A Smarter Meter: IEEE-1459 Power Definitions in an Off-the-Shelf Smart Meter

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Abstract—**With respect to harmonics, revenue meters have suffered from inconsistent power definitions and ambiguous metering Specifications for decades. Modern digital metering technology and new power definitions can correct these issues. The IEEE-1459 Standard provides consistent and unambiguous power definitions ideal for revenue metering purposes. Its primary innovation is the separation of the fundamental frequency power components P_1 and Q_1 from the apparent power S. This paper will demonstrate that these definitions can easily be implemented in an off-the-shelf Smart Meter at no additional hardware cost, by modifying the firmware in the metering chip. Harmonic distortion tests proposed by the OIML [2] were applied to the reprogrammed meter, and results evaluated with a commercial meter test set. The paper concludes that modern digital meter technology can implement the IEEE-1459 power definitions and existing Reference Standards can be used to test and calibrate these Smarter Meters. Copyright IEEE 2015.**

***Index Terms*— Revenue Metering, Power Definitions, Harmonics, IEEE 1459-2010**

I. Introduction

Electricity meter Specifications used in North America (ANSI C12 series) and Europe (IEC 62052/3 series) do not currently cater adequately for non-sinusoidal conditions. Meters are designed to meet the specifications, and any deficiency in the specifications results in flawed meter designs. Metering errors due to harmonics have been reported for decades [e.g. 6-8], but the solution is complex. Suitable power definitions must be accepted by academics, standards authorities, and utilities before they will be implemented by meter manufacturers.

The IEEE-1459 Standard [3] provides appropriate power definitions for revenue metering under sinusoidal and non-sinusoidal conditions. However, if the new power definitions cannot be implemented cost-effectively, or be tested with available test equipment, or have an unknown impact on consumer bills, they will not be adopted in specifications and implemented in meters. The author has shown previously that the IEEE-1459 power definitions can be easily implemented by reprogramming the metering chip used in the Plogg appliance load meter [1]. This paper will extend that work to implement the new power definitions in an off-the-shelf Smart Meter and test them using currently available meter test equipment and reference standards.

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The Harmonic Impact Project (HIP) was initiated to obtain empirical data to compare traditional P, Q, and S meter readings and IEEE-1459 P_1, Q_1, and S_1 readings from 50 to 60 diverse consumers. The HIP project will address the ability of smart meter technology to implement fundamental-only power definitions, the cost of doing so, and the impact of the new measurements on consumer bills. To do this, we had to reprogram commercial Smart Meters to measure the new quantities. A previous project had required porting the Plogg code to a commercial Smart Meter. This reprogrammed Vision meter was the obvious choice for the HIP project. This paper will show that only a simple firmware change is necessary to implement a fundamental-only energy meter, and that the new non-fundamental power quantities can be included with additional firmware calculations. The HIP meters will be installed alongside regular Smart Meters for one or two years.

II. Revenue Meters and Harmonics

Power utilities generate and purchase electric energy for trade. This energy is generated at a single frequency, usually 50Hz or 60Hz. No utility equipment or consumer load is designed to generate, transfer, or make use of power at any other frequency. In many jurisdictions the regulator or other authority clearly states the frequency of power delivery to be 50Hz or 60Hz. The purchase or sale of electric energy at harmonic frequencies is therefore at best unethical and at worst illegal. Harmonics are undesirable electric pollution, and must be treated as such. Revenue meters should meter only the fundamental power components for trade, and if possible, measure the harmonic components for power quality purposes.

Electromechanical meters attenuated harmonic components, but could not eliminate them entirely. When the first analog electronic meters appeared about 50 years ago, they included (some) harmonic components *as a side effect* of the power calculation process. It was possible, but expensive, to filter the harmonics in analog electronic meters, and so the side-effect was successfully marketed as a beneficial feature for metering non-linear loads, under the presumption that the meter *should* meter *all* power flowing at the metering point, including harmonics. Digital meters have been on the market for about 20 years. This technology can filter harmonics easily and cheaply, as this paper will demonstrate. Time is now past due for bringing power definitions, Metering Standards, and meter designs into alignment.

The shortcomings of power definitions and algorithms, based on the Budeanu [4] and Fryse [5] models, have been discussed widely [e.g. 6-8]. Several improved models have been proposed, including those of Depenbrock [9], Czarnecki [10], Emanuel et al [11], and others.

The Emanuel model, which evolved into the IEEE-1459 Standard, was the first to recognise the importance of separating the fundamental active and reactive power components P_1 and Q_1 from apparent power S, where S = VI. These are the two most important components of S from a revenue metering viewpoint. The remaining component of S was termed 'non-fundamental apparent power' S_N. The three quantities P_1, Q_1, and S_N are mutually orthogonal:

$$S = \sqrt{P_1^2 + Q_1^2 + S_N^2} \quad (1)$$

The model then resolves S_N into new components that can be associated with responsibility for distortion power. The quantity D_V is associated with voltage distortion and D_I with current distortion. The remaining component of S_N is the harmonic apparent power S_H. Again, D_V, D_I, and S_H are mutually orthogonal:

$$S_N = \sqrt{D_I^2 + D_V^2 + S_H{}^2} \quad (2)$$

Since generally, the utility is responsible for any voltage distortion by way of non-zero source impedance, and generally the consumer is responsible for current distortion by way of uncompensated non-linear loads, D_V and D_I may be useful as revenue metering quantities for allocating harmonics related costs between consumers and the utility. The last quantity S_H reflects the active harmonic power and cross products.

III. The Technology of a Smart Meter

Most modern Smart Meters, essentially digital meters with communications capability, contain a Digital Signal Processor (DSP) for metrology and one or more additional processors for handling the meter, communications, and security functions.

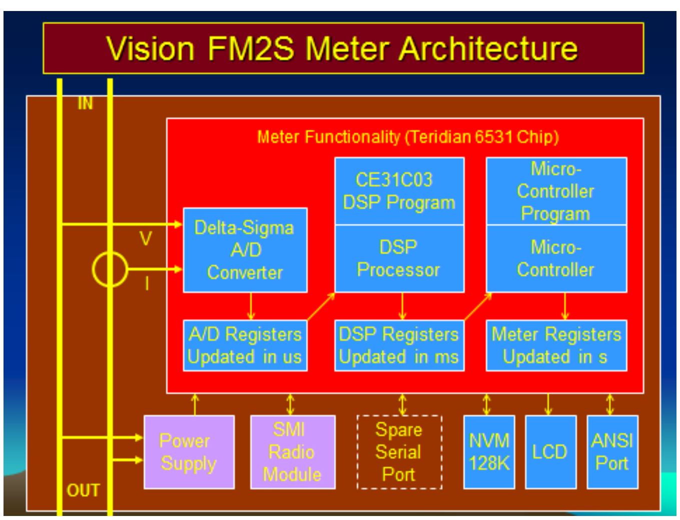

Fig. 1 – Architecture of a Vision Smart Meter

Sometimes this functionality is incorporated into a single chip. The 71M65xx family of chips by Maxim is used by several meter manufacturers. The DSP in these metering chips can be reprogrammed to provide measurements based on different definitions. (The DSP code, in the "Metrology" section of the meter, is in a protected area of memory, and altering it would not normally be possible.) Fig. 1 shows the basic architecture of the Vision FM2S meter.

The chip measures voltage and current samples 2520 times per second, using a single multiplexed A/D converter. This updates the A/D Registers for all inputs roughly every 400µs. All other quantities are calculated from the measured V and I samples.

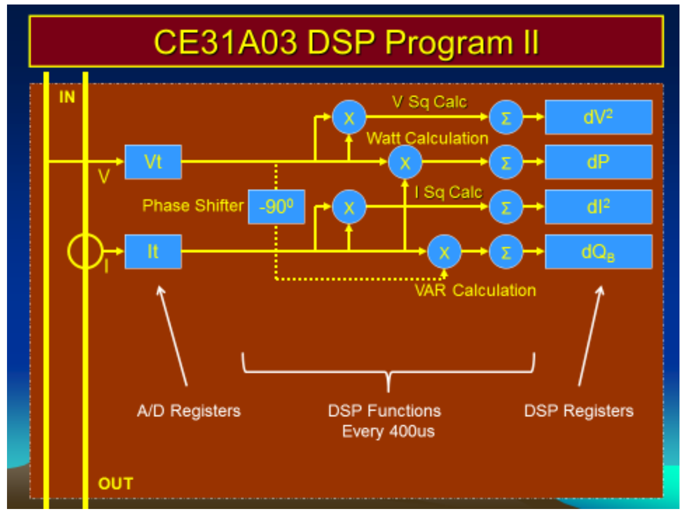

Fig. 2 – Functions of the CE31A03 DSP Program

The DSP processor does all the calculations necessary to update the DSP registers every A/D conversion cycle. The standard DSP program for the chip is CE31A03. The sampled values are digitally interpolated to eliminate the time delays caused by multiplexing the single A/D. The voltage and corresponding current samples are multiplied to produce instantaneous power values, which are accumulated in the DSP's dP register. The voltage gets a 90^0 phase delay, using a digital integrator. This shifts all harmonics by 90^0 to approximate Budeanu's reactive power definition, but also attenuates the harmonics. The phase shifted voltage gets multiplied by the current and the product is accumulated in the dQ_B register. Voltage and current are squared and then summed in dV^2 and dI^2 registers. The DSP performs various other tasks such as temperature compensation and frequency measurement. The DSP metrology process is shown in Fig. 2.

About once a second the microcontroller reads the four relevant DSP registers and updates the meter registers with the new data, performing additional calculations as necessary. Vrms and Irms are obtained by taking the square root of the dV^2 and dI^2 registers. Apparent power S is calculated from Vrms and Irms (Fig. 3). The microcontroller also updates the meter's display, manages register data storage, and controls communications over the RF-WAN network. Modern digital meters have architectures similar to the Vision meter, and the concepts used here could be applied to any digital meter.

IV. The HIP Meter DSP Program

The HIP meter must measure both traditional and IEEE-1459 quantities to compare them. As with the Plogg harmonics project [1], this means replacing the DSP code and altering the microcontroller code to process the additional data from the DSP. The new DSP and microcontroller programs provide power (and energy) measurements using both traditional and IEEE-1459 definitions. Teridian (now Maxim) provided the author with another version of the DSP program, CE31A06. This added Narrow Band Pass (NBP) Filters to the voltage and current to extract the fundamental frequency components, and included power calculations for the filtered signals. The digital integrator was replaced by an all-pass filter that does not attenuate harmonics. Three new registers were added for the fundamental active power and the sums of the squares of the fundamental voltage and current (Fig. 4). The performance of the NBP filters is described in the CE31A06 Application note [12]. This note indicates that the pass-band attenuates the fundamental component by less than 0.02%. In the stop-band, the second harmonic is attenuated over 60dB while the third harmonic and higher are attenuated over 80dB. The filter pass-band center frequency tracks the fundamental frequency. The seven DSP registers provide the microcontroller with all the information needed to implement all the IEEE-1459 single-phase power definitions.

V. The Prototype HIP Meter

The simplest way of converting a P meter to a P_1 fundamental power meter is to repurpose an existing microcontroller P register as the P_1 register. The CE31A03 DSP code was replaced by the CE31A06 code in the prototype HIP meter, and the existing kWh (Received) register was used to record the kWh (Delivered) from the P_1 DSP register (Fig. 5). (The kWh (Rec) register was not required for the prototype meter.) This approach required only to replace the DSP program and change one line of microcontroller code, to update the kWh (Rec) register from the DSP dP_1 register instead of the DSP dP register.

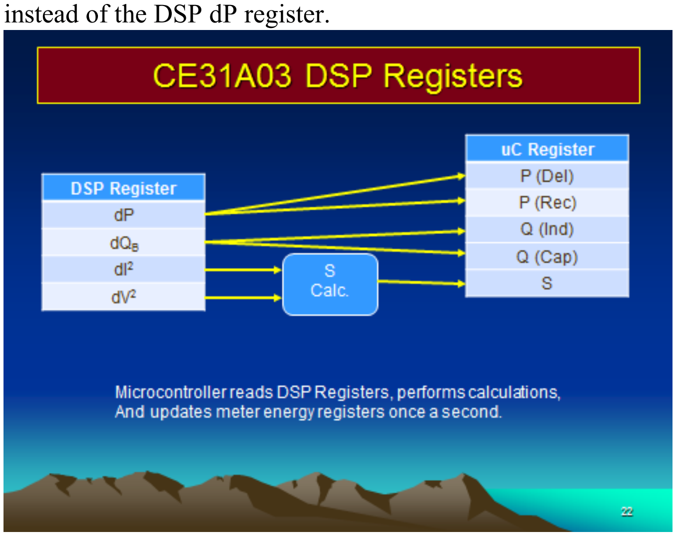

Fig. 3 – Microcontroller use of CE31A03 Registers

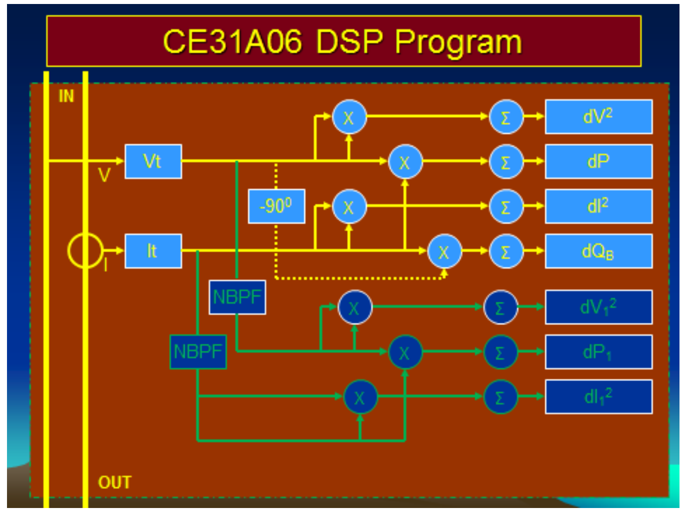

Fig. 4 – Functions of the CE31A06 DSP Program

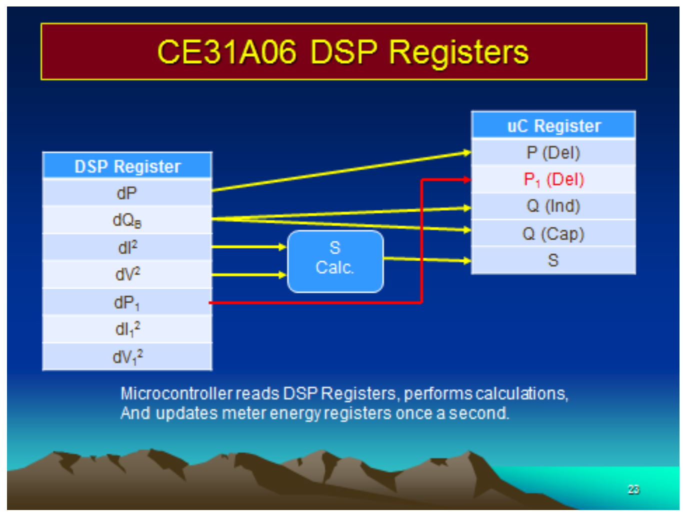

Fig. 5 – Repurposing the Meters Energy Registers

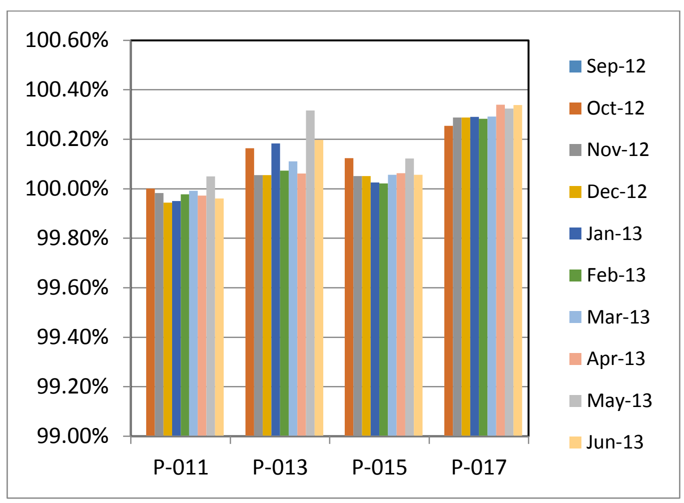

Fig. 6 – Ratio P_1/P monthly over 9 months.

Four of these meters were put into the field for a year, at residential consumers. Fig. 6 shows the ratio between P_1 and P over 9 months, with 3 meters indicating a slightly higher P_1

and one a slightly higher P. This indicates that 3 consumers were generating small amounts of harmonic power while the fourth (P-011) was absorbing harmonic power.

VI. QUANTITIES FOR THE HIP METER

Confident that the new DSP code was working as expected, the microcontroller program was then modified to calculate all the IEEE-1459 power quantities (for single phase loads) from the seven DSP registers. Since the CE31A06 DSP code did not include a register for Q_1, this was derived from S_1 and P_1, as follows:

$$S_1 = V_1 I_1 \tag{3}$$

$$Q_1 = \sqrt{S_1^{\ 2} - P_1^{\ 2}} \tag{4}$$

Voltage and current distortion V_H and I_H were obtained from V, V_1, I, and I_1. The non-fundamental power quantities were then calculated:

$$S_N = \sqrt{S^2 - S_1^{\ 2}} \tag{5}$$

$$S_H = V_H * I_H \tag{6}$$

$$P_H = P - P_1 \tag{7}$$

$$D_V = V_H * I_1 \tag{8}$$

$$D_I = V_1 * I_H \tag{9}$$

These new power quantities may prove useful for revenue metering, as they provide an indication of the magnitude of distortion power and its likely association with consumer (current) and supplier (voltage). Note that the original DSP registers are still available to provide Vrms, Irms, P and Q_B. Finally, the traditional PF and fundamental frequency PF_1 power factors can be determined. All these quantities are available as instantaneous (1 second average) values. There are two registers each (Delivered and Received) for P, P_1, Q_B, Q_F, and Q_1, and one register each for S and S_1. All of the registers as well as the V, V_1, I, and I_1 can be recorded in the interval data memory (NVM), with intervals between 1 minute and 120 minutes. The 12 registers are maintained internally, and are non-volatile. (The first version of the HIP meter does not have energy registers for the new IEEE-1459 non-fundamental power quantities. These will be included in a future version.)

VII. PROPOSED HARMONICS TESTS

The OIML recently issued their Recommendation 46 (R46) [2] for active electrical energy meters. This document describes several tests for influence quantities, including three for harmonics in both voltage and current. These tests, intended to confirm the inclusion of (some) harmonic components by the meter, can also be used to confirm exclusion of these components. The author applied the OIML R46 "Quadriform Waveform" and "90^0 Thyristor Fired Waveform" tests to the HIP meters. The most important feature of the OIML harmonics tests is that the distortion content is *pre-defined mathematically* in terms of order, magnitude, and phase. This establishes the relationships between the power quantities precisely. P_H as a percentage of P can be calculated for each test, and then P_1 can be derived by simply subtracting P_H from P.

VIII. EQUIPMENT USED TO TEST THE HIP METERS

A Radian 4150 Meter Test Set [13] was used to calibrate and test the HIP meters. The Radian 4150 is a complete set of equipment for testing ANSI C12 meters under sinusoidal or non-sinusoidal conditions. It contains voltage and current waveform generators and power amplifiers to generate voltage and current waveforms to be applied to the meter under test. The voltage and current waveforms can be defined in terms of magnitude and phase for each harmonic, exactly as they are defined in the R46 tests. The 4150 includes a Radian RD-30 series energy Reference Standard for determining the accuracy of the meter under test. The Radian RD-30 measures P, but has been calibrated only with sinusoidal waveforms – ie it is calibrated for P_1. The Radian 4150 has an uncertainty of 0.04% and a valid calibration certificate.

If one accepts that the Radian RD-30 measures P accurately for the defined waveforms, one can deduce that the measurement of P_1 derived as above, will also be accurate, since P_1 is a component of P. The Radian can serve as the Reference Standard for P_1 where the harmonic levels are defined mathematically and within the bandwidth of the Radian.

IX. HIP METER TEST PROCEDURE

The first Vision meters to be reprogrammed were 240V, 200A ANSI Form 2S types, suitable for single phase residential or small commercial consumers.

A. *Calibration of the HIP Meter*

The meter was first calibrated with the Radian 4150 and sinusoidal waveforms of 240V and 15A applied. The voltage, current, and phase calibration factors in the 6531 chip were adjusted to minimise the meter's error. The calibrated accuracies for V, I, and P are listed in Table II. The "Ideal" column lists quantities from a spreadsheet model built from the R46 definitions. "Radian" contains the Radian 4150 registered values, and "Meter" shows the values reported by the meter. The last column indicates the error of the meter relative to the "Ideal" values. Values directly reported by the Radian are in bold. Although the Radian does not explicitly register V_1, I_1, P_1, Q_1, or S_1 values, they are identical to V, I, P, Q, and S under sinusoidal conditions, and have been imputed to the Radian and inserted into the table in italics. Table II shows the HIP meter calibrated to within 0.1% of the Radian for the quantities P, P_1, S, and S_1, with an uncertainty of 0.04%.

Table II – Sinusoidal Calibration Test

Sinusoidal	Ideal	Radian	Meter	Error %
P	**3600.00**	**3600.00**	**3599.00**	**-0.03%**
Q_B	0.00		-21.00	
Q_F	0.00		0.00	
S	3600.00		3599.29	-0.02%
Vrms	**240.00**	**240.00**	**239.98**	**-0.01%**
Irms	**15.00**	**15.00**	**14.99**	**-0.01%**
P_1	3600.00	*3600.00*	3598.60	-0.04%
Q_1	0.00	*0.00*	0.00	
S_1	3600.00	*3600.00*	3598.66	-0.04%
V_1 rms	240.00	*240.00*	239.95	-0.02%
I_1 rms	15.00	*15.00*	14.99	-0.02%
S_N	0.00		67.34	

B. Sinusoidal Power Factor Test

The meter was then subjected to a Power Factor (PF) test, with 240V and 15A applied and a phase angle of 60 degrees corresponding to 0.5 PF. All three reactive power definitions Q_B, Q_F, and Q_1 should give identical correct values for this test, and similarly P and P_1 should both equal 50% of S. As can be seen, the HIP meter has an accuracy of better than 0.1% for P, Q_B, Q_F, S, P_1, Q_1, and S_1 measurements, with an uncertainty of 0.04%.

Table III – Sinusoidal Reactive Power Test

Sinusoidal	Ideal	Radian	Meter	Error %
P	**1800.00**	**1800.00**	**1800.30**	**0.02%**
Q_B	3117.69	**3118.00**	3117.20	-0.02%
Q_F	3117.69	*3118.00*	3117.17	-0.02%
S	3600.00		3599.70	-0.01%
Vrms	**240.00**	**240.00**	**239.99**	**0.00%**
Irms	**15.00**	**15.00**	**14.99**	**-0.02%**
P_1	1800.00	*1800.00*	1799.70	-0.02%
Q_1	3117.69	*3118.00*	3116.06	-0.05%
S_1	3600.00	*1800.00*	3598.44	-0.04%
V_1 rms	240.00	*240.00*	239.94	-0.02%
I_1 rms	15.00	*15.00*	14.99	-0.02%
S_N	0.00		95.23	

C. OIML R46 "Quadriform" Waveform Test

The "Quadriform" test applies predefined voltage and current waveforms (Table IV) representing common nonlinear loads. The load draws harmonic current components in phase with the fundamental voltage, which cause harmonic voltage components with a 180^0 phase shift due to the utility non-zero source impedance. This results in negative power flow at harmonic frequencies, such that the fundamental power P_1 is greater than the total power P. The difference, as defined in this test is almost 2%. This difference is significant, as it exceeds the accuracy limits of Class 1%, 0.5% or 0.2% meters. With phase shifts of 0^0 or 180^0, there should be no reactive power at any frequency.

Table IV – Quadriform Waveform Parameters

Harm.	V Amp.	V Phase	I Amp	I Phase	Power
1	100%	0^0	100%	0^0	100.00
3	3.8%	180^0	30%	0^0	-1.140
4	2.4%	180^0	18%	0^0	-0.432
7	1.7%	180^0	14%	0^0	-0.238
11	1.1%	180^0	9%	0^0	-0.099
13	0.8%	180^0	5%	0^0	-0.040
				Total Power P:	98.051

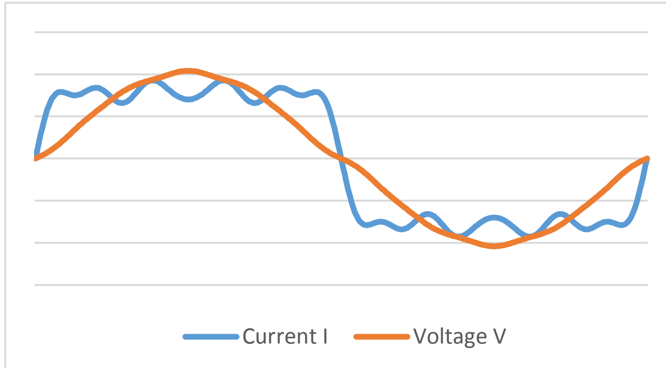

Fig. 7 – The "Quadriform" Waveforms

The Radian does not measure P_1 directly, but measures P including the predefined harmonics. For this test the harmonic power is negative and reduces the total power so that P_1 measured by the Radian will be 101.9877% of the P indicated by the Radian. The same mathematical relationship applies with V to V_1, I to I_1, and these calculated values have been imputed to the Radian and inserted into the table in italics.

Table V – Quadriform Waveform Test

R46 6.3.6	Ideal	Radian	Meter	Error %
P	**3283.92**	**3286.00**	**3285.6**	**0.05%**
Q_B	0	0.00	1.2	
Q_F	1474.55	*0.00*	1471.88	-0.18%
S	3599.78		3600.23	0.01%
Vrms	**240.02**	**240.00**	**240.02**	**0.00%**
Irms	**15.00**	**15.00**	**15.00**	**0.00%**
P_1	3348.89	*3351.32*	3351.6	0.08%
Q_1	0.00	*0.00*	13.93	
S_1	3348.89	*3351.32*	3351.63	0.08%
V_1 rms	239.72	*239.72*	239.68	-0.02%
I_1 rms	13.97	*13.97*	13.98	0.07%
S_N	1320.36		1314.61	-0.44%

Note that the meter has accounted for the negative harmonic power, with P measured as 3285.6W and P_1 as 3351.6W, which is almost 2% higher. The difference between P and S is non-fundamental power S_N, which is (incorrectly) interpreted as reactive power by the Q_F VAr definition. The HIP meter correctly identifies this power component as S_N, although the Radian is as yet unaware on this new quantity. The HIP meter has measured the P, P_1, S, and S_1 quantities to within 0.1% with an uncertainty of 0.04%.

D. *OIML R46 "90^0 Thyristor Fired" Waveform Test*

The last test was the 90^0 Thyristor Fired Waveform Test. Thyristor controls cut out sections of the load current waveform to vary the load (Fig. 8), which results in an effective phase shift for the fundamental current and generates harmonic currents. The OIML test specifies only current harmonics from 3rd to 19th, which implies no harmonic power P_H. This is challenging for a meter, as there is both a reactive Q_1 component and non-fundamental apparent power S_N, but no harmonic active power P_H, so for this test P equals P_1.

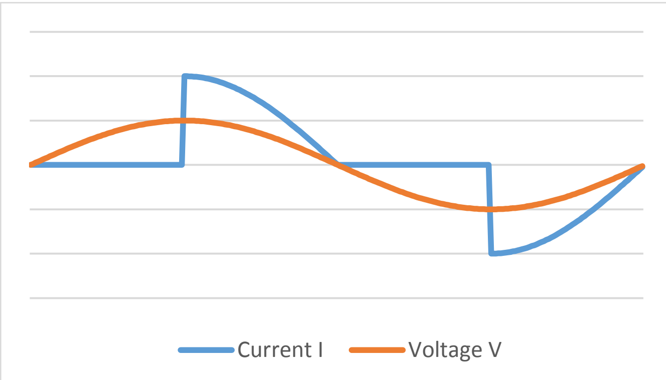

Fig. 8 – The 90^0 Phase Fired Waveforms

The test results in Table VI show that the meter was able to measure P and P_1 quantities within 0.5% (the R46 limits for Class C 0.5% meters) for this demanding test, with an uncertainty of 0.04%.

Table VI – 90^0 Thyristor Fired Test

R46 6.3.11	Ideal	Radian	Meter	Error %
P	**2,571.59**	**2,575**	**2579.90**	**0.32%**
Q_B			1641.70	
Q_F	2,519.32		2511.36	-0.32%
S	3,600.00		3600.39	0.01%
Vrms	**240.00**	**240.00**	**240.01**	**0.00%**
Irms	**15.00**	**15.00**	**15.00**	**0.01%**
P_1	2,571.59		2578.30	0.26%
Q_1	1,629.18		1641.30	0.74%
S_1	3,049.10		3056.39	0.24%
V_1 rms	240.00		240.00	0.00%
I_1 rms	12.70		12.74	0.24%
S_N	1,921.65		1902.97	-0.97%

X. CONCLUSIONS

1) A commercial off-the-shelf Smart Meter has been adapted to meter fundamental-only power quantities as defined in the IEEE-1459 Standard, by modifying the meter firmware. All the other (single phase) IEEE-1459 power quantities were implemented as well. This indicates that present Smart Meter technology can apply the IEEE-1459 power definitions at little or no additional cost – simply a firmware revision.

2) The reprogrammed meter has been tested against the OIML R46 harmonics tests and passed their requirements. The tests, designed to ensure that P is measured accurately in the presence of harmonics, apply as well to ensure that P_1 is measured correctly under these conditions.

3) The Reference Standard, measuring P but calibrated to P_1, can be used as a Reference for P_1 for distorted waveform tests where harmonic content is predefined. This means that utilities and Standards bodies will not need to purchase new Reference Standards to confirm the accuracy of IEEE-1459 compliant meters.

There are no technical or practical reasons to delay this issue any longer. The author suggests that the harmonics tests in OIML R46, and those under consideration by ANSI and Measurement Canada, should be implemented, but should be revised to *exclude* harmonic power components from the trade measure of electrical energy, rather than including them.

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He has presented papers at local and international conferences on electrical metering, load research, and related topics. He completed his M Sc in Electrical Engineering at the University of the Witwatersrand in 1997, left Eskom to start a consultancy, and then immigrated to Canada in 2000. He has led the load research team at BC Hydro in Burnaby, BC, Canada, for the past ten years, and contributes regularly at the annual AEIC and WLRA load research conferences.