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EVALUATION OF REACTIVE POWER METERS IN THE PRESENCE OF HIGH HARMONIC DISTORTION

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Abstract - Four reactive power meters, operating on different principles, were tested under nonsinusoidal conditions. Because the definition and meaning of the nonsinusoidal reactive power are still being actively debated, the readings of the tested meters were compared with four nonsinusoidal reactive powers and the first harmonic reactive power. A digital instrument, programmed to measure each of these powers, was used as a reference.

INTRODUCTION

The performance of revenue meters under distorted waveform conditions is no longer of theoretical interest only. There is a proliferation of electronic loads and their number is expected to increase at an even faster rate as energy-saving devices are promoted. Some of these devices are very nonlinear in nature, draw currents very rich in harmonics and promote voltage distortion. The electrical industry is working to minimize the effects of this situation by proposing standards restraining harmonic injection into the system. However, in the meantime it is important to examine whether current instrumentation meets the requirements of a changing situation [1].

Most of the practical tests to date have concentrated on energy and VA meters [2], [3]. There is very limited data on behavior of reactive power meters [4]. There are two reasons for this. First, the definition and meaning of the reactive power under nonsinusoidal conditions are still being actively discussed [1]. However, there is an increasing recognition between engineers that the traditionally used definition of reactive power ("Budeanu reactive power") has no physical meaning and, at least theoretically, its application can either lead to misleading conclusions or does not supply the required information. There is no agreement on whether this traditional definition should be discarded and what new definition should be used instead. Several proposals have been forwarded, each having its merits. Practically none have been used in practice or implemented in a commercial instrumentation. Second, reactive power meters are more difficult to test; there are no reactive power standard meters on the market which would operate under nonsinusoidal conditions (regardless of the definition).

The work described in [4] is a good example of these difficulties. The authors experienced unexplained problems with calibrating an induction reactive power meter. The reported results are for sinusoidal voltage only, the test conditions were restricted to available nonlinear load, and Q_F ("Fryze reactive power") was used as a reference, a quantity which is not universally recognized as the nonsinusoidal reactive power.

This paper discusses different definitions of the reactive power and gives the reasons behind each proposal. Results of nonsinusoidal tests of four reactive power meters, operating on different principles, are presented. Readings of the tested meters are compared with different reference quantities to verify whether these readings can be interpreted as approximate measures of the different definitions.

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REACTIVE POWER DEFINITIONS

Sinusoidal Situation

When the voltage and current are sinusoidal, $v(t) = \sqrt{2}V\sin\omega t$ and $i(t) = \sqrt{2}I\sin(\omega t + \Phi)$, the product of voltage and current, known as instantaneous power p, is the rate at which the electric energy is transmitted into or out of the circuit.

$$p(t) = v(t)\cdot i(t) = VI\cos\Phi - VI\cos\Phi\cos 2\omega t + VI\sin\Phi\sin 2\omega t$$
$$= P(1-\cos 2\omega t) + Q\sin 2\omega t \qquad (1)$$

The average value of p, the active power P,

$$P = VI\cos\Phi \qquad (2)$$

is the average value of energy transfer.

The reactive power Q is defined as

$$Q = VI\sin\Phi \qquad (3)$$

The reactive power is added geometrically to the active power to obtain the apparent power S.

$$S = VI = \sqrt{P^2+Q^2} \qquad (4)$$

The efficiency of the system utilization is expressed as the power factor PF.

$$PF = P/S = \cos\Phi \qquad (5)$$

The sinusoidal reactive power has several interpretations, related to its mathematical representation and the physical phenomena it expresses. The most important properties and interpretations are as follows.

(a) The reactive power is the quantity expressed in terms of $VI\sin\Phi$.
(b) The reactive power is a signed quantity.
(c) The reactive power in the system can be balanced; the reactive powers flowing into the node are equal to the reactive powers exported from the node, such that their algebraic sum is zero.
(d) The reactive power is the magnitude of the bidirectionally pulsating component of p, and the active power is the magnitude of the unidirectionally pulsating component.
(e) The reactive power is proportional to the amount by which the mean value of the stored electrostatic energy exceeds the mean value of the stored electromagnetic energy during a cycle.
(f) The reactive power can be compensated using a linear shunt/series reactive element, capacitor or inductor. It can be used to calculate the compensating shunt capacitor or inductor.
(g) The compensation of the reactive power increases the load power factor to unity.
(h) The geometrical sum of the reactive and active powers is the apparent power.
(i) The line voltage drop in transmission lines, predominantly inductive in practice, depends only on the reactive power. (The active power determines the angle of transmission.)

Nonsinusoidal Situation

The definition of the nonsinusoidal reactive power is an extension of the sinusoidal definition. However, **in a nonsinusoidal situation there is no one quantity which has the same properties as the sinusoidal reactive power**. All nonsinusoidal extensions of the reactive power definition preserve only certain properties, but do not preserve the others. The main disagreement between the different proposals can be explained as a disagreement of opinions on what is the nature of "reactiveness" of the reactive power. Is it related to the oscillation of energy? Or is it related to the method of compensation (i.e improving the load power factor)? Or is it related to some other property? Some of the definitions applied in the nonsinusoidal situations are discussed below.

First Harmonic Reactive Power

The energy transfer from a Utility to its customers is conducted at the mains frequency. Energy relations at this frequency are of primary importance, the rest of the frequencies can be treated as noise or pollution [1]. (This may not be the case for some switching loads.) If such an approach is taken, then only the value of the first harmonic reactive power Q_1 is important.

$$Q_1 = V_1 I_1 \sin\Phi_1 \tag{6}$$

where V_1, I_1 and Φ_1 are first harmonic rms voltage, current and phase shift angle.

It should be noted that no reactive power meter available on the market, apart from expensive harmonic power analyzers, specifically measures the reactive power of the first harmonic.

Budeanu Reactive Power

The classic definition of nonsinusoidal reactive power is due to Budeanu [1], and is often called the Budeanu reactive power Q_B.

$$Q_B = \sum_h V_h I_h \sin\Phi_h \tag{7}$$

where h is the harmonic number. Definition (7) has been structured to have a form analogous to the definition of nonsinusoidal active power P.

$$P = \sum_h V_h I_h \cos\Phi_h \tag{8}$$

There is a perception among engineers that Q_B expresses oscillations of energy between the source and the load, energy which is not absorbed by the load but causes transmission losses and voltage drops. This perception is false [5]. It presumes that the phase shifts between the voltage and current harmonics are caused only by reactive, energy-storing devices, capacitors and inductors. In practice nonlinear elements, such as thyristor controlled loads, also cause phase shifts between voltage and current harmonics, but do not cause energy oscillations. Generally it is impossible to distinguish whether the phase shift has been caused by a reactive element or a nonlinear load.

This definition of reactive power preserves properties (a), (b), (c), and (h), i.e. it is expressed in terms of $VI\sin\Phi$, it is a signed quantity, its algebraic sum in the node is zero. In general it cannot be used to calculate the compensating element. No commercial instrumentation is available for measuring Q_B.

Current Splitting

The following definitions of reactive power are based on a concept of dividing the load current into two or more components, presumably responsible for different energy phenomena. The load is presented in an equivalent form consisting of a linear equivalent resistor $R_e = V^2/P$ and a parallel combination of linear or nonlinear components or current sources, Fig. 1. The "basic" current component is called the "active current" i_a. This is the current flowing through the equivalent resistor R_e, Fig. 1 a, dissipating the load active power. The remaining current components are associated with the reactive power and/or other power components.

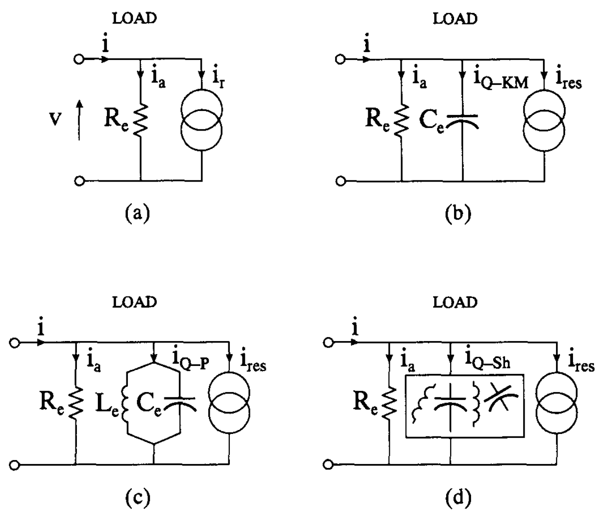

Fig. 1. Load-current splitting.

When the current splitting approach to the reactive power definition is taken then the reactive power is expressed in terms of the rms values of the voltage and the current I_Q associated with the given definition Q.

$$Q = V \cdot I_Q$$

The drawback of this approach is that it does not take into account the internal impedance of the source. In consequence, when a compensating shunt is connected the voltage and current waveforms and/or the configuration of the optimal circuit changes.

Fryze Reactive Power

The most general definition of the reactive power, based on the concept of the load current splitting is due to Fryze (c.f. [6] and [7]). The load current is decomposed into two components, Fig. 1 a, called the active and reactive currents

$$i = i_a + i_r \tag{9}$$

The reactive current i_r is the "useless" current component which does not contribute to the net transfer of energy, but which has to be delivered to the load together with the active current. This "useless" component causes transmissions losses and voltage drops. The active, reactive and apparent powers are expressed in terms of the rms values of voltage V and these two currents, I_a, I_r.

$$Q_F = VI_r = \sqrt{(VI)^2 - (VI_a)^2} = \sqrt{S^2 - P^2} \tag{10}$$

Q_F can be calculated directly from the apparent and active powers; there is no need to have a separate reactive power meter. The drawback of this approach is a loss of accuracy due to the calculation using the difference of squares. The active and reactive powers add geometrically to produce the apparent power.

Q_F is always positive; leading and lagging power factors cannot be distinguished. It retains properties (g) and (h). Its compensation, by injection of the compensating current $-i_r$, leads to the unity power factor. Several compensators operating on this principle are discussed in the literature.

Kusters-Moore Reactive Power

The compensation of the reactive power is carried out in practice by installing a bank of capacitors close to the load. The optimal value of this capacitor bank, for given voltage and current waveforms, can be determined as follows.

The load current is decomposed into three components, active, capacitive reactive and residual currents. The capacitive reactive current, $i_{Q\text{-}KM}$ in Fig. 1 b, has the same waveform and phase as that of the current in a capacitor with the same voltage across it. The magnitude of this current is such that it minimizes the rms value of the residual current. If an equivalent capacitor C_e, drawing this capacitive reactive current, has a negative value then a compensating capacitor connected in parallel with the load will compensate completely its loading effect. The compensating capacitor is the optimum capacitor for the given voltage and current waveforms.

The power of this equivalent capacitor, called the capacitive reactive power Q_{KM}, and calculated as

$$Q_{KM} = -\sum_h h V_h I_h \sin\Phi_h \sqrt{\frac{\sum_h V_h^2}{\sum_h h^2 V_h^2}} \qquad (11)$$

was proposed by Kusters and Moore [8] as the general definition of the reactive power.

If the capacitive reactive power is positive then no capacitive compensation is possible. In this situation an inductive reactive current and an inductive reactive power can be defined [8].

The Kusters-Moore definition preserves properties (b) and (f), with the reactive power being a signed quantity compensable by a single linear shunt capacitor/inductor.

<u>Sharon Reactive Power</u>

The definition of the reactive current as a current drawn by an optimum reactive shunt compensator of given configuration can be further extended for a two-element shunt, Fig. 1 c, Page [9], or to the maximum reactive current which can be compensated by a theoretical optimal combination of capacitors and inductors, Fig. 1 d. No better compensation can be achieved by the use of linear reactive elements. The reactive power resulting from such approach was first proposed by Shepherd in [10], [11], and generalized by Sharon [12]. Czarnecki interpreted this quantity using the load-current-splitting concept [13].

The following formula is used to calculate the Sharon reactive power Q_{Sh}.

$$Q_{Sh} = V\sqrt{\sum_h I_h^2 \sin^2\Phi_h} \qquad (12)$$

This definition preserves in a general sense the property (f).

<u>Power Factor</u>

The load power factor PF is considered to be a measure of efficiency of the energy utilization by the load. In a single phase sinusoidal situation only a purely resistive load has unity power factor, all other loads have a power factor lower than one. In a sinusoidal three-phase system only a symmetrical resistive load can have a unity power factor, [7].

The power factor is defined in terms of the active and apparent powers; however, in practice it is often calculated from the readings of active and reactive power/energy meters. The result of this approach PF' is always larger than PF (thus disadvantageous to Utilities).

$$PF' = \frac{P}{\sqrt{P^2 + Q_B^2}} > \frac{P}{\sqrt{P^2 + Q_B^2 + D^2}} = \frac{P}{VI} = PF \qquad (13)$$

where D is the "Budeanu distortion power".

In a nonsinusoidal situation PF has no relation to the phase shift (i.e. $PF \neq \cos\Phi$). For this reason some commercial instruments also display displacement factor DF, which is the power factor calculated for the first harmonic ($DF = \cos\Phi_1$).

<u>Applications of Reactive Power</u>

The discussion about the nonsinusoidal reactive power is a discussion about the "reactiveness", which quantity inherits sufficient number of the sinusoidal reactive power properties to be called the nonsinusoidal reactive power. In the past the most important properties were considered as related to the oscillations of non-dissipated energy (i.e. (d) and (e)). At present the compensation aspect appears to be stressed (properties (f) and (g)).

In practice what a given quantity is called is not important. It is important to understand what a given quantity expresses, what it does not express and to use the right indicator for the given task. This is why the classic definition of the reactive power Q_B is misleading. In the nonsinusoidal situation it does not reflect any important property of the network.

Aside from the theory one can distinguish three general areas where the reactive power is used: power system management, load compensation and customer billing.

In system management the first harmonic active/reactive energy generation, flow, and absorption is of interest. The nonsinusoidal reactive powers proposed to date would not help in determining, for example, how to control the system voltage through reactive power injection. The first harmonic reactive power appears to be the most appropriate indicator.

In the nonlinear load compensation the primary objective is bringing the load current to the sinusoidal-like zero-phase-shift condition. How this objective is achieved and what indicator is selected to monitor the difference between the compensated and non-compensated state depend on the design. To varying degrees the nonsinusoidal reactive powers Q_F, Q_{KM}, Q_{Sh} are such indicators.

In customer billing two factors appear to be important. First, how much of the first harmonic reactive power is the customer drawing? This causes transmission and distribution losses, upsets the reactive power balance and the node voltage. Second, is the client's load/current distorted, i.e. polluting the system and increasing the distribution losses? The first factor can be monitored by measuring the first harmonic reactive power or displacement factor DF, the second by measurement of the load current total harmonic distortion (THD). It is doubtful that a nonsinusoidal reactive power can be used for this purpose.

TESTED METERS

A sample of four meters, using different operating principles, representative of Ontario Hydro practice, were tested. The meters are denoted below as DIG, ANA, IWHM, IWHT 2e.

DIG - This is a sampling (i.e. purely digital) multi-function polyphase meter. The instrument takes instantaneous samples of three voltages and three currents and calculates quantities such as active power/energy, reactive power, voltage and current rms values, power factor, etc., from these digital samples. Apparent power (VA) is calculated using voltage and current rms values. The manufacturer does not provide particulars as to how the reactive power is calculated. Assuming, that the 90° phase shift is obtained by quarter-period time-delay of samples of one of the inputs, the reactive power reading of the meter, expressed in terms of reactive/active harmonic powers, is proportional to

$$Q_{DIG} = \frac{1}{T}\int_0^T v(t)\, i\left(t - \frac{T}{4}\right)dt = Q_1 - P_2 - Q_3 + P_4 + Q_5 \ldots$$

ANA - This is a solid-state (i.e. electronic) Wh/Lag/Lead Varh demand meter. The active power is measured by Time-Division Multiplier (TDM) elements and the reactive power is measured by multiplying current by voltage shifted by 90°. An active (inverting) integrator is used to perform the phase shift. The reading of the reactive power element is thus proportional to

$$Q_{ANA} = \frac{1}{T}\int_0^T \omega_1\left[-\int v(t)dt\right] i(t)dt = Q_1 + Q_2/2 + Q_3/3 \ldots$$

The apparent power is calculated from $\sqrt{P^2 + Q_{ANA}^2}$.

IWHM - This meter consists of two separate three-element induction watthourmeters and a microprocessor-controlled calculator and display. This is essentially an induction watthourmeter with a digital display. The potential coils of the second watthourmeter are lagged by 60° (rather than by 90°) by cross-phasing and the meter measures so called Qhour Qh. The reactive power is calculated as

$$Q_{IWHM} = \frac{2Qh - P}{\sqrt{3}}$$

The meter displays the active power, reactive power and apparent power demand calculated from $\sqrt{P^2 + Q^2_{IWHM}}$. In a nonsinusoidal situation the calculated reactive and apparent powers are complex functions of active and reactive harmonic powers.

IWHT 2e - This is a two-element combination energy and kVA thermal demand meter. An induction watthourmeter is used to measure energy. The apparent power is measured using a recti-thermal register; the voltage and current waveforms are rectified, filtered and then multiplied in a thermal quarter-square multiplier, $S_{IWHT} \sim \overline{|v(t)|}\,\overline{|i(t)|}$.

DESCRIPTION OF THE TESTS

Test System

The schematic diagram of the NRC test system is shown in Fig. 2 [2]. It consists of six computer-controlled digital arbitrary waveform generators, three voltage amplifiers and three current amplifiers. The test conditions, i.e. voltage waveform and current waveform numbers, amplitudes, and phase shifts, are entered from the keyboard. The program loads the required waveforms, stored previously on a hard disk, into the arbitrary waveform generators and sets the appropriate magnitude of their outputs. This outputs are then amplified to the required levels by set of three voltage and three current amplifiers. The tests were performed using the "phantom load" technique.

Voltages and currents, converted by a set of shunts to voltages, are measured using two wideband thermal ac voltmeters. Active power is measured using a standard Time-Division-Multiplier (TDM) wattmeter. Reactive powers (Q_I, Q_B, Q_F, Q_{Sh}, Q_{KM}) are measured using an instrument marked as a digital recorder, shown in detail in Fig. 3. The digital recorder consists of two digital multimeters and a PC-AT 386 type computer. The multimeters sample the test signals. These samples are sent via the IEEE-488 bus to the computer which calculates the required quantities. This

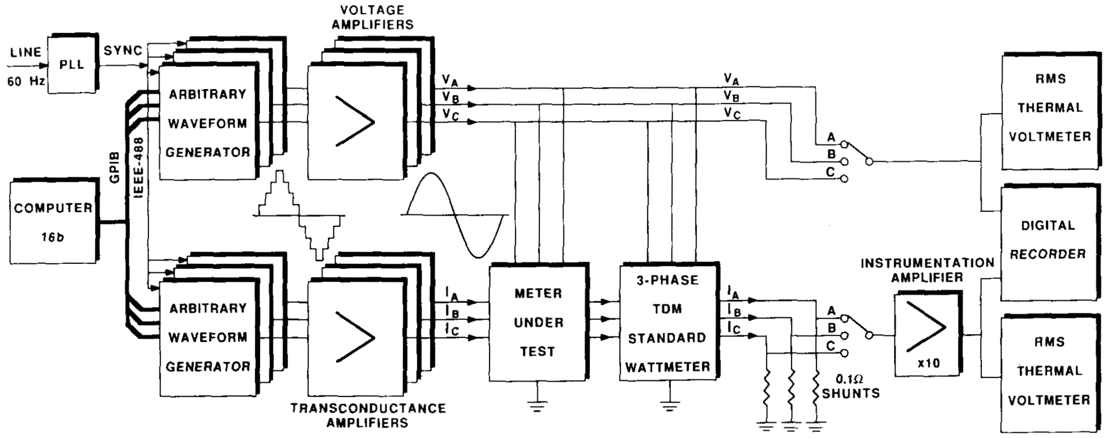

Fig. 2. Three-phase nonsinusoidal calibration system.

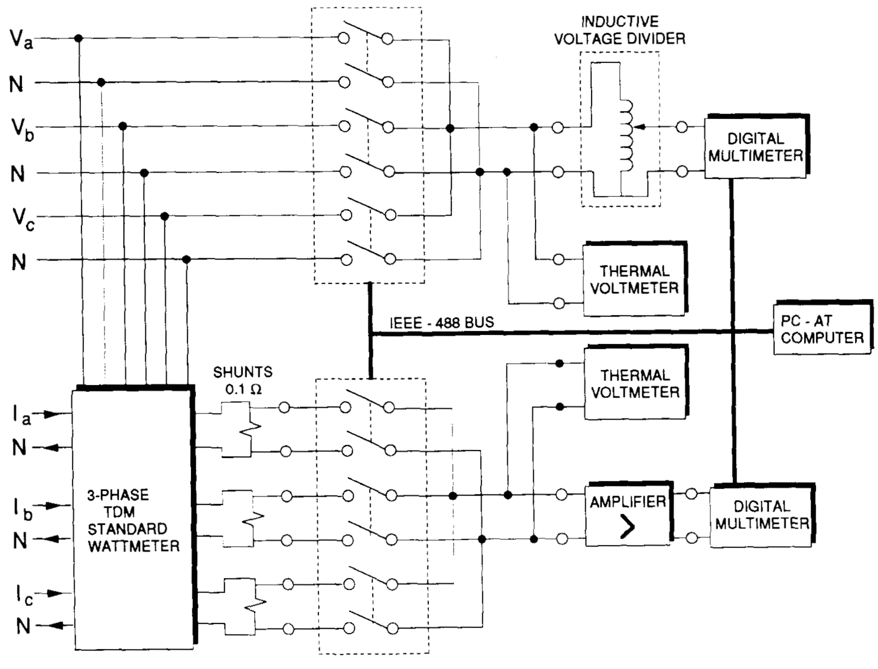

Fig. 3. Digital recorder.

is done either by operation on the time samples (Q_F) or on frequency components obtained after a fast Fourier transform of the data (Q_1, Q_B, Q_{Sh}, Q_{KM}). Sampling is synchronized with the fundamental harmonic frequency of the test waveforms, which in turn is synchronized with the main frequency, Fig. 2. The harmonic content of the test waveforms was limited to 128 harmonics. For this reason the sampling frequency was selected to be equal to 512 times the fundamental frequency, i.e. four times the maximum harmonic frequency.

Test Conditions

The meters were tested under sinusoidal conditions and eight nonsinusoidal conditions. The nonsinusoidal test waveforms are shown in Fig. 4. These waveforms were acquired in the field harmonic problem locations and, after limiting their spectra to 128 harmonics, stored in the NRC waveform library. The meters were thus tested under simulated field conditions. Table 1 shows voltage/current test waveform numbers, test active power, power factor, reactive powers as well as voltage and current harmonic distortions. The first two tests (001/001) refer to the sinusoidal conditions with the nominal phase angles ±30°. As the data in Table 1 indicate the test conditions generated in practice differ slightly from the nominal test conditions. The test voltage was 120 V_{rms}, the test current 5 A_{rms}, except for conditions 250/251 and 252/253 where it was 4 A_{rms} and 4.5 A_{rms}, respectively.

Table 1. Test Conditions.

TEST	P W	PF p.u.	Q_1 VA	Q_B VA	Q_F VA	Q_S VA	Q_{KM} VA	THD_V %	THD_I %
001/001	1557	0.865	+904	+904	+904	+904	-904	0	0
001/001	1562	0.867	-896	-896	+896	+896	+896	0	0
137/138	1588	0.882	+746	+746	+851	+796	-611	9.5	20
139/140	1637	0.908	+27	-2	+757	+504	+74	7.1	41
179/180	1663	0.923	+538	+533	+696	+635	-490	2.8	24
192/193	1620	0.898	+731	+731	+794	+753	-167	6.6	13
250/251	1235	0.855	+3	-18	+748	+228	+64	10	75
252/253	598	0.366	+1081	+994	+1522	+1342	-392	13	77
254/255	1550	0.859	+771	+745	+923	+807	-322	15	17
256/257	637	0.352	+1540	+1511	+1695	+1649	-314	13	37

Test Uncertainty

The uncertainty of the test results depends on the accuracy of the reference instruments, the stability of the test conditions and the repeatability and resolution of readings of the tested meters. It varies with the measured quantity, the test conditions and the tested meter.

The uncertainty of the reactive power reference meter is difficult to estimate in nonsinusoidal situations. However, assuming a linear operation, and taking advantage of the known harmonic content of the computer generated waveforms, the influence of a particular error source can be computed from the frequency characteristic of the error. Linear operation of the instrument must be verified by comparison with a different reference.

In order to simplify the presentation of results the maximum calibration system uncertainties and meters' uncertainties are cited below.

The calibration uncertainties include combined uncertainties of the standard instruments such as wattmeters, voltmeters, and digital recorder as well as the statistical uncertainty due to results averaging. At the three standard deviation level ($3-\sigma$) the reactive powers were measured with uncertainty of 0.09% of full scale i.e. 1800 VA.

The meters' uncertainties originate from a non-repeatability of readings, which varies with the test conditions, and a resolution uncertainty. For example, IWHT meter does not indicate the reactive power, it has to be calculated as $Q_{IWHT} = \sqrt{S^2 - P^2}$. Error propagation in this equation is very unfavorable. For example, the resolution uncertainty of a IWHT 2e meter equals ±0.5 division i.e. 10 W or 0.55% at 1800 VA level. The resolution uncertainty of the reactive power calculations can attain

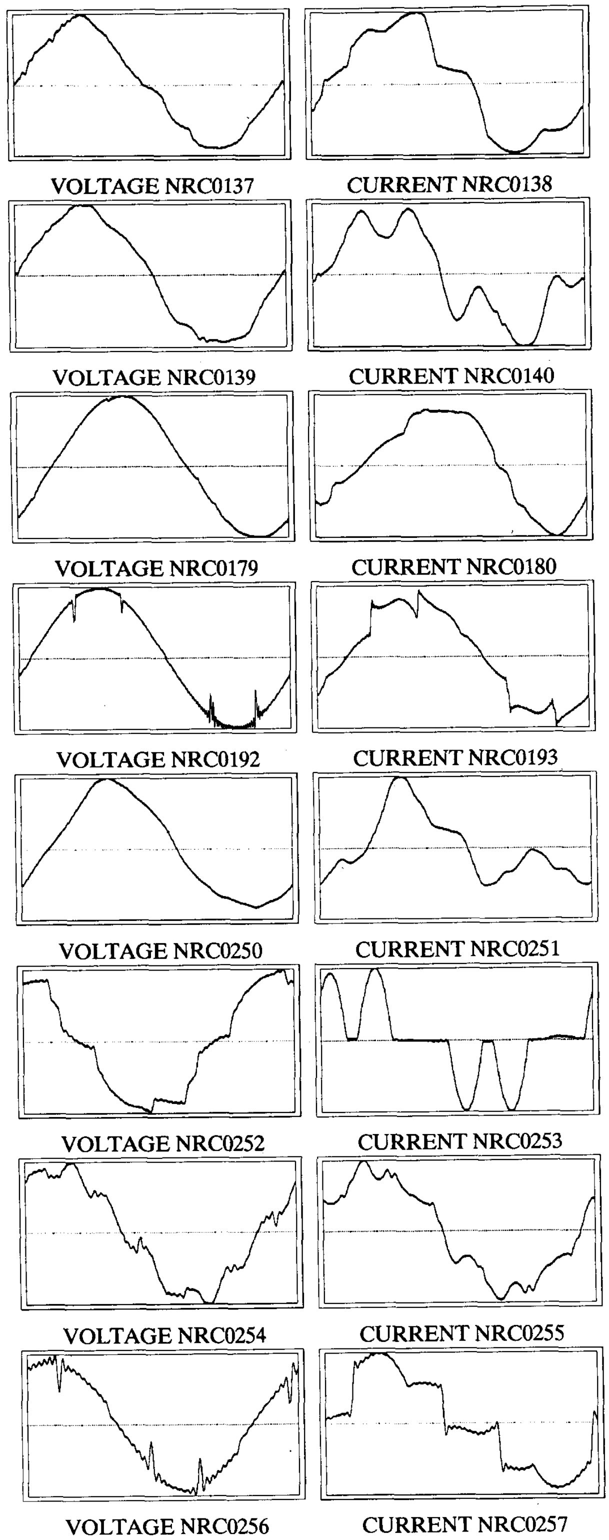

Fig.4. Test waveforms.

$\sqrt{(1800+10)^2-1800^2}=190$, i.e. 11% of the full scale at the 1800 VA level.

The combined uncertainties of the test results were estimated as not exceeding: DIG, 0.10%, ANA, 0.10%, IWHM, 0.2%, IWHT 2e, 1.4%.

TEST RESULTS

The test results are presented in Table 2. All errors are referred to the full scale of the test level, i.e. 1800 VA. For each meter the first column shows the relative difference between the readings of the meter and the first harmonic reactive power Q_1. The second and the third columns, use, respectively Q_B and Q_F as the reference reactive powers.

Table 2. Test Results. Reactive Power Measurement Errors.

$$\Delta=(Q_{meter}-Q_{reference})/\text{ Full Scale VA}$$

meter = DIG, ANA, IWHM, IWHT

$$Q_{reference}=Q_1, Q_B, Q_F$$

TEST	Δ_1 %	Δ_B %	Δ_F %	Δ_1 %	Δ_B %	Δ_F %
	DIG			ANA		
001/001	-0.1	-0.1	-0.0	+0.1	+0.1	+0.1
001/001	-0.0	-0.0	+0.0	-0.1	-0.1	+0.1
137/138	+0.4	-0.4	-5.8	+0.0	+0.0	-5.4
139/140	-1.1	+0.5	-42	-0.4	+1.2	-41
179/180	-0.1	+0.4	-8.6	-0.1	+0.2	-8.8
192/193	-0.1	-0.2	-3.6	0.0	-0.0	-3.5
250/251	-3.0	+4.1	-38	-0.5	+0.7	-41
252/253	-2.8	+2.0	-27	-0.8	+4.0	-25
254/255	+1.0	+2.4	-7.4	-0.2	+1.3	-8.6
256/257	-0.5	+1.1	-9.1	-0.2	+1.4	-8.9
	IWHM			IWHT		
001/001	+0.2	+0.2	+0.2	+3.4	+3.4	+3.5
001/001	-0.7	-0.7	+0.7	+3.4	+3.4	+3.4
137/138	+0.2	+0.2	-5.6	-8.2	-8.2	-14
139/140	-1.3	+0.3	-42	+34	+35	-6.9
179/180	+0.2	+0.4	-8.6	+4.7	+4.9	-4.1
192/193	+0.1	+0.1	-3.4	+2.4	+2.3	-1.0
250/251	+0.5	+1.6	-40	+32	+31	-9.2
252/253	+2.2	+7.0	-22	-1.6	+3.1	-26
254/255	-0.4	+1.0	-8.8	+14	+15	-5.0
256/257	+1.4	+3.1	-7.2	-4.0	+5.6	-4.2

Discussion of Test Results

All meters were designed to operate properly under sinusoidal conditions, thus to measure correctly the first harmonic reactive power. The difference between the reactive power registered by the meter and the first harmonic reactive power is therefore the most meaningful indicator of the accuracy of the meter. DIG, ANA and IWHM type meters register the first harmonic reactive power with errors exceeding the 1% level in only a few cases. The largest errors, reaching -3% for the DIG meter, are for conditions where Q_1 is small, i.e. 250/251, c.f. Table 1. Similar comment can be made about the results obtained when Q_B was used as a reference.

Very large errors, reaching +34%, were recorded for the IWHT type meter. Here the main sources of error are a poor resolution of the VA register and the method of calculating the indicated reactive power from the root-difference-square equation. These errors are largest when the difference between the active and apparent powers is smallest.

To clarify the source of the errors, Table 3 shows the differences between the reference first harmonic reactive power Q_1 and the four other reactive powers, Q_B, Q_F, Q_{Sh}, Q_{KM}. By comparing the figures in Tables 2 and 3 one can find whether the meter error is specific to the meter design or to the selected definition. It is clear that in most cases the selected definition is the main source of the error. For example, under conditions 250/251 there is a very large difference between the readings of the meters DIG, ANA and IWHM, close to -40%, and Q_F. Table 3 shows that this is due to the difference between Q_1 and Q_F, equal to -41%, rather than to any particular meter design.

Table 3. Reactive Power Differences.

$$\Delta_{1-A}=(Q_1-Q_A)/\text{ Full Scale VA}$$

$$A = B, F, KM, Sh$$

TEST	Δ_{1-B} %	Δ_{1-F} %	Δ_{1-KM} %	Δ_{1-Sh} %
137/138	+0.0	-5.8	+7.5	-2.8
139/140	+1.6	-41	-2.7	-26
179/180	+0.2	-8.7	+2.7	-5.4
192/193	-0.0	-3.4	+31	-1.2
250/251	+1.1	-41	-3.4	-12
252/253	+4.8	-24	+38	-14
254/255	+1.4	-8.4	+25	-2.0
256/257	+1.6	-8.6	+68	-6.0

Table 3 additionally shows how the readings of the meters compare with the two others definitions of the reactive power, Q_{KM} and Q_{Sh}. It is obvious from the magnitude of these differences, often larger than 10% and even approaching +68%, that none of the tested meters could be used to measure these reactive powers. Energetic relations in the load, expressed by these quantities, cannot be estimated from the readings of conventional reactive power meters.

CONCLUSIONS

Indication of reactive power meters in nonsinusoidal situations depend on their operating principles. However, in practical situations, such as discussed in this paper, there is a relatively small difference between the indicated reactive power and Q_1. With errors not exceeding a few percent (-3% in this paper) readings of the DIG, ANA and IWHM meters can be considered to reflect Q_1. It should be recognized that for certain applications this is the reactive power of interest. An effort should be made to measure this quantity accurately. Only expensive harmonic analyzers measure Q_1 quantity explicitly.

The classic definition (7) of reactive power Q_B has no physical interpretation; there is no need to increase accuracy of these measurements. None of the meters tested actually measured this quantity.

IWHT type meters should not be used in nonsinusoidal situations. Their VA demand registers can exhibit large errors under these conditions [2]. The root-difference-square method of calculating the reactive power from their readings is prone to large errors.

There can be a large difference, exceeding several percent, between the reactive power as indicated by the tested meters and quantities Q_F, Q_{Sh}, Q_{KM}. It means that the readings of the tested meters cannot be used to determine an optimal compensating capacitor (Q_{KM}, errors up to +68%), or the maximum compensable reactive current/power (Q_F, errors up to -41%) or the maximum reactive current/power compensable by linear shunt elements (Q_{Sh}, errors up to -26%).

When monitoring nonlinear loads, one should take into account not only the consumption of the first harmonic power but also harmonic "pollution" of the system by the load and harmonic-related increased distribution losses. There is no agreed upon indicator which accentuates the second factor. In this application the DIG type meter appears to be the best of the tested meters. It measures Q_{DIG}, which approximates Q_1 and can be thus used to estimate the displacement factor DF. It also measures rms values (harmonics included) of voltages and currents and PF based on these values.

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