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INVESTIGATION AND ANALYSIS OF INDUSTRIAL POWER METERS IN INDUSTRIAL PLANT

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ABSTRACT
This paper describes the analysis of industrial power meters in the presence of harmonics and unbalanced three phase systems. The measuring instruments are used for the analysis of alternating current systems, in particular where conventional analogue measuring instruments no longer fulfil continuously growing demands. This is especially applicable where harmonics distortion is crucial in addition to current, voltage and power.

KEY WORDS
Power System Harmonics, Power measurements, IEEE Working Group, Power Definitions, Power meters.

1. Introduction

More than a century of study and dealing with energy flow and electrical power has passed, yet there is still some confusion with regards to the power phenomena in electrical circuits. This is unfortunate since electric energy has become the backbone of our technological advances and betterment of human life. There have been numerous publications and discussions showing that the relation between energy flow and power as well as the power phenomena in electrical circuits are misinterpreted and not clearly understood.

The increase in recent decades of electrical equipment that produce harmonics has posed significant problems for electrical networks and power quality. Harmonics are sinusoidal voltages or currents, the frequency of which are a multiple of the fundamental frequency (50 Hz) of the power system. Because electrical devices that act as non-linear loads draw current non-linearly, they are responsible for injecting harmonic currents into the electricity network. Some problems caused by harmonics include cable/conductor failure and the overheating of transformer windings.

The harmonic measurement process in industrial plants begins with the choice of equipment and techniques that will determine the validity of results. Power measuring instruments are initially calibrated on a pure sinusoidal current and subsequent use on a distorted electricity supply can be prone to error. One cannot buy just any power meter thinking that it will serve the required purpose.

A number of researchers have proposed different theories for the definition of power in circuits with distortion. When choosing a meter for an industrial plant, care must be taken that these meters measure power quantities correctly and that the meters do not use power theories that give erroneous results.. It is also important to decide which power quantities are important to measure for the specific application. For this Engineers in industries have to be knowledgeable about the different power theories. This is difficult for the man in the industry, who needs to understand it in order to design, specify and service equipment. Only rarely can the industry afford to sacrifice the time and effort demanded by an understanding of these theories. It is true that the different definitions suit different applications better than others and that the diversity is sometimes advantageous.

To most electrical engineers the apparent power S in three phase circuits is the quantity calculated by either of the following two methods:

$$S_A = U_R I_R + U_S I_S + U_T I_T \tag{1}$$

This is known as the arithmetic apparent power. Where U is the RMS voltage and I is the RMS current at load terminals R, S and T.

$$S_V = \sqrt{P^2 + Q^2} \tag{2}$$

This is known as the vector apparent power. Where P is the active power and Q is the reactive power of the load.

Definitions (1) and (2) were introduced in Ref. [1] and supported by the IEEE Standard 100 [2].

There is also a rather unknown method to determine the apparent power S, which is however not even mentioned in Ref. [2]. In 1922 Buchholz defined [3] the apparent power S in three phase systems as:

$$S_B = \sqrt{I_R{}^2 + I_S{}^2 + I_T{}^2} \cdot \sqrt{U_R{}^2 + U_S{}^2 + U_T{}^2} \tag{3}$$

This is known as the Buchholz-Goodhue apparent power. Where again U is the RMS voltage and I is the RMS current at load terminals R, S and T. This definition for apparent power was explained in 1933 by W. M. Goodhue [4] and is supported by the IEEE standard 1459 [5]. Thus there are multiple accepted definitions for the apparent power S, however they do not yield the same value of S under certain conditions. Modern day meters also differ in this sense, hence there is no norm.

Expression (1) originates from the following expression:

$$S = (V_{LN} I)_a + (V_{LN} I)_b + (V_{LN} I)_c = 3V_{LN} I \qquad (4)$$

where a, b and c denotes the different phases. This expression (4) is a well known method which along with expression (2) originating from the power triangles of an electrical circuit is taught in early engineering courses. Expression (3) is recommended for use by the IEEE standard 1459 [5] and originates from the Buchholz-Goodhue apparent power.

2. The IEEE Working group definitions

The work of the IEEE Working Group [6] on non-sinusoidal situations presents a set of practical definitions for distortion power in terms of the total, fundamental and harmonic constituents. It has been decided that these definitions will later be analyzed numerically in the measurements, to evaluate their practical utility.

The RMS value of a general complex time-dependent periodic waveform can be expressed for voltage as:

$$U = \sqrt{\sum_n \boldsymbol{U}_n \boldsymbol{U}_n^*} = \sqrt{\sum_n |\boldsymbol{U}_n|^2} \qquad (5)$$

Similarly, the effective value of the current is:

$$I = \sqrt{\sum_n \boldsymbol{I}_n \boldsymbol{I}_n^*} = \sqrt{\sum_n |\boldsymbol{I}_n|^2} \qquad (6)$$

The harmonic RMS components in (5) and (6) can be separated into their fundamental and harmonic components:

$$U^2 = U_1^2 + U_H^2 \qquad (7)$$

and

$$I^2 = I_1^2 + I_H^2 \qquad (8)$$

with:

$$U_H = \sqrt{\sum_{n \neq 1} |\boldsymbol{U}_n|^2} \qquad (9)$$

and

$$I_H = \sqrt{\sum_{n \neq 1} |\boldsymbol{I}_n|^2} \qquad (10)$$

The *total apparent power S* is defined as:

$$S = \sqrt{\sum_n |U_n|^2 |I_n|^2} \qquad (11)$$

and the *total non-active power N* as:

$$N = \sqrt{S^2 - P^2} \qquad (12)$$

3. Industrial considerations

The following selection criteria were used when choosing a power meter.

- The readings of the meter must be understandable. It is of the utmost importance that when a meter reads reactive power, it should agree with the general understanding of reactive power in sinusoidal conditions.
- The power theory (mathematics) used by the meter manufacturer to define active, reactive and apparent power must be readily available.
- The meter must be able to do measurements with harmonics.
- The meter should have good software capability and availability.
- The cost of the meter should be economical.

Meters that were installed and new meters that were considered for use will be described in two industrial pants namely the Satellite Application Centre and a Chemical plant.

4 Industrial plant 1 – Satellite tracking station

Electrical network diagram of the Satellite Application Centre is shown in Fig 1.

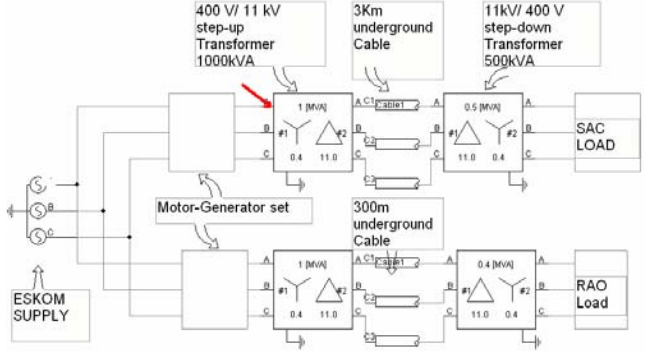

Figure 1. Network diagram

The two networks are coupled to the same bus on the Utility (ESKOM) side. The two networks are not directly coupled to the grid; each network has its own converter (50Hz – 60Hz). A measurement (Fig 2) was taken at the generator, on the primary side of the 400V/11KV, 1MVA step-up, just after the motor-generator set transformer as shown in fig. 1. Due to the age of the SAC (Satellite Application Centre) supply, it was advisable to replace the existing meters because of hardware problems and the maintenance of the meters. One cannot buy just any power meter thinking that it will serve the required purpose.

The apparent power is a quantity that is very useful in the predominantly sinusoidal practice. When the current and the voltage are distorted, different aspects of the voltage and the current relationship become important, depending on the power equipment and the problem. Fig 2 shows that the current waveform is non-sinusoidal; this shows that there are non-linear loads on the network, propagating harmonics all over the network and back to the power source. Two power meters were considered for use in SAC Meter A and Meter B. These meters appropriates will now be considered for use in the supply network.

4.1 Meter A

Company A sells a power meter that the company suggested should be adequate for use by SAC. The meter was demonstrated and weighted against the selection criteria. They did not supply a meter for field tests. Therefore, it was not possible to do experiments. The formulas that were given in the datasheet were used instead. A program was developed in MATHCAD to show how METER A calculates power by using the supplied formulas by the manufacturer and comparing the results with the IEEE definition. The results are shown in Table 1. Figure 2 shows the waveforms used for this comparison.

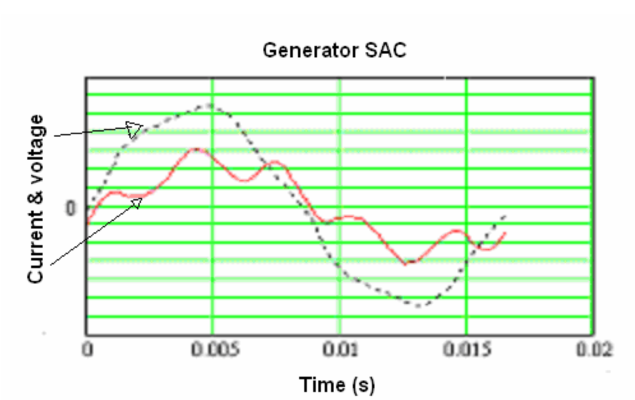

Figure 2. Current and voltage waveforms used for comparing METER A and IEEE

The results show that there is a huge difference in the reactive power due to the way in which METER A calculates their reactive power because they combine the harmonic components with the fundamental components unlike the IEEE definition of reactive power [1], where the harmonic components are separated from the fundamental components.

Table 1
Comparison of IEEE and METER A Fundamental power

Description	METER A	IEEE
Apparent power (S1)	36.8kVA	36.8kVA
Active power (P1)	32.6kW	32.8kW
Reactive power (Q1)	3.3kVar	12kVar

One may ask whether METER A will work when it is coupled to the supply. From the theory of the IEEE, this will not work properly because the utility generates a sinusoidal voltage waveform at 50Hz frequency. The objective of the transmission is to deliver as much of the power as possible through the 50Hz positive sequence component to the consumer. It therefore makes sense to separate the fundamental and the harmonic components from each other in the analysis by the IEEE definition of fundamental active and reactive power.

4.2 Meter B

The supplier of Meter B did not supply formulas to show how to calculate active, reactive and apparent power. Therefore, instead of calculations, measurements were taken (Fig 2) in Table 2, to compare METER B and the fluke using the IEEE as the benchmark.

Table 2
Measurement and calculated comparison

60W Bulb with light dimmer to generate harmonics				
Description	METER B	Fluke	IEEE	% Difference METER B and Fluke
Voltage (V)	227.6	228	227.7	0.4
Current (A)	0.224	0.23	0.235	0.006
Active Power (W)	47.2	48	48.3	0.8
Reactive Power (Var)	10.9	10	10.2	0.9
Apparent Power (VA)	50.9	53	53.5	2.1
Power Factor	0.94	0.90	0.90	0.04
60 W bulb without light dimmer (no harmonics)				
Voltage (V)	227.8	228	227	0.2
Current (A)	0.258	0.28	0.22	0.022
Active Power (W)	59	62	59.3	3
Reactive Power (Var)	0	5	3.5	
Apparent Power (VA)	59	63	59.4	4
Power Factor	1	0.98	0.998	0.02

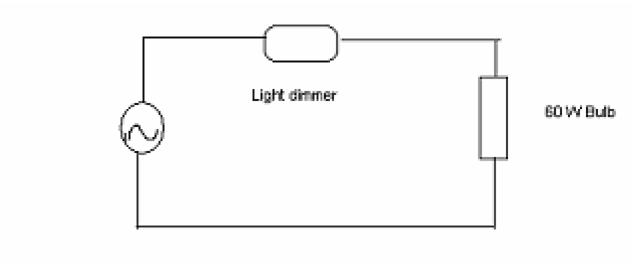

Figure 3. Circuit diagram used for comparing METER B and fluke

The results from Table 2 show a small percentage difference between METER B and the fluke, so this meter can serve the purpose. Note the measurement in the absence of the light dimmer. The reactive power of METER B is 0Var but the reactive power of the fluke is 5Var and the IEEE is 3.5Var, which is fundamental. The 60W bulb is not a purely resistive element. It has some reactive components as well.

The most important aspect for comparing these two power meters is to compare the values of the reactive power. The readings of the apparent power and the active power are not affected by harmonics, but harmonics present a problem to the measurement of reactive power since this reactive power is defined with respect to a sinusoidal waveform. The main cause of uncertainty due to harmonics at the reactive power measurement is that there is no generally accepted reactive power definition when harmonics are present in the system.

The major reason for this confusion about the reactive power definition in the sinusoidal situation is that it is assigned some very useful physical properties, but when extended to the non-sinusoidal situation, no definition can maintain all these properties [7,8].

The confusion over the definition of reactive power and the large difference in the measurement based on the different definitions makes it impossible to disregard the definition problem. A basic solution to this problem is to consider what information is really wanted or needed from the measurement taken and then to choose the measurement method. The most important aspect with harmonic measurements is to check that the instrument used to measure is measuring according to the expected definition. This is a seldom-mentioned effect, but an important one.

5. Industrial plant 2 – Chemical plant

Readings versus theoretical calculations

5.1 Method 1 (M1)

The system was configured using the three phase, four wire system. Hence, for total power calculation at a specific point in time equation 13 will be applicable.

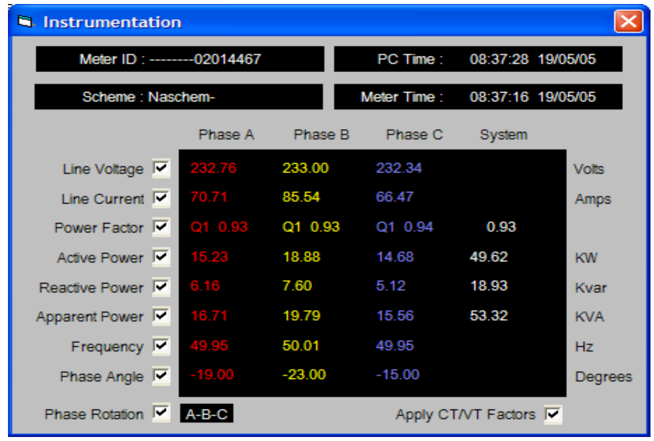

Figure 4. Real Time: Administration Blocks (Meter 1)

Voltage, current and phase angle data are extracted from the real time analysis (figure 4) for an administration block.

$$P = V_{AN}.I_A.\cos\phi_A + V_{BN}.I_B.\cos\phi_B + V_{CN}.I_C.\cos\phi_C \quad (13)$$

$V_{AN} = 232.76$ V, $I_A = 70.71$ A, $\phi_A = 19^\circ$

$V_{BN} = 233$ V, $I_B = 85.54$ A, $\phi_B = 23^\circ$

$V_{CN} = 232.34$ V, $I_C = 66.47$ A, $\phi_C = 15^\circ$

Hence, the power for each phase will be as follows:

$$P_A = V_{AN}.I_A.\cos\phi_A \quad (14)$$

$$P_B = V_{BN}.I_B.\cos\phi_B \quad (15)$$

$$P_C = V_{CN}.I_C.\cos\phi_C \quad (16)$$

This means that the total power as indicated in equation 13 can be stated as in equation 17.

$$P = P_A + P_B + P_C \quad (17)$$

Calculating each area's power and then the total power, follows:

$$P_A = V_{AN}.I_A.\cos\phi_A = 15.561 \text{ kW} \quad (18)$$

$$P_B = V_{BN}.I_B.\cos\phi_B = 18.346 \text{ kW} \quad (19)$$

$$P_C = V_{CN}.I_C.\cos\phi_C{}^\circ) = 14.917 \text{ kW} \quad (20)$$

$$P = P_A + P_B + P_C = 49.824 \text{ kW} \quad (21)$$

Using the tanϕ function, the reactive kVARs for each can be calculated and a total provided as well.

$$Q = Q_A + Q_B + Q_C = 17.14 \text{ kVARs} \quad (22)$$

Similarly, the apparent power per phase and the total thereof, can be calculated by using the cosϕ function.

$$S = S_A + S_B + S_C = 51.831 \text{ kVA} \quad (23)$$

The meter readings and the calculated quantities have been tabulated below for referencing.

Table 3
Meter Readings versus Calculations

Function	Meter Measured	Calculated M1	Unit
P_A	15.23	15.561	Kw
P_B	18.88	18.346	Kw
P_C	14.68	14.917	kW
P	*49.62*	*49.824*	*Kw*
Q_A	6.16	5.356	kVAR
Q_B	7.60	7.787	kVAR
Q_C	5.12	3.997	kVAR
Q	*18.93*	*17.14*	*kVAR*
S_A	16.71	16.458	kVA
S_B	19.79	19.930	kVA
S_C	15.56	15.443	kVA
S	*53.32*	*51.831*	*kVA*

The phase values do not seem to be very far apart however, significant difference is noted for the total power in each category. The most notable differences are in the calculation of reactive power where differences of up to 21% are shown in Table 3. A difference of 3% in the total apparent power also warrant further investigation. Additionally, not much harmonics could be identified. Refer to annexure L for waveform profile.

5.2 Method 2 (M2)

$$S = \sqrt{ (\{V_{AN}^2 + V_{BN}^2 + V_{CN}^2\} \times \{I_A^2 + I_B^2 + I_C^2\} } = 52.137 \text{ kVA} \quad (24)$$

Table 4
Apparent Power Meter Readings versus Calculations

Function	Meter Measured	Calculated M1	Calculated M2	Unit
S	53.32	51.831	52.137	kVA

It can be clearly seen that for the three methods used to attain the total apparent power, three different quantities resulted. Hence, the accuracy of the meters are questionable and are perhaps dependant on the method used to calculate the necessary outputs. This could be further dependant on the uneven phase consumption.

6. Conclusion

With increasingly non-linear loads in the system, measuring reactive energy accurately becomes a key issue for energy distributors. The traditional measurement method, such as the power triangle, shows limitations in the presence of harmonics or line frequency variation.

Existing methods of calibrating power measurement devices have their limitations, although until recently these have largely been somewhat inconsequential. As electricity distribution systems develop, these limitations will begin to impact on the requirement to make more accurate and more complex measurements.

As a response to improved billing, the measurement of reactive power is gaining interest. This growing interest in measuring reactive power leads to the question: what method should a power meter designer implement to measure the reactive power accurately? Although the electronic digital signal processing enables the reactive power measurement to be closer to the theoretical value, there is no consensus in the field of power metering on the method of measurement.

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