Smart Meters should be Smarter

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Abstract— **For over a century, most revenue meters have been unable to separate the distortion components from metered power quantities, leading to inaccurate measurements under non-sinusoidal conditions. With IEEE Standard 1459 and modern DSP technology, Smart Meters should be able to treat harmonics separately. However, there is a persistent view that doing so is impractical, or would add to the cost of Smart Meters.**

This paper will illustrate the problem with power definitions by example, and demonstrate the ability of a common metering chip, as used in many Smart meters, to meter fundamental power quantities P_1, Q_1, and S_1, accurately with no additional cost to the meter, building on previous tests of metering chips [1].

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

I. Introduction

As a colleague wrote a decade ago, "Utilities must be able to install *any* meter in *any* electrical environment (sinusoidal or non-sinusoidal), with full confidence that they will all give the *same readings* for the *same load*. Anything else is unacceptable." [2]. The case that brought this issue to his attention is worth covering in a little more detail.

A meter was replaced at a customer's premises, and the new meter registered a significantly lower power factor (0.88) than the original meter had recorded (0.95). This led to the customer being billed a 4% low power factor penalty, simply because BC Hydro had changed their meter. Both meters were approved for revenue metering in Canada, and the load had not changed, but the meter readings were different.

Investigation revealed that the two meters were applying different methods of measurement. The original meter determined active power P, reactive power Q_B, and apparent power S, as follows:

$$P = \sum V_h I_h \cos\theta_h \qquad = 115 \text{ kW} \qquad (1)$$

$$Q_B = \sum V_h I_h \sin\theta_h \qquad = 20 \text{ kVAR} \qquad (2)$$

$$S_V = \sqrt{P^2 + Q_B{}^2} \qquad = 121 \text{ kVA} \qquad (3)$$

$$PF = \frac{P}{S} \qquad = 0.95 \qquad (4)$$

The replacement meter did things differently:

$$P = \sum V_h I_h \cos\theta_h \qquad = 115 \text{ kW} \qquad (5)$$

$$S = VI \qquad = 131 \text{ kVA} \qquad (6)$$

$$Q_F = \sqrt{S^2 - P^2} \qquad = 63 \text{ kVAR} \qquad (7)$$

$$PF = \frac{P}{S} \qquad = 0.88 \qquad (8)$$

Both meters use methods and power definitions commonly accepted and believed to be correct and accurate. Both meters complied with relevant Measurement Canada specifications and ANSI C12 Standards. How could both be correct? How could 20 kVAR be the same as 63 kVAR, or 121 kVA be identical to 131 kVA?

Further investigation revealed that the loads were adjustable speed drives, and that their currents contained significant levels of distortion.

The original meter probably calculated its reactive power as an approximation of Budeanu's definition (2). This definition nets reactive components at different frequencies, affecting the accuracy of the measurement of the fundamental component that must be compensated.

The new meter derived reactive power Q_F from active power P and apparent power S, a method proposed by Fryze and often applied by utilities. This definition treats all non-active power as reactive power. Under non-sinusoidal conditions Q_F can be larger that Q_B for the same load, as in this case.

Under sinusoidal conditions, $Q_B = Q_F$ and $S = S_V$ and the power triangle works:

$$S^2 = S_V{}^2 = \sqrt{P^2 + Q_B{}^2} = \sqrt{P^2 + Q_F{}^2} \qquad (9)$$

Clearly, under non-sinusoidal conditions, the two meters were not measuring the same reactive and apparent power quantities. Also, the ANSI C12 standards and Measurement Canada specifications do not include tests to ensure correct

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measurements under non-sinusoidal conditions. This results in approved, compliant meters that produce differing measurements for the same quantities on the same load – an undesirable situation. One might argue, as one meter vendor has done [2], that the meters are not approved for metering of nonlinear loads, and therefore should not be used where distortion is present! This provides little comfort for the metering engineer trying to ensure that all customers get billed fairly for the power they purchase. Customers operate more variable speed drives, electronic equipment with switching power supplies, and other nonlinear loads than ever, and this trend is likely to continue.

There are three parts to the solution of this problem:

1) *Power definitions that are consistent under nonsinusoidal conditions,*

2) *Meter technology capable of implementing the consistent definitions with negligible additional cost.*

3) *Meter standards with tests that ensure that these power definitions are correctly implemented.*

The IEEE 1459 Standard solves the definition problem by separating fundamental power components P_1, Q_1, and S_1 from the complex power present under non-sinusoidal conditions. The non-fundamental components are defined separately but inclusively, so that all the power components are clearly related. This elegant solution – at least for revenue metering – now needs to be put into practice. Filtering the voltage and current was impossible for electromechanical meters and expensive for analogue electronic meters. Digital Smart Meters, however, include digital signal processing (DSP) capability, and filtering of harmonics is done easily. Poly-phase digital meters capable of separating fundamental power components have been commercially available since at least 1990. However, poly-phase meters are used for larger customers where a slightly higher meter cost is tolerable.

A challenge has been the perceived additional cost of adding this capability to cheaper single-phase meters, as used for the vast majority of utility customers. The perception may be a consequence of the complexity of the IEEE-1459 document itself, or the complexity of instruments built to research the new power quantities [eg 4, 5]. However, this perception is incorrect. The primary change necessary for a digital meter to measure P_1, Q_1, and S_1 is the insertion of DSP code to apply digital filtering to the voltage and current sampled data. In the Maxim 71M6511 chip, this amounts to less than 600 bytes of extra program, which fits comfortably within the allocated DSP program space. This paper will demonstrate the ability of the 6511 with the additional DSP code, to measure the single phase power quantities defined in IEEE-1459 accurately.

The third part of the solution will be the most difficult to implement, and will follow once the first two are clearly solved. This is covered in Section VII.

II. Appropriate Power Definitions for Revenue Metering

The IEEE Standard 1459 [1] provides a range of related power definitions without providing guidance as to the most appropriate for different applications – this was left to the user.

Fundamental active power is the primary quantity generated by the utility, traded, and used by customers. Harmonic active power is a consequence of nonlinear loads (creating harmonic currents) and the utility's non-zero source impedance (creating harmonic voltages). This power may flow from the load to the utility, utility to load, or one load to another. It is 'derived' or 'converted' from fundamental power. This harmonic power has no value to either customer or utility, and can be detrimental to both. Nevertheless, the utility must generate and distribute the fundamental frequency power than the load converts to harmonics, and absorb any harmonic power converted. This often happens in the distribution transformers or capacitor banks, but excessive harmonic levels may require the installation of harmonic filters. From a revenue metering perspective, a meter should measure the total fundamental frequency active power supplied to the customer.

$$P_1 = V_1 I_1 \cos\theta_1 \qquad (10)$$

In AC power systems, fundamental reactive power is a consequence of inductive and capacitive elements. It is usually undesirable at a metering point. Poor power factor – a consequence of excessive fundamental reactive power - results in underutilized infrastructure or overinvestment in distribution systems. Utilities and customers manage fundamental reactive power by installing capacitive or inductive elements, and utilities manage local voltage variations by varying the reactive elements in distribution systems. Customers with poor power factors can be penalized by fundamental reactive power (kVAR) or reactive energy (kVARh) charges.

Reactive power at harmonic frequencies is associated with harmonic active power as discussed above. It has no benefit to either customer or utility, and no bearing on the cost of correcting poor fundamental power factor. Revenue meters should measure the fundamental reactive power component.

$$Q_1 = V_1 I_1 \sin\theta_1 \qquad (11)$$

An alternative means of charging customers for poor power factor is the use of apparent power demand charges (kVA). For revenue metering, fundamental apparent power (S_1) is the appropriate measure. The traditional 'power triangle' relating P, Q, and S holds only for P_1, Q_1, and S_1. This is important as many utilities measure two quantities and then derive the third for billing purposes.

$$S_1 = V_1 I_1 = \sqrt{P_1^{\,2} + Q_1^{\,2}} \quad (12)$$

For revenue metering purposes, the fundamental power factor is appropriate.

$$PF_1 = \frac{P_1}{S_1} \quad (13)$$

III. How Should Revenue Metering Treat Non-Fundamental Power Components?

All non-fundamental power components, however defined, are ultimately converted from the fundamental frequency power, by the non-linear load and interacting components of the power system. These converted components are all reflected in the new IEEE 1459 non-fundamental apparent power S_N. This in turn is decomposed into voltage distortion power D_V, current distortion power D_I, and harmonic apparent power S_H, which shed additional light on the nature of the distortion power.

A Smarter Meter should measure these quantities and make them available for power quality monitoring or billing for excessive distortion powers. The use of the new powers in rates will evolve over time. The most important issue at the moment is to build them into meters and recognize them in metering standards.

IV. Ploggs and the Teridian 71M6511 Meter Chip

The Load Analysis Group at BC Hydro has been using UK made plug loggers, Ploggs, (Figure 1) for appliance load research for over three years. The Ploggs are based on one of the earliest Smart Meter chips, the Teridian 71M6511. The Plogg measures up to 12 electrical parameters and stores the data to a non-volatile memory at preselected time intervals. Periodically it transfers this data to a PC using Zigbee radio.

The 71M6511 was the first of a family of "System-on-a-Chip" metering chips developed by Teridian (now owned by Maxim). All of these chips have a similar basic architecture, though the later versions have more memory and can operate at higher speeds.

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 each input roughly every 400us.

The DSP processor does all the calculations necessary to update the DSP registers every A/D conversion cycle. 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 W0SUM register. The voltage gets a 90^0 phase delay and gets multiplied by the current and these values are accumulated in the VAR0SUM register. Voltage and current are squared and then summed in V0SQSUM and I0SQSUM registers. In addition, the DSP performs various other tasks such as temperature compensation and frequency measurement.

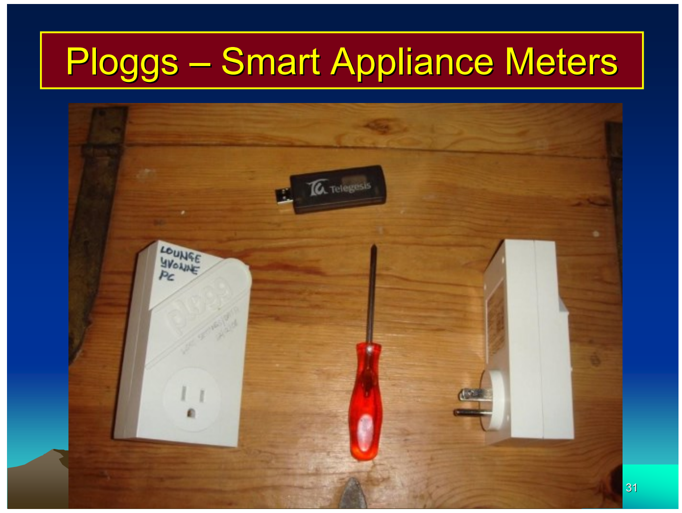

Figure 1 - Plogg

About once a second the microcontroller reads the relevant DSP registers and updates the Plogg's metering registers with the new data, performing additional calculations as necessary. Vrms and Irms are obtained by taking the square root of the V0SQSUM and I0SQSUM registers respectively. Apparent power S is calculated from Vrms and Irms. Data storage and communications over the Zigbee network are managed.

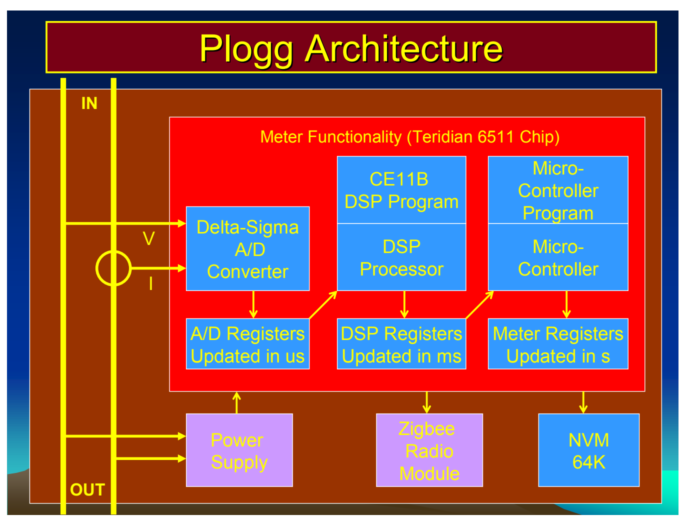

Figure 2 – Plogg Architecture

The more accurate implementations of Q_B use an all-pass digital filter to get a constant phase shift over a wide frequency range. Some implement the phase shift with a digital integrator, which attenuates higher harmonics:

$$Q_{BI} = \sum \left(\frac{1}{h} V_h I_h \sin \theta_h \right) \tag{14}$$

The ‘broadband’ VAR calculations in the CE11B and CE11C03 use a digital integrator. As the higher harmonics are attenuated by this process, the Q_{BI} measurement is close to Q_1 unless there are considerable second and third harmonic reactive power components. This definition is not ideal for billing, as it nets reactive powers at different frequencies.

The Teridian/Maxim series of metering chips are unique in that the DSP program can be updated to provide measurements based on different definitions. The standard DSP program for the 6511, as described above, is the CE11B. Teridian provided the author with another version of the DSP program, CE11C03, which enhanced CE11B for fundamental power measurements. It applied digital filtering to the voltage and current, and added four new registers for the fundamental active and reactive power, and the sums of the squares of the fundamental voltage and current.

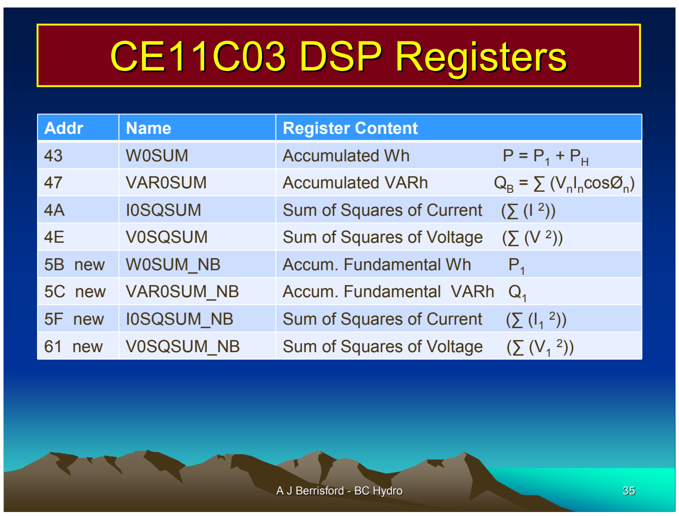

Figure 3 – CE11C03 Registers

These four new registers allow one to calculate the important fundamental power quantities P_1, Q_1, and S_1. In addition, they make it possible to calculate the new power quantities defined in IEEE 1459:

$$S_N = \sqrt{S^2 - S_1^{\,2}} \tag{15}$$

$$S_H = V_H * I_H \tag{16}$$

$$P_H = P - P_1 \tag{17}$$

With fundamental rms voltage and current values, the Smarter Meter can also calculate the newly defined distortion powers D_I and D_V:

$$D_V = V_H * I_1 \tag{18}$$

$$D_I = V_1 * I_H \tag{19}$$

These new power quantities may prove useful for revenue metering, as they provide a clear view of the magnitude of distortion power and its likely association with customer (current) and utility (voltage).

Finally, the traditional and fundamental frequency power factors can be determined.

V. Testing the CE11C03 DSP Program

The author previously tested the ability of several Smart Meter chips to extract the fundamental frequency power components from distorted voltage and current signals [1]. These included the 6511, and proved it capable of the calculations necessary to apply the fundamental frequency power definitions accurately.

This paper takes the tests from the laboratory to the real world, and examines the Plogg measurements of several appliances using the IEEE-1459 definitions. The phase shift of the Plogg’s 20A DC tolerant CT was compensated (but the additional temperature compensation suggested by Teridian [6] was not applied as the Plogg was operated in a temperature controlled environment). Three appliances were chosen to represent different types of load. The Plogg was reprogrammed with the new CE11C03 DSP program and the selected appliances monitored for several hours each.

The quantities produced by the CE11C03 DSP program were read out of the DSP registers manually, and a spreadsheet was used to perform the calculations. All tests were repeated to confirm that the results were consistent. The tests emphasize the relationships between the different quantities to illustrate the shortcomings of P and Q_{BI} in the presence of harmonics.

The accuracy of the 6511 is within 0.5% over a 2000:1 range [7], which implies that the results for quantities below about 1 W, VA, or VAR, the accuracy of the reported results may exceed 0.5%.

VI. Test Results

A. A kitchen kettle

The first appliance selected was a simple kitchen kettle. This has a load near the maximum for the Plogg, which will provide good resolution, and it is expected to be a linear resistive load. The measurements, derived from the DSP register readings processed in a spreadsheet, are tabulated below:

Table I – Kitchen Kettle Power Values

	Quantity	Value
P	Active Power (W)	1288.8
Q_{BI}	Budeanu Reactive Power (VAR)	0.3

S	Apparent Power (VA)	1288.9
P_1	Fundamental Active Power (W)	1288.6
Q_1	Fundamental Reactive Power (VAR)	0.3
S_1	Fundamental Apparent Power (VA)	1288.6
P_H	Harmonic Active Power (W)	0.2
S_N	Non-fundamental Apparent Power (VA)	28.2
D_I	Current Distortion Power (VAR)	19.3
D_V	Voltage Distortion Power (VAR)	20.6
S_H	Harmonic Apparent Power (VA)	0.3
PF	Power Factor	1.00
dPF	Displacement Power Factor	1.00
THD_V	Total Harmonic Distortion - Voltage	1.6%
THD_I	Total Harmonic Distortion - Current	1.5%

The 'total' and fundamental power measurements are as expected. The small amounts of non-fundamental power S_N, D_V, and D_I are probably reasonable. The THD_V, THD_I, and P_H values also appear reasonable.

B. A kitchen fridge

The second appliance selected was a kitchen fridge expected to have a reactive load with little distortion. The Plogg measurements are in Table II

Table II – Fridge Power Values

	Quantity	Value
P	Active Power (W)	137.76
Q_{BI}	Budeanu Reactive Power (VAR)	190.13
S	Apparent Power (VA)	235.21
P_1	Fundamental Active Power (W)	137.58
Q_1	Fundamental Reactive Power (VAR)	190.09
S_1	Fundamental Apparent Power (VA)	234.71
P_H	Harmonic Active Power (W)	0.07
S_N	Non-fundamental Apparent Power (VA)	15.40
D_I	Current Distortion Power (VAR)	14.64
D_V	Voltage Distortion Power (VAR)	4.78
S_H	Harmonic Apparent Power (VA)	0.30
PF	Power Factor	0.59
dPF	Displacement Power Factor	0.59
THD_V	Total Harmonic Distortion - Voltage	2.0%
THD_I	Total Harmonic Distortion - Current	6.2%

The fridge has a poor power factor, and generates little harmonic active power, but strangely the current distortion is higher than the voltage distortion, indicating that the fridge generates some current distortion. A repeat of the tests gave similar figures, confirming this unexpected result.

C. A kitchen microwave oven

The third appliance selected was a kitchen microwave oven. This also has a load near the maximum for the Plogg, and it is expected to generate significant current distortion. The Plogg measurements are listed in Table III.

Table III – Microwave Oven Power Values

	Quantity	Value
P	Active Power (W)	1180.1
Q_{BI}	Budeanu Reactive Power (VAR)	73.1
S	Apparent Power (VA)	1256.2
P_1	Fundamental Active Power (W)	1190.1
Q_1	Fundamental Reactive Power (VAR)	74.9
S_1	Fundamental Apparent Power (VA)	1193.1
P_H	Harmonic Active Power (W)	-10.0
S_N	Non-fundamental Apparent Power (VA)	393.2
D_I	Current Distortion Power (VAR)	391.0
D_V	Voltage Distortion Power (VAR)	39.5
S_H	Harmonic Apparent Power (VA)	12.9
PF	Power Factor	0.94
dPF	Displacement Power Factor	1.00
THD_V	Total Harmonic Distortion - Voltage	3.3%
THD_I	Total Harmonic Distortion - Current	32.8%

The microwave has some interesting load characteristics that the new definitions highlight. The current distortion of 33% adversely affects the voltage distortion, increasing it from the background 2% to 3%. This combination generates over 390 VA of non-fundamental apparent power, most of which is current distortion power.

It also generates 10 W of harmonic power, converted from the supplied fundamental power, and feeds this back into the supply network. This amounts to about 0.75% of the fundamental power supplied to the microwave, a difference of more than the error allowed by accuracy class 0.5% or 0.2% Smart Meters.

Should a Smarter Meter indicate the P value of 1180.1 W or the P_1 value of 1190.1 W? One might argue that the microwave oven presents a net load of only 1180.1 W, as the harmonic power performs no service for the customer. However, from a revenue metering perspective, the utility has to generate 1190.1 W for the microwave, even though it only makes use of 1180.1 W. In fact the utility also has to accommodate the 10 W of unwanted harmonic power, which adds to their distribution losses and reduces their equipment's useful life. A Smarter Meter should record both quantities, allowing the debate to continue for those still undecided.

The non-fundamental apparent power amounts to a surprising 393 VA, almost a third of the active load. This is mostly current distortion power (361 VAR) and a little voltage distortion power (39.5 VAR). These new power quantities provide insight into the nature of the distortion and may become vehicles for billing the additional costs of supplying nonlinear loads. One could for example attribute the voltage distortion power (39.5 VAR) and an equivalent amount of current distortion power to the utility, and the difference between the voltage and current distortion power (353.5 VAR) to the nonlinear load.

The differences between P and P_1 for the kettle and fridge are insignificant. However, the difference for the microwave oven exceeds the limits of accuracy class 0.5% or 0.2% meters. This highlights the importance of clear definitions for accurate revenue metering.

VII. Standards and the Smarter Meter

North American utilities use the ANSI C12 series of standards [8] for revenue metering. These standards specifically require sinusoidal voltage and current waveforms for their compliance tests. The tests actually evaluate the meter's performance at measuring fundamental power P_1, not total power P. The effect of harmonic distortion on an ANSI C12 compliant meter is therefore unknown and unstated. This means than no ANSI C12 compliant meter would measure the microwave load above with a certifiable accuracy. The IEC 62053 standards [9] are used by most of the rest of the world for revenue meter requirements. IEC 62053-21 includes tests to ensure that harmonics do not adversely affect the meter's energy reading, but is unclear as to whether the reading should be P or P_1. IEC 62053-23, which covers VARh meters, explicitly states that the standard applies to only fundamental reactive energy.

As a consequence, we have the bizarre situation where

a) We have a revenue metering need to measure *fundamental* quantities P_1, Q_1, and S_1 under sinusoidal or nonsinusoidal conditions,

b) While vendors supply Smart Meters that record approximations of P, Q_B, Q_F, or Q_{BI} and S, which may include some harmonic components,

c) Which have all been certified to measure only *fundamental* quantities P_1, Q_1, and S_1 under only sinusoidal conditions!

Smarter Meters will require amendments to ANSI C12 standards and IEC 62053 standards, including:

1) Distinct definitions of the fundamental and 'total' power quantities P, P_1, Q, Q_1, S, and S_1.
2) Tests to determine the meter's ability to extract the fundamental components under non-sinusoidal conditions.

These amendments will signal meter manufacturers and metering chip manufacturers that the new definitions are the answers that metering engineers have been seeking for decades.

VIII. Conclusions

A change to the DSP program in a common Smart Meter chip has implemented the new power definitions in IEEE Standard 1459. The new DSP code was programmed into a Smart Appliance Meter and tests on several common appliances indicated that the new power definitions were being applied correctly and accurately. These new power definitions have the following advantages for revenue metering:

1) Utilities will be able to bill customers for the products they generate and sell – fundamental frequency energy, fundamental demand in kW or kVA, and fundamental power factor management in kVAR or dPF.
2) Any meter measuring P_1, Q_1, and S_1 can be replaced by any other meter applying the same definitions, on any load, and the meters will produce the same readings.
3) The additional non-fundamental power definitions S_N, D_V, D_I, and S_H provide new and well-defined views of harmonic impacts at a metering point. It will take some time for metering engineers to become familiar with these measurements and their implications. These quantities could form the basis of power quality measurements and rates in the future.
4) Customers will not be penalized or benefit from metering errors caused by inadequately defined quantities.

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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 eight years, and contributes regularly at the annual AEIC and WLRA load research conferences.