated accuracy class.

The results obtained in the experimentation confirm that the developed transducer and associated measuring system can be conveniently used in the on-site calibration of 0.5 and 0.2 class transformers, typically installed in the measurement board of the MV/LV substation switchgears. Its features make its use promising in the test of VTs in presence of harmonics, and for direct measurements of power quality parameters on the MV plants.



CMI Impulse method for HV divider calibration

CMI activity was focused on the development of calibration procedures for HV dividers in the frequency range up to 20 kHz. Several methods for HV and MV divider calibration were developed and experimented.

For calibration of HV dividers at 50 Hz two different calibration procedures were proposed and implemented. First, the instrument voltage transformer and digital sampling multimeters were used for calibration of HV divider. Second, the HV divider calibration was realized by means of the instrument voltage transformer, inductive voltage divider and lock-in amplifier.

For calibration of HV divider at wider frequency range by means of impulse measurement (see figure), generated kilovolt impulses were applied to the reference HV probe and the HV divider under calibration and the output voltages were compared using FFT mode of the dual channel digital oscilloscope.

3.5 A HARMONISED METHODOLOGY AND IMPLEMENTATION OF THE TRACEABLE MEASUREMENT OF POWER QUALITY PARAMETERS

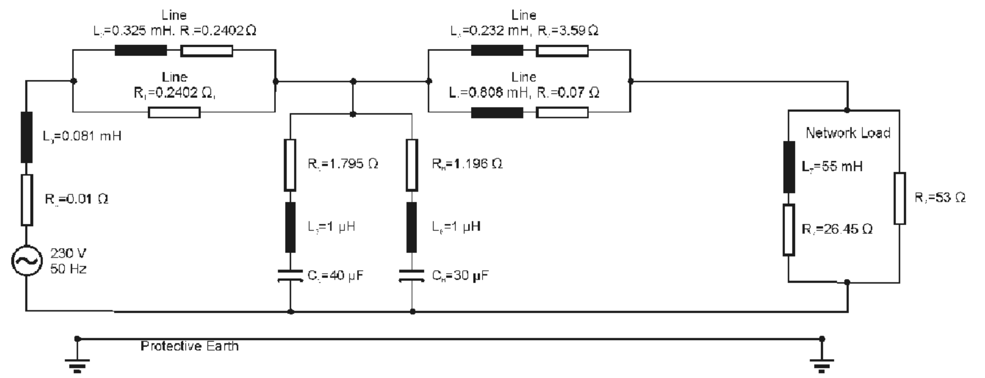
This Section describes the integration of the technologies described in Sections 3.1 to 3.4 into a measurement system and the demonstration of its use in on-site tests. This includes a study of the role of the network impedance and how it influences on-site power quality measurement and the formulation of an uncertainty framework for the measurements.

In addition, to support the regulatory regimes that ensure a high quality electricity supply, an EU wide protocol for the calibration of power quality analysers was formulated to ensure a consistent harmonized approach in laboratories throughout Europe.

3.5.1 INVESTIGATE FINITE BUS IMPEDANCE EFFECTS ON PQ PARAMETERS.

A number of power quality parameters measured on the network will be influenced by its impedance at the point of measurement. This is of great importance as the assessment of the power quality of grid connected generators or loads at a given point in the network may not be valid at another location or time where the network impedance and overall power quality have changed. As such it is necessary to have a quantifiable grasp of the influence of the network impedance on power quality measurements and their uncertainties. In some cases it may also be necessary to measure the network impedance in cases where the uncertainty may be too high. This work is therefore separated into two parts. The first task is to create models of typical electricity networks and to use these models in simulation to assess the sensitivity of various power quality parameters to changes in the network impedance. The second part of the work is to investigate methods of measuring the grid impedance.

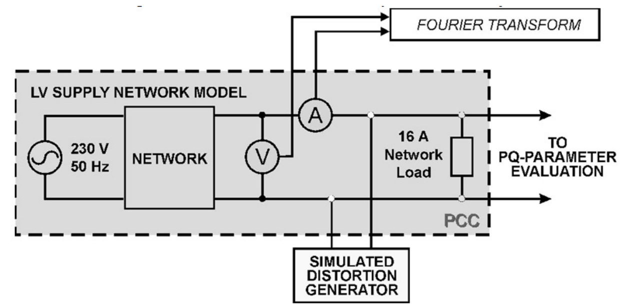
A mathematical model of the electrical grid was developed and implemented in MATLAB such that the effect of various perturbing loads could be modelled to assess the effect of the finite network impedance on various power quality parameters over the operating frequency range. The models were refined in light of the initial runs to better represent expected behaviour based on reports and power quality and network standards. The chosen network model is shown in the Figure.



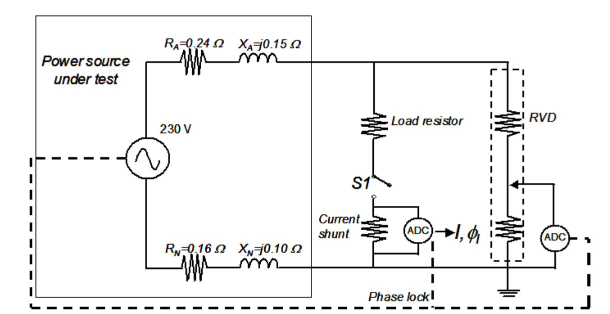
Network Model

The influence that small changes in the magnitude of the network impedance may have on the spectral distribution of the non-sinusoidal current was studied using the simulated setup illustrated in the following Figure.

The effect of a 10 % mains impedance variation on the harmonic structure of the current drawn by various loads was then assessed up to 9 kHz. A similar experiment was conducted to assess the effect on voltage fluctuation which is the key component of Flicker. Overall, the results show a significant dependence of power quality measurements on the network impedance. A 10 % change in network impedance can cause a change of 1 % or greater in some power quality measurements, e.g. of current and voltage harmonics, power and flicker. This is significant in terms of the final uncertainties for on-site measurements and a method of measuring the network impedance would provide greater confidence in these power quality measurements. The impedance measurement would allow a sufficiently accurate uncertainty evaluation or enable a correction to be applied.



Simulation set-up for assessing effect of network impedance on harmonic distortion



Impedance measurement circuit

The results of this work emphasises the importance of network impedance measurement. This is an extremely challenging task and beyond the scope of this project to completely implement and test. Therefore, a laboratory based method that could also be used for the calibration of power sources used in flicker compliance testing was developed as a proof of concept that may be applied to network impedance measurement with some further work.

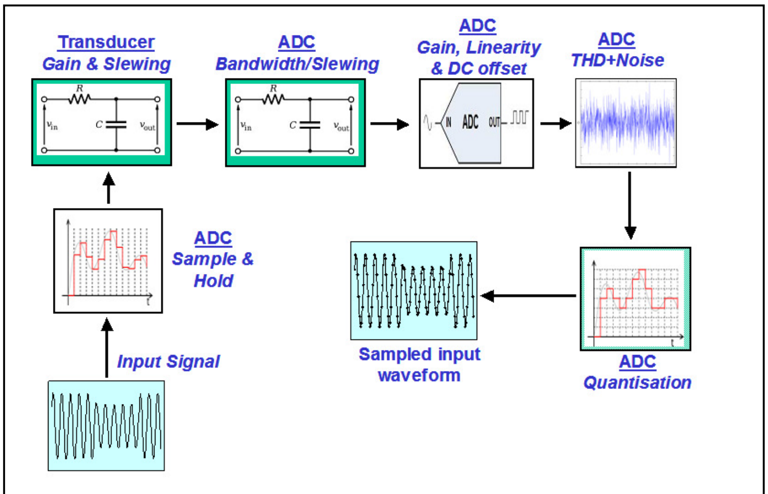
Out of the candidate methods that were investigated, the most promising was implemented and is now ready for use in the laboratory for routine power source calibrations. The method relies on measurements to determine the voltage output of the power source under test when the device is driving a load and when in open circuit condition. The resistance, *R*, and reactance, *X*, of the power source can be calculated from analysis and measurements on the test circuit shown in the figure.

The method has been tested against alternative low power impedance methods and agreement was achieved within 200 ppm, well within the target uncertainty of 500 ppm for flicker compliance test power source impedance measurement. With some further work the method could be adapted to grid impedance measurement.

3.5.2 DEVELOP AN UNCERTAINTY ANALYSIS METHODOLOGY TO DETERMINE THE PROPAGATION OF MEASUREMENT ERRORS THROUGH POWER QUALITY TRANSFORMS.

Many power quality measurements involve complex parameters and require complex measurement systems, algorithms and waveform transforms to convert digitally sampled data into meaningful quantities. Assigning uncertainties to these quantities is a challenging task and cannot be achieved by simple calculations using linear equations. As such a framework for analysing the propagation of measurement uncertainties through waveform transforms and algorithms is required.

The first stage of developing this framework was to build a model of the data acquisition process. Using this model, uncertainties can be assigned to all variable aspects of the process and the non-linear relationship between these input quantities and the final power quality parameters can be studied. A diagram of the model is shown in the Figure. The various potential contributions to measurement uncertainty in a typical digital sampling system are included in the model and estimates were made of the uncertainty contribution of each.



Model of the data acquisition process

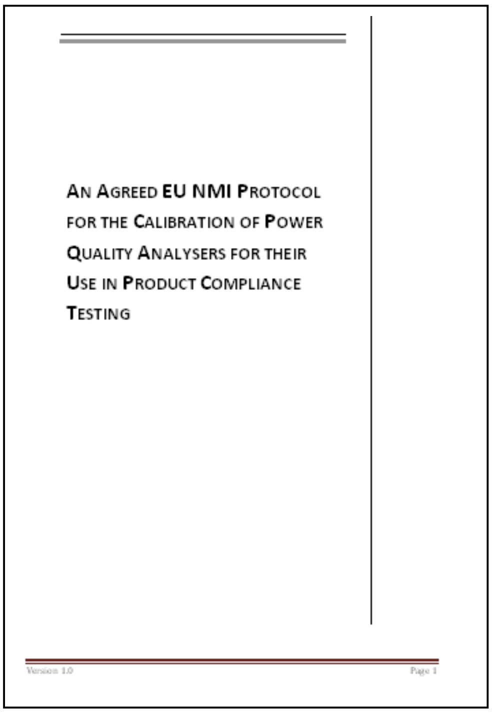
A demonstration of the use of the model in uncertainty evaluation was carried out on flicker measurements. Flicker perceptibility is a complex non-linear quantity that is intended to reflect the amount of irritation a typical human would experience if subject to a given amount of light flicker. It is not possible, or at least extremely difficult to assign an uncertainty to such a quantity using a standard analytical approach. A monte carlo calculation was therefore performed in which distributions were assigned to each of the model input quantities and these were varied in simulation to provide an input to a model of a standard flickermeter. A number of trials were run in which a value was chosen for each input quantity within the assigned distribution and range. A standard deviation of the resulting flicker readings was then obtained, which can be used to give a final uncertainty estimate.

It was found that the final uncertainty was heavily dependent on the type of input waveform, an important result with potential implications for flickermeter users, manufacturers and calibration laboratories.

Although effective, this method of uncertainty evaluation can be computationally intensive and time consuming. A more refined method employs Bayesian inference (described in Section 3.3), since probability density functions underpin estimations of functional parameters defined by the user as in regression analyses. This task is thus intimately related that described in Section 3.3. Bayesian inference is of considerable mathematical complexity and the assessment of uncertainties demands elimination of parameters (so called “nuisance” parameters). The same probability density function employed to estimate parameters of a functional relation is approximated by a Taylor expansion around the “modes” (peaks). Integration of this probability density over all frequency estimates allows a “noise” variance to be numerically estimated. From noise estimation, a variance for each frequency may be computed and from the model, covariances for the estimated amplitudes are found, leading to uncertainties of magnitudes.

PTB have developed software for spectral analysis with uncertainties using Bayesian Analysis.

3.5.3 HARMONIZATION OF METHODOLOGY AND VERIFICATION MEASUREMENT OF PQ PARAMETERS.



AN AGREED EU NMI PROTOCOL FOR THE CALIBRATION OF POWER QUALITY ANALYSERS FOR THEIR USE IN PRODUCT COMPLIANCE TESTING

Version 1.0 Page 1

Power Quality Analysers are used by EMC Testing Laboratories for the type-testing of electrical appliances (consumer and professional goods) to ensure their compliance with IEC/EN standards on harmonics and flicker. Failure of these type-tests will prevent the sale of the given product in the EU.

Power Quality regulations are pan-European, however compliance type testing and enforcement to date has been implemented at a national level. Individual National Measurement Institutes are required by their national industry and accreditation bodies, to provide power quality traceability in support of this type testing. In view of this joint European interest in underpinning EU regulation, it is important to avoid the scenario where NMIs work individually to provide national traceability solutions.

The purpose of this work was to agree amongst the participating partners a methodology for the calibration of Power Quality Analysers. The scope of the work was limited to those analysers used for laboratory compliance testing, particularly harmonics and flicker.

The work resulted in a protocol document presenting a 25-page calibration methodology, agreed by a consortium of EU NMIs, which will ensure a harmonized approach to the calibration of Power Quality Analysers across the EU.

3.5.4 DEVELOPMENT OF MOBILE REFERENCE MEASUREMENT SYSTEMS FOR THE DISSEMINATION OF TRACEABILITY FOR POWER LOSS AND POWER QUALITY PARAMETERS TO GENERATION AND MANUFACTURING SITES.

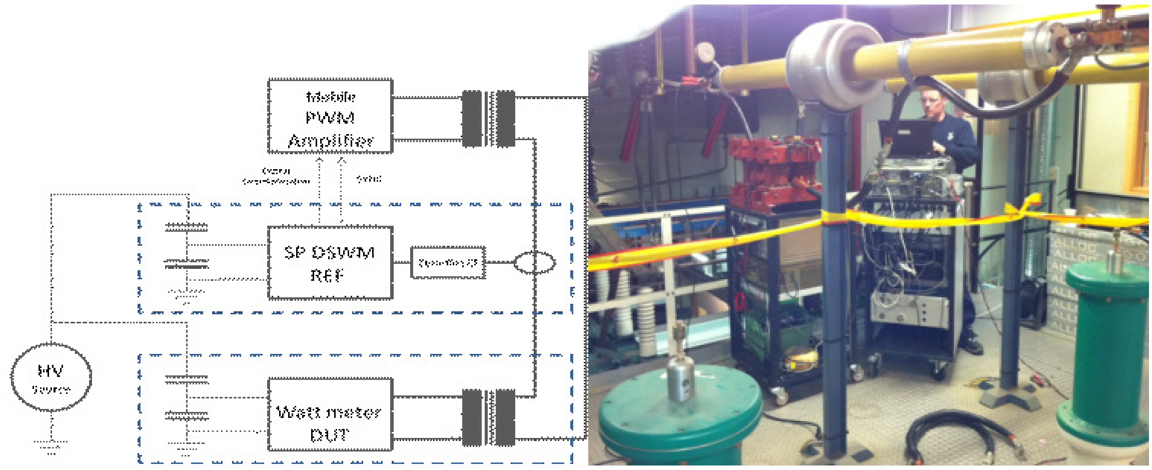
On-Site Power Loss

Producers of large electric equipment, like electric motors and transformers, often have advanced measuring equipment to verify the performance of their products. It is of vital importance that the measurements are correct because of the large investments going into the products. Accurate measurements at very low power factor are both important and complicated to do. For large power transformers the power factor can be as low as 0.01 or even less. At this operating point both currents and voltages can be relatively high, but the active power (losses) is very low. For example, to verify if a design change of a product has been successful it is vital to be able to trust the measurements. The loss power measurement system has to be properly calibrated.

A typical power measurement system consists of one Voltage Transducer (VT), one Current Transducer (CT) and one power analyzer per phase. In high voltage applications the measurement system is often built into the facility requiring on-site calibration. It is relatively straight forward to calibrate the VT:s and CT:s separated from the system to verify their individual performance, but a total system calibration is more complicated and require a more sophisticated method. The voltage is usually at a very stable operating point and does not change much. The current on the other hand has to be varied in a wider span, both in amplitude and in phase relative to the voltage during a calibration.

One method to make a system calibration is to use the voltage available on site and create a phantom power by producing a current with the correct amplitude and phase through the CT. This current can be injected by disconnecting the CT under test from the main voltage and connect the CT to a separate circuit feeding the CT with a controllable current. This current can be generated with a power amplifier that both control the amplitude and the phase relative voltage of the current.

The schematics below show the connection being used for the calibration of one phase. The picture shows an on-site calibration.



An On-Site Power Measurement at Low Power Factor.

The calibration setup involves the Device Under Test (DUT) that is normally built in to the facility, and the reference system (REF), that is brought to the facility for the calibration event. The VT:s of the two systems are connected to the same voltage source (left side) and the current is fed in series through the CT:s of both the DUT and REF. This setup ensures that both the DUT and REF are sensing the same voltage and current. The current is produced by an amplifier that is controlled from the reference system. With this setup it is relatively easy to sweep through a wide range of current amplitudes and power factor in a short time.

The developed system was used for an on-site calibration of a loss power measuring system in a power transformer factory. This calibration spanned a voltage range of 20-40 kV, a current range of 10-1500 A and power factor range of 0,01 to 0,9 and was able to reveal new systematic errors not previously revealed by component calibration.

On Site Power Quality Measurements

Demonstrating the capability of making an on-site power quality measurement was the culmination of many strands of this project.

Site Measurement in substation: Fitting Rogowski coil to a live bus bar

NPL carried out a full system test of the digitizer, transducers and algorithms as described in the previous Sections in two on-site measurements, one at a local substation and another in a substation in Northern England. The later site was chosen as it was associated with a distribution network operator who has a high mix of renewable energy sources and this measurement was part of the process of gaining the confidence of the DNO prior to future measurement campaigns. The sub-station in question was of interest because it was connected to a combined heat and power plant capable of exporting to the grid.

Prior to the measurement extensive preparation work was required in order to meet safety and EMC codes required by the DNO. This entailed modification to the NPL digitizer to meet various standards and to comply with EN61010 required for safety. Overvoltage protection boxes were constructed to protect the personnel and the instrumentation should faults on the network occur.

It is intended that the instrumentation be left to monitor the networks for a prolonged period (c 1 month) to detect any PQ events and monitor general trends. Such test result in huge data sets and a general desire to monitor the instrument remotely and download data as the tests continue led to the implementation of mobile communications systems with the instrument. Both GSM 2G and 3G connections were fitted enabling remote monitoring and configuration, uploads of new software as required and downloads of data.

An initial week test in a local substation was carried out in order to gain confidence and check the equipment and communications. Many lessons were learned from this test. Following this test the equipment was taken to the sub-station in Northern England and a further test performed.

The NPL software used asynchronous sampling to measure an extensive range of power and power quality parameters many of which are described in earlier Sections of this report. Results were logged every 0.2 seconds continuously over the test period.

This work has taught us many lessons; not least the significant underestimation in effort required getting ready for tests of this nature. The capability developed here is now ready for a planned eight different measurement scenarios as part of the new metrology for SmartGrids EMRP project. It is also hoped that it will form the basis of a commercial measurement service.

4. ACTUAL AND POTENTIAL IMPACT

4.1 SCIENTIFIC IMPACT

These challenges of on-site power loss and power quality measurements particularly associated with renewable technologies have been the catalyst for this JRP and the development of the new measurement infrastructure required to support these technologies. This will enable the future SmartGrids that will be used to integrate renewables into the electricity distribution network. In contrast to the state-of-the-art prevailing at the project's inception which consisted of lab-based measurements of sinusoidal ac signals, the next generation of power and energy measurements will be made directly at generation and distribution sites and will involve the accurate measurement and analysis of complex wave shapes. The infrastructure for these measurements has been the main scientific outcome of this JRP. The scientific outcomes are described in a high level of detail in the previous Section of this report.

Providing this infrastructure is a significant technical challenge; designers of new technology such as wind-turbines or low-loss transmission equipment will require in-situ power loss and generation efficiency measurements. Complex, non-stationary waveforms are implicit to present and future power quality normative standards and new techniques are required to underpin a EU regulatory framework that oversees the multi-billion Euro markets for electrical goods and power generation. These developments will represent a radical departure for ac power metrology involving measurement and signal analysis challenges that will require novel solutions within a metrology framework.

The scientific outcomes are described in a high level of detail in the previous Section of this report. Some of these scientific impacts are summarized as follows:

- Wide-band power measurements capabilities which can be used to measure the efficiency of low energy lighting products.
- Calibrations and methodologies to underpin the regulatory regime for the type-testing of almost all domestic electrical products in the EU.
- On-site power loss measurements of transmission and distribution equipment leading to lower losses.
- Calibrations associated with the revenue metering of electricity.
- On-site power quality measurements of renewable energy installations and technology
- Project outcomes are essential to future metrology for SmartGrids and High Voltage DC distribution systems.
- 24 peer reviewed papers which will be cited and influence future research work.
- World leading design development knowledge of precision current and voltage transducers.

4.2 SOCIO-ECONOMIC/POLICY IMPACT

Society demands energy supplies that are secure, sustainable and of high quality. In the next decade, Europe is facing potential energy shortages as oil and gas supplies run down and nuclear power facilities age. Pressure to reduce the green house gas emissions will lead to a requirement for more renewable energy generation, efficient appliances, energy management and improved electricity distribution efficiencies. Commerce will demand an electricity supply of the highest quality, free from momentary voltage interruptions or interference sources. The EMRP2007 describes these demands and requirements as part of the "Energy Grand Challenge" for European metrology in the coming years.

Policy makers have sought to meet the environmental and energy gap challenges by actively pursuing renewable technologies and encouraging the upgrade in electricity network infrastructure that is required to integrate them into reliable and effective use. This project cannot claim to have developed these multi-billion euro technologies, however the role of the metrology it has developed is crucial for manufacturers and network operators as these technologies start to be adopted and information is sought on their behaviour, efficiency and reliability.

Poor quality of electricity supply has a significant financial impact and can in extreme cases lead to localized power failure that can have obvious social consequences. Regulation to ensure high quality electricity supply by the EU cites domestic electrical appliances and the performance of generation equipment to ensure that these devices meet emissions limits. Such limits can only be assured through measurement and the developments and infrastructure developed in the JRP have been central to underpinning this regulatory regime and informing the standards making process regarding the development of new norms.

Accurate revenue metering of electricity has clear economic importance. As electricity networks become distributed and less centrally controlled the number of parties enacting transactions will increase significantly. The accurate development of transducers and digitizers in this project will become key infrastructure in providing traceably for metering at the highest level.

4.3 MAIN DISSEMINATION ACTIVITIES

A key dissemination element in the project is a User Committee (stakeholders who are not partners in the JRP), to which there are some 15 instrument manufacturers, electricity companies, wind turbine manufacturers and testers, and IEC technical experts have committed their membership. Throughout the project the user committee has assured focus of the project on the customer needs and assure a timely and smooth take-up of the project results. Working together with this committee, this project has developed and disseminated a metrology infrastructure consisting of equipment designs, algorithms, procedures and techniques that will enable NMIs to meet the needs of the power and energy industry.

Several members of the User Committee regularly attended project meetings and took part in the planning of the project work packages.

On-site measurements to verify the performance of transducers, measure grid power loss and on-site power quality have all involved close cooperation and support from User committee members and other industrial contacts that have made their sites available. Ultimately these partner organizations have benefitted from these early results in return for the time they have put in to supervising and ensuring the safe working of project members whilst working on their sites.

A key dissemination activity for the project was a 2 day workshop attended by 75 delegates from industry and national laboratories. This workshop was a showcase for the project outputs and an opportunity to discuss the future applications of this work to on-site power and energy measurements. The workshop included discussions, oral presentations, a poster session and an exhibition of instruments from project members and commercial instrument manufacturers. The project web site contains a hyperlinked agenda of all the presentations and posters. It is an excellent resource for anybody wanting to view the details of the project outputs. The web site can be viewed here: http://projects.npl.co.uk/power_energy/meeting.html

The scientific results originating from tackling the indicated technological challenges will be primarily disseminated through scientific publications in peer reviewed journals and through presentations at conferences and workshops for specialists in the field. The project was highly successful in this aim resulting in 24 peer reviewed journal publications and at least 124 other dissemination activities (conferences, workshops, presentations). See the “Use and dissemination of foreground report” for further details.

4.4 EXPLOITATION OF RESULTS

It is envisaged that the results of the project will be exploited in the following ways:

- Measurements Services (laboratory and on-site)
- Design of new hardware and software in the next generation of commercial power / power quality instrumentation

- Sale of complete instruments / transducers
- Consultancy and advise to industry

New and enhanced *measurement services* have resulted particularly in the area of power quality. Power quality analysers are used to underpin regulation for domestic electrical appliances in the EU. This is a multi-billion euro market and errors in conformance testing can be highly expensive to manufacturers of high volume electrical goods which could miss their time to market due to an erroneous test. Conversely the value of the hugely valuable electricity network protected by this regime is put at risk if the tests erroneously pass poor equipment. Consequently calibration has real significance and new service to calibrate these instruments will be offered by several of the project partners using the technology, protocol methodology and guidelines developed in this JRP.

Furthermore we anticipate the development of *on-site measurement services* where the portable apparatus developed in this project will be used to assess the power quality of new designs of renewables on test sites or when actually installed. Manufacturers are clearly interested in the performance of their designs both in term of PQ and the efficiency of operation under real conditions. Network operators are also concerned at the effect of new generators such as renewables when connected en mass to their networks. The facilities developed in this JRP will be highly valuable in answering these questions.

Some excellent state-of-the-art instrumentation has been developed as part of this JRP. Some partners will make their instrument available commercially. The shunts and precision voltage dividers are of the highest precision available and are of interest to other NMIs and top end laboratories. The portable dividers for MV use are also of significant interest. The digitizers are also highly marketable and NPL plans a second version of their instrument suitable for volume production. Algorithms also have commercial value and one such asynchronous sampling algorithm has been protected by patent by PTB.

4.5 PROJECT WEB SITE

This can be viewed at: http://projects.npl.co.uk/power_energy