XVII IMEKO World Congress
Metrology in the 3rd Millennium
June 22–27, 2003, Dubrovnik, Croatia

TRACEABLE CALIBRATION OF POWER HARMONICS AND FLICKER ANALYSERS

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Abstract – The paper describes a precision measurement system developed at NML for the calibration of three-phase instruments measuring harmonics of current up to 16 A, voltage fluctuation and flicker. Particular attention is given to establishing a traceable link to the Australian primary standards of electrical quantities. Current and voltage harmonics up to the 99th and fluctuating voltages can be generated and measured with relative uncertainties close to 1×10^{-5}.

Keywords: harmonics, flicker, standards.

1. INTRODUCTION

In recent years the International Electrotechnical Commission (IEC) has introduced a series of standards on Electromagnetic Compatibility (EMC). In particular, IEC61000-3-2 and IEC61000-3-3 specify the limits of harmonic current and flicker introduced into the supply network by equipment with input current less than or equal to 16 A per phase. Several types of Power Analysers (PA) designed for accurate measurements of current harmonics, voltage fluctuations and flicker are available commercially, requiring traceable calibration by National Metrology Institutes (NMIs). Several NMIs have already reported work on low-frequency EMC standards [1], [2]. This paper describes a high-precision harmonic and flicker measurement system developed at NML, Australia, and gives results of its characterisation.

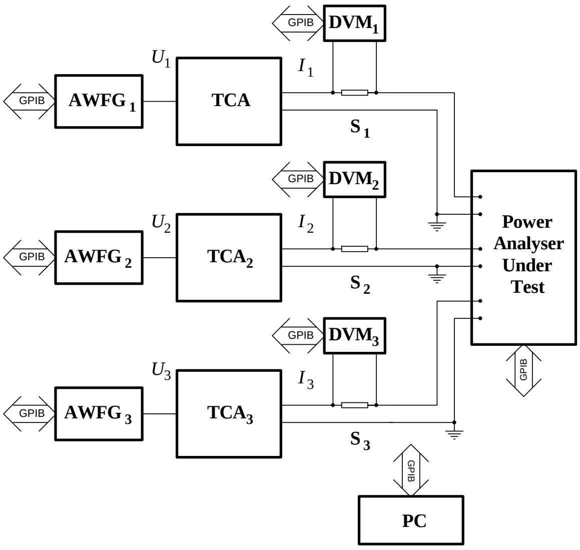
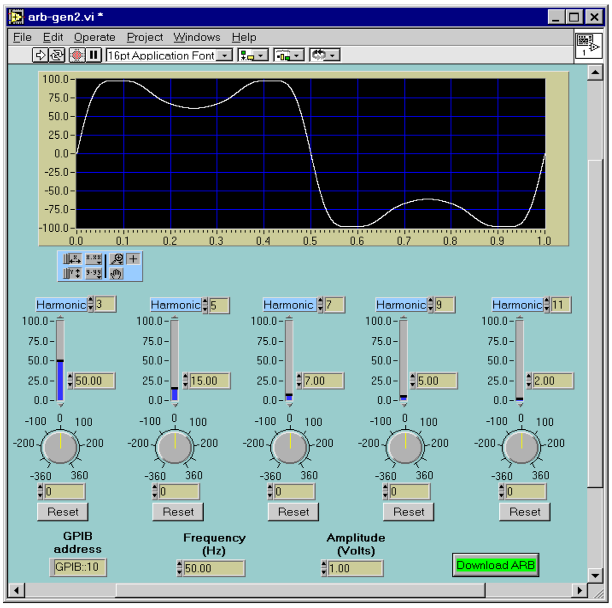


Fig. 1. Simplified diagram of the digital system for generation and measurement of harmonics

2. DIGITAL SYSTEM FOR GENERATION AND MEASUREMENT OF HARMONICS

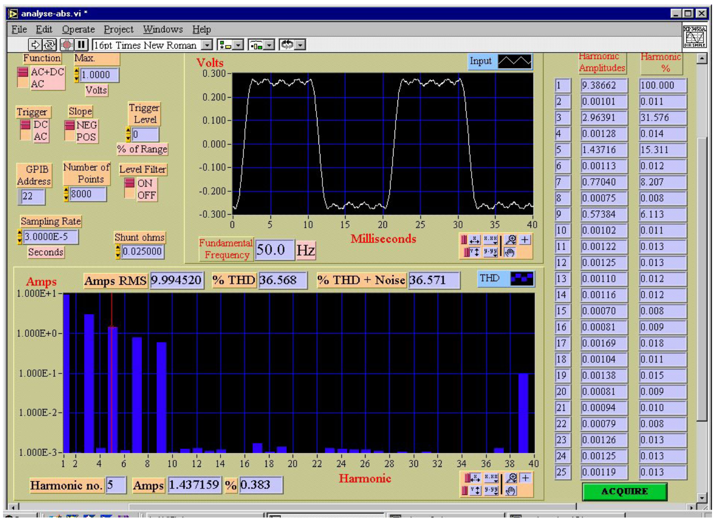
Fig. 1 shows a simplified schematic diagram of the system configured to calibrate a three-phase PA for current harmonic measurement. Three computer-controlled Arbitrary Waveform Generators $AWFG_1$ to $AWFG_3$ produce voltage signals, U_1 to U_3, containing any chosen combination of a 50 Hz fundamental and its harmonics, up to the 99th. The voltages are transformed, with the use of transconductance amplifiers TCA_1-TCA_3 into three test currents, I_1 to I_3, which are applied to the PA under test through three precision current shunts S_1-S_3. The output voltage of the shunts is digitised by precision digital voltmeters DVM_1-DVM_3, and the harmonic measurement software performs Fourier analysis of the captured waveforms and calculates harmonic amplitudes and phases.

The Arbitrary Waveform Generators have a waveform length of 16 000 points with 12-bit resolution per point. The software (see Figure 2) generates an array of 16 000 numbers for the fundamental ($k = 1$) and for each of the harmonics ($k = 2…99$) as needed. These arrays are added together, then normalised so that the maximum and minimum values are 2047 and –2047 respectively which maps to the 12 bit resolution exactly. The array is then sent to the AWFG in binary format via the GPIB.



Harmonic 3: 50.00, 0
Harmonic 5: 15.00, 0
Harmonic 7: 7.00, 0
Harmonic 9: 5.00, 0
Harmonic 11: 2.00, 0
GPIB address: GPIB::10
Frequency (Hz): 50.00
Amplitude (Volts): 1.00

Fig. 2. Screen Printout of Harmonic Generation Software



Function: AC+DC / AC
Max.: 1.0000 Volts
Trigger: DC / AC
Slope: NEG / POS
Trigger Level: 0 % of Range
GPIB Address: 22
Number of Points: 8000
Level Filter: ON / OFF
Sampling Rate: 3.0000E-5 Seconds
Shunt ohms: 0.025000
Fundamental Frequency: 50.0 Hz
Amps RMS: 9.994520
% THD: 36.568
% THD + Noise: 36.571
Harmonic no.: 5
Amps: 1.437159
%: 0.383

	Harmonic Amplitudes	Harmonic %
1	9.38662	100.000
2	0.00101	0.011
3	2.96391	31.576
4	0.00128	0.014
5	1.43716	15.311
6	0.00113	0.012
7	0.77040	8.207
8	0.00075	0.008
9	0.57384	6.113
10	0.00102	0.011
11	0.00122	0.013
12	0.00125	0.013
13	0.00110	0.012
14	0.00116	0.012
15	0.00070	0.008
16	0.00081	0.009
17	0.00169	0.018
18	0.00104	0.011
19	0.00138	0.015
20	0.00081	0.009
21	0.00094	0.010
22	0.00079	0.008
23	0.00126	0.013
24	0.00125	0.013
25	0.00119	0.013

Fig. 3. Screen Printout of Harmonic Measurement Software

The voltage measured across the current shunts is digitised by the digital multimeters every 30 µs. Up to 65 k samples can be stored in the multimeter before sending the samples to a PC over the GPIB. The measurement software (See Fig. 3) then computes the power spectrum and extracts the amplitude of each harmonic and displays it as a percentage of the amplitude of the fundamental.

The current shunts, whose design is described briefly in [3], are shown in Fig. 4. Their ac-dc difference has been evaluated at frequencies up to 1 MHz against micropotentiometer resistors [4] and is shown in Fig. 5. Table 1 shows the dc parameters of the shunts.

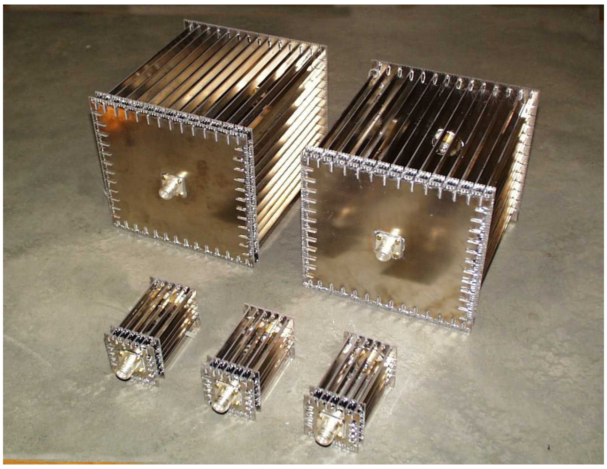


Fig. 4. Precision Current Shunts

TABLE I. DC Parameters of the Shunts

Parameter	Value
Rated Current	0,5 A, 20 A
DC Resistance Error	< 200 µΩ/Ω
Power Coefficient of Resistance	0,5 - 3 µΩ/Ω/W

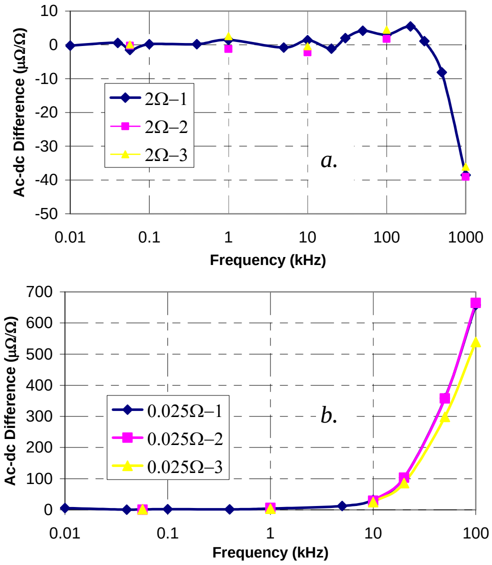


Fig. 5. Measured ac-dc difference of the 0,5 A (*a*) and 20 A (*b*) current shunts

3. TRACEABILITY TO NATIONAL STANDARDS

Traceability of the digital measurement system to Australian national standards of alternating quantities has been established by measuring current and voltage harmonics using a Thermal Power Comparator [5], as described in [6]. The Thermal Power Comparator, which is characterised in terms of NML thermal voltage converters [7], is configured to measure one harmonic of the composite signal at a time. This serves as an ultimate verification of the digital system.

The above measurements, performed on a 10 A rms current signal with fundamental frequency of 50,00 Hz and containing five harmonics ranging from 0,01% to 20% of fundamental, showed agreement between the two methods within 1×10^{-5} of the fundamental.

4. FLICKER GENERATION AND MEASUREMENT

To calibrate the flicker function of the PA a number of modulated voltage signals with relatively small (up to 2,5%) but precisely known modulation depth must be generated. One of three identical channels of the setup realising this is shown in Fig. 6.

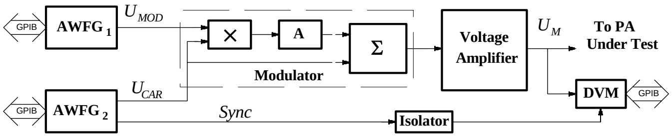


Fig. 6. Flicker generation and measurement

The modulating signal U_{MOD} (sine or square wave) and carrier signal U_{CAR} (mains frequency sine wave) are produced by generators $AWFG_1$ and $AWFG_2$ respectively. The modulated voltage U_M is formed from U_{MOD} and U_{CAR} by an external modulator, containing an analogue multiplier ×, attenuator A and adder Σ, followed by a voltage amplifier. Each minimum and maximum of U_M, occurring every 10 ms, is measured by a DVM which is synchronised with AWFG$_2$.

The modulation depth is calculated as

$$\frac{\Delta U}{U}=\frac{U_{M\,\max}-U_{M\,\min}}{0{,}5(U_{M\,\max}+U_{M\,\min})}, \qquad (1)$$

where $$U_{M\,\max}=\frac{1}{2}\left(U_{M\,\max+}-U_{M\,\max-}\right) \text{ and} \qquad (2)$$

$$U_{M\,\min}=\frac{1}{2}\left(U_{M\,\min+}-U_{M\,\min-}\right), \qquad (3)$$

as per Fig. 7

Advantage is taken of the internal delay function of the DVM to align the measurement window with the peak of U_M. The standard deviation in the measurement of $\Delta U/U$ using a 200 μs window of the DVM is typically less than 0,0001. To achieve this, high stability of U_M is needed. In conventional signal generators this stability is limited by the noise in the analogue multiplier working at the bottom of its dynamic range. Here the multiplier is fed with two full-scale input signals and produces an output signal with close to 100% modulation depth which is further attenuated and mixed with the sine wave carrier to give a stable modulated voltage with the required low modulation depth.

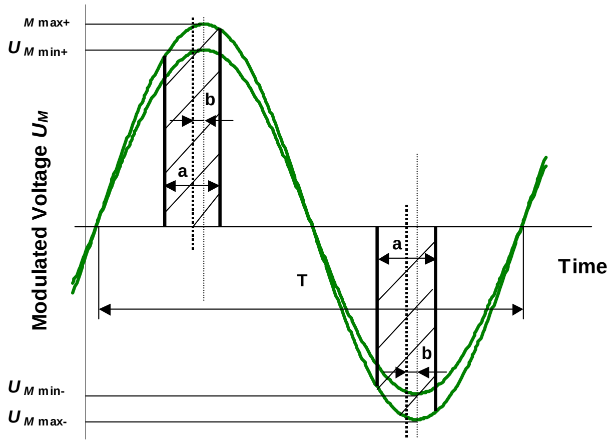


Fig. 7. Measurement of peak value of voltage using an integrating DVM

As shown in Fig. 7, each maximum and minimum of U_M is measured by the DVM over a measurement window with aperture a which may be shifted from the peak by a displacement b. In order to achieve an acceptably small noise level, a certain minimum value of a is required. Similarly, displacement b cannot be made precisely zero without significantly complicating the hardware. It is, therefore, important to consider the errors that may arise from the use of an integrating DMM to measure the peak values of U_M.

The reading M of an ideal integrating DVM that corresponds to $U_{M\,\max}$ is:

$$M=\frac{1}{a}\int_{\frac{T}{4}+b-\frac{a}{2}}^{\frac{T}{4}+b+\frac{a}{2}} U_{M\max}\, Sin\left(\frac{2\pi}{T}t\right)dt, \qquad (4)$$

where T is the period of the signal, nominally 20 ms. From (4) the relative error δ of the measurement of each minimum and maximum equals

$$\delta=\frac{T}{2a\pi}\left(Sin\left(\frac{\pi}{T}(2b+a)\right)-Sin\left(\frac{\pi}{T}(2b-a)\right)\right)-1, \qquad (5)$$

which, neglecting the terms higher than the first order, can be conveniently written as $\delta=\delta_1+\delta_2$, where

$$\delta_1=-\frac{\pi^2}{6}\left(\frac{a}{T}\right)^2 \text{ and } \delta_2=-2\pi^2\left(\frac{b}{T}\right)^2. \qquad (6)$$

However, since these errors apply equally to the measurement of $U_{M\,\max}$ and $U_{M\,\min}$ in (1), their contribution to the measurement of $\frac{\Delta U}{U}$ is cancelled.

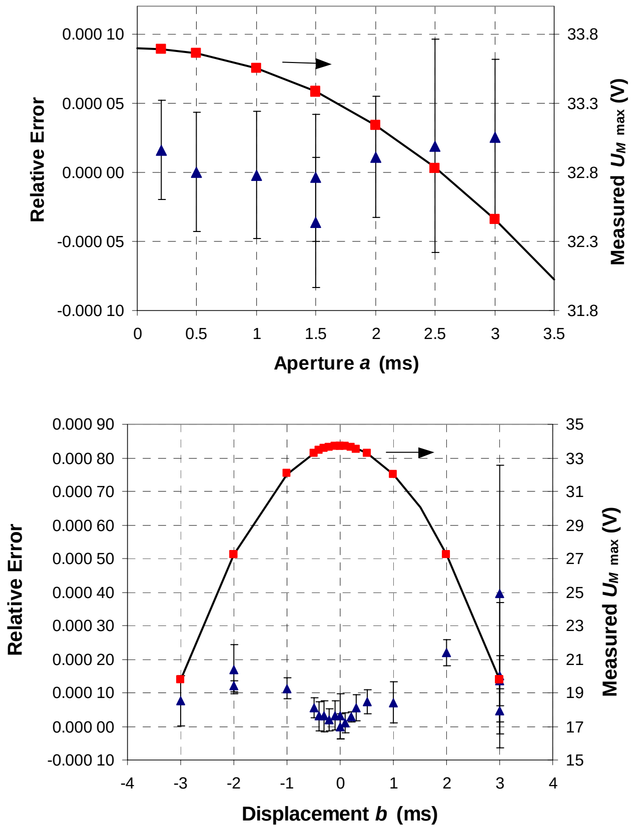


Fig. 8. Relative error and standard deviation of measuring modulation depth $\frac{\Delta U}{U}=0{,}0274$ with square wave modulation at 1 change per minute (triangular markers). The square markers show the measured values of peak voltage. Theoretical values, calculated in accordance with (5) and (6), are shown by the solid lines.

To prove this, the largest modulation depth specified by IEC868:1986 for nominal flicker severity (modulation depth of 0,0274 with square wave modulation at 1 change per minute) was measured using various values of aperture and displacement of the window. The results of these measurements are shown in Fig. 8.

As seen from the graphs, although the measured value of peak voltage depends greatly on both the aperture and displacement of the window, there is no appreciable change in the measured value of the modulation depth for a and b up to 1 ms. This justifies a choice of $a = 200$ μs and $b < 200$ μs. To achieve the latter the following technique is used. The DVM measurement is triggered by an external square wave signal *Sync* that is in phase with the sine wave to be measured. For each trigger event, the DVM is instructed to take two measurements separated by 10 ms (for 50 Hz mains). In order to centre the measurement around the peaks of the sine wave the delay between trigger and the first sample is set to $(5 – (a/2))$ ms.

5. UNCERTAINTIES

The uncertainties of the measurement of current harmonics and modulation depth are summarised in Tables II and III respectively. The uncertainties have been calculated in accordance with [8].

The largest component of the uncertainty of harmonics measurement is due to the drift and instability of the DC resistance of the shunts. However, its influence on the final result is proportional to the amplitude of the measured harmonic and ranges from $0,1\times10^{-6}$ (for smaller harmonic amplitudes) to 30×10^{-6} (for the fundamental). The uncertainty of modulation depth (flicker) measurement is mostly dependent on the estimated standard deviation of the mean (ESDM), which does not exceed 35×10^{-6} for 10 or more measurements.

TABLE II. Uncertainties of Current Harmonics Measurement (in Parts in 10^6 of the Fundamental)

Component	Component Values			
	U_i	k_i	c_i	$c_i u_i$
ESDM	1.6 - 17	1	1	1.6 - 17
Voltage Measurement	10 - 20	2	1	5 - 10
Shunts (DC Resistance)	0.1 - 30	2	1	0.05 - 15
Shunts (AC-DC Difference)	0.1 - 12	2	1	0.05 - 6
Rounding	1 - 10	1.73	1	0.6 - 6
Combined Uncertainty				5.3 - 26
Expanded Uncertainty **(95% Confidence Level)**				**10.6 - 52**

TABLE III. Absolute Uncertainties of Modulation Depth Measurement (in Parts in 10^6)

Component	Component Values			
	U_i	k_i	c_i	$c_i u_i$
ESDM	2.7 - 35	1	1	2.67 - 35
Voltage Measurement	10 - 20	2	1	5 - 10
Window Aperture	5 - 10	2	1	2.5 - 5
Window Displacement	10 - 30	2	1	5 - 15
Rounding	1 - 10	1.73	1	0.6 - 6
Combined Uncertainty				8.0 - 40
Expanded Uncertainty **(95% Confidence Level)**				**16.0 - 80**

6. CONCLUSIONS

A system for the calibration of quasi-stationary harmonics and flicker meters has been developed. Through a combination of a software and a hardware approach, a relative measurement uncertainty of the order of 1×10^{-5} has been achieved with a minimum of hardware development.

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