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Characterised measuring system for PQ measurements on the MV grid

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Abstract- The features of a Power Quality measurement system which includes both voltage and current transducers and a self-developed measuring instrument are described. The system is intended for measurements in substations at medium voltage level. A Rogowski coil and a voltage divider are the used transducers, whereas the measuring system is based on a Reconfigurable I/O-FPGA system with embedded software. Attention is focused on the procedures adopted for the characterisation of the current sensor, which is carried out taking into account the expected on-site measurement conditions, allowing reduction of the measurement uncertainty of nearly an order of magnitude. An example of use of the measurement system in a private substation that connects an industrial load and two photo-voltaic generation plants to the public MV voltage network is presented, together with the associated current uncertainty budget.

I. Introduction

The measurement of the quality of the electrical supply is today gaining more and more attention, since its accurate evaluation is crucial for the assessment of the compliance to the limits indicated for public distribution networks, the identification and location of disturbances and the verification of the impact of newly connected distributed sources [1-3].

As to the power quality (PQ) measurement systems, attention is generally mainly focused on the performances of the measuring instruments. Test procedures, expected performances and uncertainties are prescribed for the measuring instruments in the relevant standards [4, 5]. When dealing with PQ measurements in medium and low voltage grids, reduction of current and voltage level is needed. In most cases, the instrument transformers already available in the measurement site are used for the current and voltage reduction, even if their use for the measurement of PQ events can be not completely satisfactory [6]. As an alternative, non-conventional transducers are more and more considered, because of their better performances as regards linearity and frequency response and the low level power output [7-10]. Indications for the measurement uncertainties of transducers used in PQ measurements are given in [6, 11]: the percentage error has to be within 1% of the measured value for the first and second harmonics and within 5% for the higher order ones.

The paper deals with a system for PQ measurement at medium voltage (MV), which makes use of a voltage divider and a Rogowski coil (RC) as transducers and is completed by a measuring instrument based on a NI Compact Reconfigurable I/O programmable automatic controller platform. The use of an openable and flexible coil for the current measurement enables its positioning in harsh and narrow sites, where measurement conditions quite far from the laboratory ones are met, without need of power circuit disconnection and/or outage. However, the same features, flexibility and presence of a coil turn gap, make the sensor more sensitive to perturbing effects and less accurate with respect to rigid, closed coils, with consequent expected measurement uncertainty of the order of the percent or higher. Attention is then focused on the characterisation procedure of the current sensor that, if carefully performed under conditions that reproduce the experimental ones, can allow the decrease of the on-site measurement uncertainty and make possible its use in compliance with the given accuracy limits [6, 11]. Application of the system to PQ measurements in a private MV/LV substation, which supplies an industrial load and is connected both to the public supply network and to Photo-Voltaic (PV) generations plants, is finally shown.

II Measurement system

The scheme of the measurement system (single-phase measurement configuration) is shown in Figure 1a. The MV voltage is reduced by a resistive 24 kV voltage divider developed at INRIM, with 10000 transformation ratio and 1 MΩ rated load, equipped with a 10 m coaxial cable.

The current transducer is a flexible and openable RC, manufactured by Rocoil Ltd, with 125 mm diameter, connected by its 5 m coaxial cable to the associated three channel integrator with selectable transformation ratios from 100 A/V, to 100 kA/V (Figure 1b).

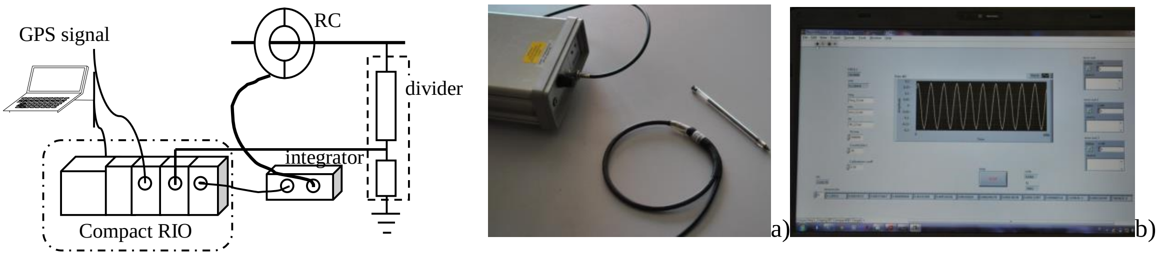


Figure 1. a) PQ measuring system scheme; b) RC coil ($\Phi = 120$ mm); c) control panel.

The transducer voltage signals are digitized and recorded by a NI Compact Reconfigurable I/O (NI Compact RIO) programmable automatic controller platform, which includes a CRIO embedded real-time controller with a 4 slots reconfigurable chassis, equipped with a user-programmable FPGA. Two 16 bit A/D cards 10 V, 1 MS/s/ch, a GPS timestamping and synchronisation module and two SD cards for data recording (Figure 1c) complete the assembly. The NI Compact RIO platform and the acquisition and elaboration strategy are shown in Figure 2. The quantities of interest (frequency, rms value, harmonics, THD,..) are evaluated according to [4, 5]. Different time aggregation starting from 3 s can be user selected, as a function of the measurement approach, and saved.

III Sensor characterisation

The on-site operating conditions are generally quite different from those taking place in laboratory during system calibration and can significantly affect the performances of the sensor as a function of its construction characteristics. In particular for openable RCs, the path of the primary and return conductors, the presence of external magnetic field sources and the non-orthogonality of the coil with respect to the primary conductor can lead to a considerable variation of the coil mutual inductance, whose amount depends on the sensor characteristics and construction solutions [12].

To investigate the sensitivity of the used coil to influence and perturbing factors and predict their effect on the expected measurement accuracy, an extensive characterisation of the coil with its integrator is performed in laboratory, under configurations similar to those expected on-site. Characterisation of the current sensor, whose rated accuracy is of the order of the percent, includes: calibration at power frequency and determination of the transformation ratio; linearity over the expected measurement range; frequency response determination, evaluation of return conductor proximity effects and perturbing source presence, estimate of the temperature effects.

All the measurements are carried out by centering the coil by a rigid, but easily moveable conductive support to limit the uncertainty contribution due to coil positioning. Considering the small coil dimensions, both the shape of the primary conductor and its diameter are chosen similar to that of the plant MV cable. Calibration at power frequency and linearity tests are carried by generating currents in the range 1 A to 100 A by a transconductance amplifier supplied by a stabilised generator. The current value is obtained by measuring, the voltage across a calibrated non-inductive shunt (Tinsley Standard 0.05 Ω resistor). Acquisition of the reference and RC signal is carried out by two synchronised Agilent 3458A multimeters. Deviation of the measured RC ratio from the rated one is within $6 \cdot 10^{-4}$ when the return conductor is 30 mm distant from the coil loop. A quite systematic increase of $+1 \cdot 10^{-3}$ is found when the acquisition system is included in the measurement chain for currents higher than some amperes. A fairly linear decrease of $2 \cdot 10^{-4}$/A for currents lower than 10 A is found, due to the low value of

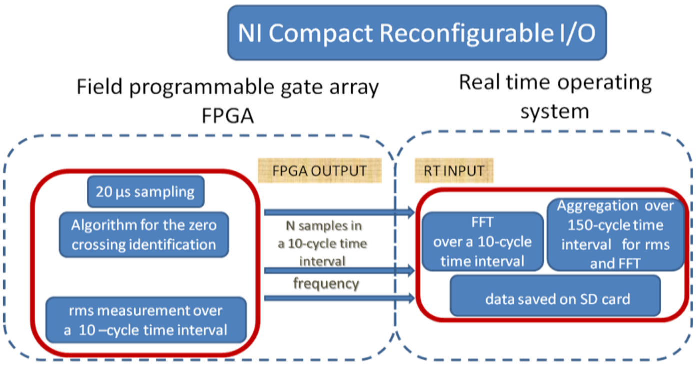


Figure 2. NI Compact RIO platform and adopted acquisition and elaboration scheme.

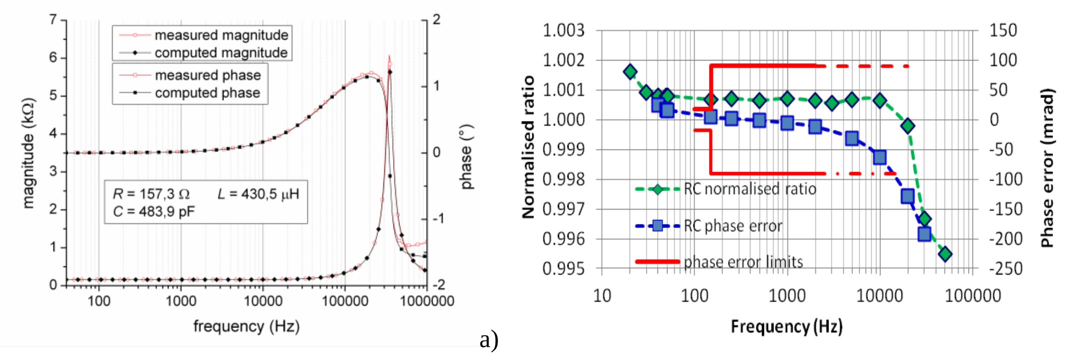
the digitiser input voltage.

The impedance magnitude and phase versus frequency of the only coil are first investigated by an Agilent 4294A impedance analyser. Figure 3a compares the measured behaviours with those obtained by considering a simple RCL coil model. The resonance frequency is around 300 kHz. The frequency behaviour of the RC and its integrator with the connection cable is then measured in the same circuit used for linearity evaluation, where the reference resistor for current measurement is a Guildline 7320 AC shunt, whose AC/DC difference is within 200 ppm at 10 kHz. Evaluation of the RC phase error is done exploiting the digiting features of the Agilent multimeters configured in SubSampling mode. Since the system is intended for use in sites where a wide harmonic spectrum is expected (e.g. PV generation), measurements are carried out up to some tens of kilohertz. Figure 3b shows the RC ratio, normalised to the rated one, and the phase error measured over the range 20 Hz to 40 kHz with the return conductor 35 mm distant. Limit values given by [11] for the phase are shown for comparison.

Measurements are repeated by varying the minimum distance of the return conductor from the coil loop from 30 mm to 200 mm. RC ratios normalised to the rated value are shown in Figure 4a, for two distances *d* of the return conductor (conf. i) 30 mm and ii) 200 mm) with the coil gap external to the current loop (Figure 4b). The behaviour measured with the gap internal, when the distance is 200 mm (conf. iii), is also shown. A quite constant deviation of about $3.2\cdot10^{-3}$ is found between conf. i) and conf. iii).

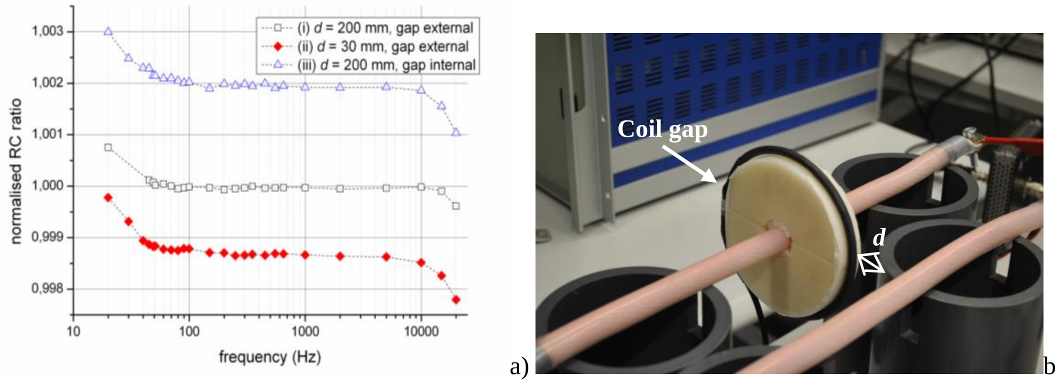
Finally, the influence of external magnetic field sources is investigated by measuring the coil stray signal induced by a current flowing in a conductor external to the coil loop, placed at increasing distances *D*.

As regards the voltage sensor, scale factor and linearity of the divider are measured at 50 Hz at MV by comparison with a reference measurement voltage transformer, by reproducing the on-site measurement divider arrangement as described in the next section. The frequency response is investigated at low voltage (600 V) from DC to 90 kHz. The divider ratio error complies with the standard requirements up to 1.3 kHz; for higher frequencies the correction of its behaviour according to the method described in [13], can allow optimisation of its frequency behaviour.



a) b)

Figure 3. Measured RC magnitude and phase versus frequency: a) RC coil; b) RC coil with integrator (current 5 A, distance from the return conductor 35 mm).



a) b)

Figure 4. a) RC with integrator frequency behaviour (magnitude) for various distances *d* from the coil (ratio values normalised to the rated one); b) Positioning of the coil around the primary conductor

IV On-site measurement

As a first application, the developed system is used in a 15 kV/400 V, 70 A MV/LV private substation, connected to the public MV network, which supplies a factory with two PV plants. The private network can absorb up to 800 kVA from the Distribution Network Operator (DNO) and supply up to 1 MVA.

Measurements are performed at MV level after the protection circuit-breaker of the 800 kVA PV plant. Since connection of the divider to the MV busbars cannot be made inside the switchgear, the transducers is inserted into a grounded metallic box to ensure safety insulation of the divider and the MV connection is made by an insulating bushing.

The RC is centered and fixed around the insulated MV cable, by the same support used during its laboratory characterisation (Figure 4b). The coil is rotated so that its gap is opposite to the other supply conductors, which are about 80 mm (*d*=30 mm) distant from its center. Current rms value, harmonics and total harmonic distortion (THD) are recorded with a 150-cycle aggregation time. Figure 5a shows the current variations over 8 hours in a sunny autumn day, and the relevant waveforms and THDs. The measured current is quite constant around 20 A, but it fast reduces with the decrease of the solar irradiance [14]. The measured THD is around few percents for the highest current values, but increases up to 10% when the current reduces. Figure 5b shows the same relevant quantities measured the following day under cloudy conditions. Table I gives the measured harmonic content of the currents shown in Figure 5c and 5d respectively. Only the 5th harmonic component is found higher than 1% of the fundamental one, for the Figure 5c behaviour. Values from 1.2% to 5.5% are found for the 3th, 5th, 11th and 7th for the most distorted and lower current of Figure 5d.

The uncertainty budget for rms current values from 5 A to 30 A is shown in Table II. It is evaluated taking into account the calibration uncertainty of the assigned RC coil ratio and associated measurement system (acquisition and evaluation system), its linearity, the effect of the other MV conductors and that of the plant LV conductors. Two estimates are presented: in the first case, a more conservative evaluation is given (A), whilst the second one is performed considering correction factors and uncertainties relevant to the specific measurements conditions, evaluated taking into account the characterisation carried out as detailed in the previous sections (B). The resulting uncertainty (95% coverage level) reduces from 2% to 3.5 part per thousand.

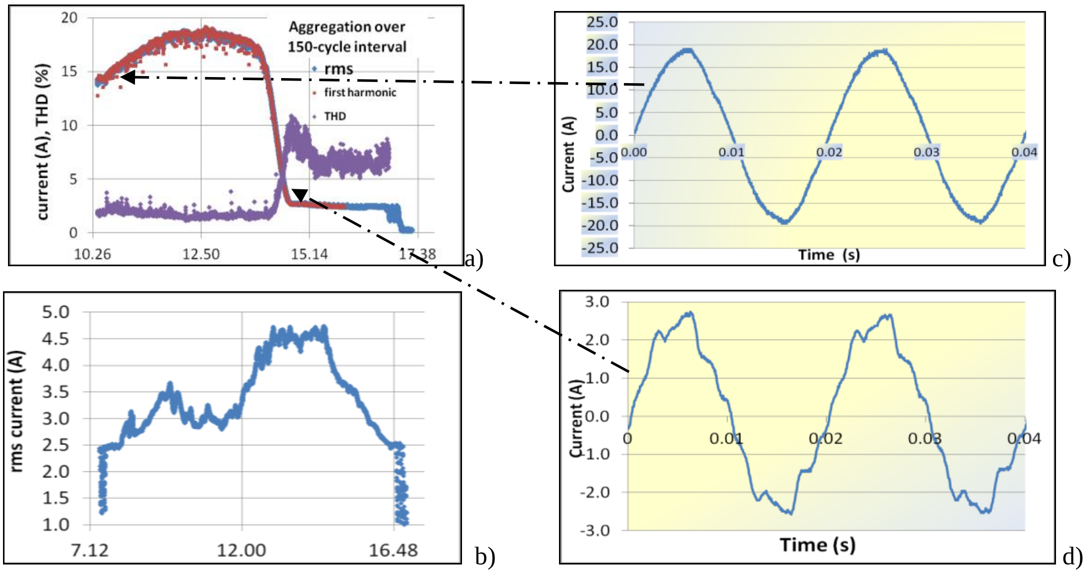


Figure 5. Measured rms current, THD and first harmonic over 8 hours in a sunny (a) and in a cloudy day (b);
c) current waveform recorded in the central hours of the day;
d) current waveform recorded before sunset.

Table I – Current harmonics

	Current harmonic order								
	1	3	5	7	9	11	13	15	17
% of the fundamental	100	0.57	1.44	0.51	0.15	0.62	0.29	0.13	0.16
	100	1.21	2.44	5.3	0.38	3.43	0.54	0.02	0.95

Table II– Uncertainty budget (rms from 5 A to 30 A)

Quantity/influence factor	**Relative standard uncertainty (·10^{-3})** **A**	**Relative standard uncertainty (·10^{-3})** **B**
RC and acquisition system ratio	0.25	0.25
Linearity	1.15	0.6
Return conductor, gap position variation and orthogonality of the sensor	6.5 30 mm<d<350 mm,	0.8 (30 mm<d<35 mm, gap external, sensor centered)
Peturbing magnetic field sources	7 (D>100 mm)	1.2 (D=600 mm)
Ambient Temperature	2.9 T_a=(20 °C±10))	0.4 T_a=(15 °C±4)
Stability and repeatability	2	0.8
Expanded relative uncertainty (95% coverage probability	**21**	3.5

Conclusions

PQ measurement accuracy in MV and HV plants can significantly depend on the performances of the used transducers in relation to the real measurement conditions. The measurement uncertainty can be estimated and reduced by carrying out a careful characterisation of the transducers. Taking into account the conditions likely to occur in PQ measurement in a MV/LV substation, which supplies an industrial load and is connected both to the public supply network and to Photo-Voltaic (PV) generations plants, characterization procedures have been experimented on a current measurement system which includes an openable and flexible RC current sensor, whose expected on-site accuracy is of the order of some percent. By taking into account the results obtained for the evaluation of the uncertainty contributions and making use of suitable correction factors for the assigner RC ratio, the uncertainty of the current measurements carried out during a PQ measurement campaign is reduced to some part per thousand.

Acknowledgments

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