The IEEE Standard 1459: What and Why?

Jacques L WILLEMS
Faculty of Engineering
Ghent University, Ghent, Belgium.
Jacques.Willems@UGent.be

Abstract — **This contribution presents the main ideas of the IEEE Standard 1459 on definitions for the measurement of electric power quantities under sinusoidal and nonsinusoidal, single-phase and poly-phase, balanced and unbalanced situations. The motivation of the Standard is discussed. The problems encountered in trying to generalize the well known concepts of active power, reactive power, apparent power and power factor, very well established for single-phase sinusoidal systems, are pointed out. The IEEE Standard 1459 is compared with the related DIN Norm 40110.**

Keywords: active power, reactive power, apparent power, power factor, IEEE Standard

I. Introduction

The concepts of active power, reactive power, apparent power, and power factor have been used in electrical engineering for almost a century now. For sinusoidal single-phase power systems and sinusoidal balanced three-phase systems they have proved to be very useful and efficient for characterizing the quality of the power transmission, for designing the equipment, for billing purposes, and for compensation. These definitions serve the industry well, as long as the current and voltage waveforms remain nearly sinusoidal and balanced three-phase.

However, important changes have occurred in the last 50 years. The new environment is conditioned by the following facts:

- Power electronics equipment, such as adjustable speed drives, controlled rectifiers, cyclo-converters, electronically ballasted lamps, arc and induction furnaces, and clusters of personal computers, represent major nonlinear and parametric loads proliferating among industrial and commercial customers. Such loads have the potential to create a host of disturbances for the utility and the end-user. The main problems stem from the flow of non-active energy caused by harmonic currents and voltages.
- The traditional instrumentation designed for the sinusoidal 60/50 Hz waveform and balanced systems is prone to significant errors when the current and the voltage waveforms are distorted.
- Microprocessors and minicomputers enable today's manufacturers of electrical instruments to construct new, accurate, and versatile metering equipment that is capable of measuring electrical quantities defined by means of advanced mathematical models.

There is therefore a need to quantify correctly the distortions caused by the nonlinear and unbalanced loads and to apply a fair distribution of the financial burden required to maintain the quality of electric service. Therefore the concepts of active, reactive, and apparent powers and the related concept of power factor have to be adapted to the new environment such that measurement algorithms and instrumentation can be designed which give guidance with respect to the quantities that should be measured or monitored for revenue purposes, engineering economic decisions, and the determination of major harmonic polluters.

II. Genesis of IEEE Standard 1459

In view of the considerations given in the previous section, the Power System Instrumentation and Measurement Committee of the IEEE Power and Energy Society drafted IEEE Standard 1459, which was published as a Trial Use Standard in 2000 [9] and was confirmed as a full Standard in 2002. A revised version [10] was reconfirmed in February 2010. The publication of this Standard was preceded by the work of a Working Group on non-sinusoidal situations which analyzed the definitions of powers in non-sinusoidal and unbalanced situations [11].

Based on debates in a number of succeeding international workshops in Italy, A. Ferrero proposed a set of definitions for non-sinusoidal and unbalanced poly-phase situations [8]. The German Institute for Standardization (DIN) published two standards, respectively for two-line [3] and multi-line [4] circuits, with definitions generalizing the classical definitions for sinusoidal and balanced power systems. The DIN norms are commented upon and illustrated by examples in a booklet by Späth [13].

It is important to emphasize what the IEEE Standard 1459 intends to do and what not. It is clearly not intended to propose which measurements should be made and under which conditions, nor to propose algorithms for the measurement of power quantities. It is the purpose to propose the concepts and the definitions which may be useful and interesting for the evaluation of the quality of electrical energy transmission, for billing purposes, for the development of measurement algorithms, and for the design of measurement instrumentation.

In this paper the main ideas and the main proposed concepts of IEEE Standard 1459 are reviewed. Some items of

978-1-4244-7374-8/10/$26.00 ©2010 IEEE

discussion are also put forward. The relationship with definitions proposed in the DIN Standards mentioned above is briefly discussed.

III. The Single-Phase Sinusoidal Situation

The well known and universally accepted concepts for the single-phase sinusoidal situation are explicitly given in the IEEE Standard as well as the DIN Standard and serve as a reference for the more general situations. The definitions of active and reactive current and power are well established, as well as the concepts of apparent power and power factor. They have proven to be very useful in industry for the design of equipment, for billing, for metering purposes, for compensation of the load. The main aspect distinguishing the single-phase sinusoidal case from the more general cases is the fact that here the non-optimal power transmission is solely and completely a consequence of a phase shift between supply voltage and load current. This phase shift is completely due to the load characteristics. Hence the effects can be completely put on the load: billing of the additional energy and hence cost due to the reactive power or non-ideal power factor, the responsibility for compensation, … The situation is completely different in the more general case: distortion can be due to either the load or the supply, unbalance can be due to either the load or the supply, …

The IEEE Standard 1459 contains the (well known) definitions of

- active power ($P = VI\cos(\varphi)$),
- reactive power ($Q = VI\sin(\varphi)$),
- apparent power ($S = VI = \sqrt{P^2 + Q^2}$),
- power factor ($PF = |P|/S$),
- complex power ($\boldsymbol{S} = P + jQ = \boldsymbol{V}\,\boldsymbol{I}^*$).

The bold symbols denote complex numbers (phasors), V and I the rms values of the supply voltage and the load current, $\boldsymbol{V}$ and $\boldsymbol{I}$ the corresponding phasors, φ the phase lag of the current with respect to the voltage, and the asterisk the complex conjugate. The IEEE Standard also discusses the relationship between the various power quantities and the instantaneous power. Moreover the physical interpretation of the apparent power is given as the maximal active power that can be transmitted for the given rms values of load current and supply voltage, in preparation of the discussion of apparent power in the more general situations.

The active and reactive currents are not defined in the IEEE Standard; the reason is undoubtedly that the standard is concerned with *power* quantities. Nevertheless the active and reactive current concepts are very useful to generalize the power concepts to more general situations, These current components are discussed in the DIN norms (which are not limited to power concepts). In our opinion it would be commendable to introduce the concepts of active and reactive current components also in the IEEE Standard.

IV. The Single-Phase Non-Sinusoidal Situation

For non-sinusoidal situations the generalization of the classical concepts defined for the sinusoidal situation, is not at all straightforward. One of the reasons is that in the sinusoidal case there are only two (complex-valued) variables, the phasors of the voltage and the current. The current phasors can be completely characterized by a component along the voltage and a component perpendicular to it. For a nonsinusoidal (periodic) current and voltage, the dimension is much higher: at each frequency there are two complex-valued variables.

There is also an essential difference between the sinusoidal and the distorted cases with respect to responsibility, billing, and compensation. On the one hand for the sinusoidal case it is clear that the deviation from the optimal case (supply voltage and load current in phase) is due to the load and the load is responsible for the consequences. On the other hand in the nonsinusoidal situation the distortion can be due either to nonlinear effects in the load (e.g. power electronic converters) or to the presence of nonlinear elements elsewhere in the power system such that the supply voltage to the load is distorted. Obviously both effects can be (and often are) present simultaneously. The Standard does not intend to show how to distinguish between both cases, but should provide the necessary concepts which may enable to do so.

Consider the distorted periodic supply voltage and the distorted periodic load current

$$v(t) = V_o + \sum_{k \in \mathbb{N}} V_k \sqrt{2}\cos(k\,\omega\,t + \alpha_k) \tag{1}$$

$$i(t) = I_o + \sum_{k \in \mathbb{N}} I_k \sqrt{2}\cos(k\,\omega\,t + \beta_k) \tag{2}$$

The IEEE Standard defines the rms values of voltage and currents, V and I , the rms values of the components at fundamental frequency (50 or 60 Hz), V_1 and I_1 , and the rms values of the remaining terms (harmonics and d.c. together), V_H and I_H . The total harmonic distortion is defined for the voltage as $THD_V = V_H / V_1$ and for the current as $THD_I = I_H / I_1$.

A. Active power

It is clear that the average power, which is called the active power, and which determines the energy supplied to the load, is given by

$$P = V_o I_o + \sum_{k \in \mathbb{N}} V_k I_k \cos(\varphi_k) \tag{3}$$

with $\varphi_k = \alpha_k - \beta_k$. If the distortion is due to the supply voltage, and not due to load, and since in most cases (e.g. electrical motors) the energy supplied at nonfundamental frequencies is not useful to the load, but disadvantageous, the consumer should not be billed for that part of the energy. Therefore the active power is split into active power at fundamental frequency, the so-called fundamental active power

$$P_1 = V_I I_1 \cos(\varphi_1) \tag{4}$$

and the active power at other frequencies, the nonfundamental or harmonic active power

$$P = V_o I_o + \sum_{k>1} V_k I_k \cos(\varphi_k) \tag{5}$$

B. Apparent power

The apparent power is defined as

$$S = VI \tag{6}$$

The fundamental apparent power (only relating to the 50/60 Hz voltage and current) is defined as $S_1 = V_1 I_1$, the harmonic apparent power as $S_H = V_H I_H$ and the nonfundamental apparent power as

$$S_N = \sqrt{S^2 - S_H^2} \tag{7}$$

The nonfundamental and the harmonic apparent powers are different:

$$S_N^2 = S_H^2 + D_I^2 + D_V^2 \tag{8}$$

where $D_I = V_I I_H$ and $D_V = V_H I_I$ are respectively called the current distortion power and the voltage distortion power. They can readily be expressed in terms of the fundamental apparent power and the distortion factors.

C. Power factor

The IEEE Standard contains the following definitions of power factor:

- the (total) power factor $PF = P/S$
- the fundamental power factor $PF_1 = P_1/S_1$

which characterize the efficiency of the total energy flow and the energy flow at fundamental frequency (50/60 Hz), respectively.

D. Non-active and reactive power

From the apparent power and the active power the non-active power is derived:

$$N = \sqrt{S^2 - P^2} \tag{9}$$

This is the part of the apparent power which does not correspond to energy transfer. This can be due either to the supply (voltage distortion) or to the load (current distortion due to nonlinear effects, phase shift between voltage and current components, frequency dependent characteristics of the load); it is not clear how the responsibility should be divided.

As in the sinusoidal case the fundamental reactive power can be defined:

$$Q_1 = V_I I_1 \sin(\varphi_1) \tag{10}$$

such that

$$S_1^2 = P_1^2 + Q_1^2 \tag{11}$$

The reactive power Q_1 is certainly a form of non-active power due to the load.

A particular point of attention is the concept of the global reactive power. In the recent revision of the IEEE Standard [10] no definition is given of reactive power, other than the non-active power shown above and the concept of reactive power corresponding to the fundamental frequency components of voltage and current; the latter corresponds clearly to the sinusoidal situation. The previous version of the Standard [9] contained a very well known concept of reactive power, the so-called Budeanu reactive power

$$Q_B = \sum_{k \in \mathbb{N}} V_k I_k \sin(\varphi_k) \tag{12}$$

This quantity has been used for decades for characterizing the reactive character in the distorted situation, mainly because of its similarity with expression (5) of the active power. It has been deleted from the Standard in its revised version. Czarnecki [1] indeed showed that the Budeanu concept of reactive power is misleading, since it does not characterize the deviation from the optimal situation. Neither does the reduction of it necessarily yield lower line losses, nor does the annihilation of it correspond to an optimal power factor. Deleting this concept from the Standard is therefore completely justified. On the other hand some algorithms of splitting up the non-active power have been proposed [2, 16] which show fairly well the physical reasons for the presence of non-active power and which may deserve to be mentioned in later revisions of the Standard.

V. Three-phase situation

A. Balanced Three-phase Voltages and Currents

For a three-phase power system with balanced sinusoidal voltages and currents the concepts of active, reactive and apparent power and the concept of power factor are straightforward generalizations of the single-phase case. Indeed a balanced three-phase system can readily be described as a combination of three identical single-phase systems. Active, reactive, and apparent powers are defined as three times the same quantity for a single phase, and can also be expressed by formally the same expression with the line-to-line voltage replacing the phase-to-neutral voltage and using the factor $\sqrt{3}$ instead of the factor 3. The power factor is the ratio of the active power to the apparent power, equivalently computed either for one phase or for the three phases.

B. Unbalanced Sinusoidal Voltages and Currents

The situation is much more complicated when the voltages and/or currents of a three-phase system are not balanced, even if they are still sinusoidal.

1) Active power

The computation of the active power is no problem. The active power which determines the energy transfer, can be computed from the sum of the active powers of the three phases,

$$V_{Rn} I_R \cos(\varphi_R) + V_{Sn} I_S \cos(\varphi_S) + V_{Tn} I_R \cos(\varphi_T)$$

where *R, S, T* denote the phases, and *n* the neutral. In the above expression the voltages of the phases are expressed with the neutral as the reference. The voltage reference can be chosen arbitrarily, but then, in the case of a four-wire system, the power transferred by the neutral should also be taken into account; moreover then the phase differences between the line current and the voltage to the reference point should be used in the expression of the active power. The active power can equivalently be computed as the sum of the active powers corresponding to the positive sequence, negative sequence and zero-sequence voltage and current components.

2) Reactive power

For the reactive power the situation is not so clear. The reactive power can be defined for the three phases separately (as three single-phase systems with the phase conductor and the actual or virtual neutral conductor), and then summed up. It can also be calculated for the positive-sequence, negative sequence, and zero-sequence components separately, and then summed up. The two procedures clearly lead to the same result. However it is not clear what this sum physically means and for which purpose it may be used. The Standard does not give any idea on the meaning of that quantity.

The positive sequence reactive power has a practical meaning for a balanced load supplied by an unbalanced voltage. The positive sequence active power can be considered as the useful power supplied to the load, and the positive sequence reactive power as the non-active power which is due to the reactive character of the load; this reactive power is hence the responsibility of the load and should be accounted for and compensated by the load.

3) Apparent power

The IEEE Standard enumerates a number of concepts and definitions for the apparent power:

- the apparent powers per phase $S_R = V_R I_R$, $S_S = V_S I_S$, and $S_T = V_T I_T$, and their sum (the *arithmetic apparent power* S_A),
- the magnitude of the complex number with real part the sum of the active powers in the three phases and as imaginary part the sum of the reactive powers in the three phases (the *vector apparent power* S_V),
- the apparent powers corresponding to the positive sequence components, the negative sequence, components and the zero-sequence components $S^+ = 3 V^+ I^+$, $S^- = 3 V^- I^-$, $S^o = 3 V^o I^o$, and their sum,
- three times the product of the equivalent voltage V_e and the equivalent current I_e , or equivalently the apparent power of the balanced three-phase system with the voltage V_e (the rms value of the phase voltages) and the current I_e (the rms value of the line currents) (*effective apparent power* S_e).

The first three concepts have been used in the past. However no real physical meaning can be associated with them; this is also pointed out in the Standard itself. The question is whether they should be retained in the Standard. The fourth concept is to be preferred. It is a logical extension of the definition of the apparent power in the benchmark cases of a sinusoidal single-phase system or a balanced three-phase system. It however depends on the definitions of equivalent current and equivalent voltage which are discussed in more detail in the next subsection. The effective apparent power

$$S_e = 3 \mathrm{V}_e I_e \tag{13}$$

also corresponds to the original ideas put forward by Lyon, Goodhue, Buchholz, where the apparent power is the maximal active power which can be transmitted by a system with balanced voltages and currents and with the same voltage impact and the same transmission losses [14, 15] (current impact).

4) Equivalent voltage and equivalent current

The equivalent current is defined as the rms value of the balanced three-phase current which yields the same losses as the actual current. If the actual current in a four-wire three-phase line has a zero-sequence component, or otherwise said if the current in the neutral path in the actual situation, is non-zero, then the definition is not straightforward. Indeed it is normal to assume that the resistances of the three phase conductors are equivalent, but in practical cases the neutral conductor is different from the phase conductors. The expression of the line loss clearly depends on that difference [12]. The equivalent current is hence defined by

$$I_e = \sqrt{\frac{I_R^2 + I_S^2 + I_T^2 + \varrho I_n^2}{3}} \tag{14}$$

where ϱ denotes the ratio of the neutral conductor resistance to the phase conductor resistance. The problem is obviously that ϱ is not well known and practically not measurable. In practice ϱ is larger than 1, but the error by setting ϱ equal to 1 is negligible. Obviously the neutral current is not present in a three-wire three-phase system.

A similar problem occurs for the definition of the equivalent voltage. The voltage "impact" in the actual situation for a four-wire three-phase depends as well on the phase-to-phase as on the phase-to-neutral voltages. For the computation of the equivalent voltage such that the apparent power is the maximal active power for the given voltage and the same losses, the voltage should be referred to a virtual reference point which depends on the ratio of the phase resistance and the neutral line resistance [11]. It can be shown [7] that a very good approximation for practical situations (with small zero-sequence voltage) is obtained by using

$$V_e = \frac{1}{3}\sqrt{V_{RS}^2 + V_{ST}^2 + V_{TR}^2} \quad (15)$$

in the four-wire case as well as in the three-wire case. Indeed it can be proved that in the absence of a zero sequence voltage, the reference point for the voltage should also be chosen equal to the neutral terminal voltage.

5) Unbalanced power

The amount of VA caused by system unbalance can be measured by the unbalanced power

$$S_U = \sqrt{(S_e)^2 - (S^+)^2} \quad (16)$$

which includes the effect of load unbalance and voltage asymmetry.

6) Power factor

With each concept of apparent power a definition of power factor can be associated expressing how far the active power deviates from the corresponding apparent power. The power factors corresponding to the arithmetic apparent power and the power apparent power have little or no physical meaning, and one may wonder whether they merit to be still mentioned in the Standard. The following two concepts of power factor are of more interest:

- $PF_e = P/S_e$ (the *effective power factor*),
- $PF^+ = P^+/S^+$ (the *positive-sequence power factor*).

They characterize respectively the efficiency of the total power flow and the efficiency of the flow of the energy corresponding to positive-sequence currents and voltages.

C. Three-phase nonsinusoidal and unbalanced

This combines the situations considered in *IV* and *V.B,* including the resolution according to the frequencies and the resolution according to the unbalance. It is extremely complicated to enumerate all possibilities; the Standard only mentions the most essential concepts.

VI. Din-Norm 40110 (Parts 1 and 2)

The Din norm 40110 [3, 4, 13] has a similar objective as IEEE Standard 1459 to give a set of definitions for power quantities in power systems in sinusoidal and nonsinusoidal situations. Part I deals with the single-phase and Part II with the poly-phase situation. As already stated, to characterize the definitions of active and reactive power also the definitions of e.g. active and reactive currents are given. On the other hand the number of power concepts discussed in the DIN norm is much more limited compared to the IEEE Standard. In particular for poly-phase systems only the effective apparent power is discussed, as defined in Section *V.B*. A very particular difference between the IEEE and the DIN approaches is that in the DIN norm the phase conductors and the neutral conductors are considered to be identical. A three-phase four-wire system is dealt with in the same way as a four-phase four-wire system would be dealt with. The losses are hence proportional to

$$I_R^2 + I_S^2 + I_T^2 + I_n^2 \quad (17)$$

and the voltages are measured with respect to the artificial neutral point such that

$$v_R(t) + v_S(t) + v_T(t) + v_n(t) = 0 \quad (18)$$

From a practical point of view however it does not seem logical to assume that the neutral path is considered to be identical to the phases. Note however that in the absence of a zero-sequence voltage component the artificial reference point defined by (18) coincides with the neutral conductor. Hence for small zero-sequence voltage components the voltage reference in the DIN norm and the voltage reference in the IEEE Standard are very close. Also the difference in the computation of the line losses is small if the zero-sequence component of the currents is small.

It can be noted that in the DIN norm a number of power quantities which might be useful for billing and accountability purposes, are not considered, such as the positive sequence active, reactive and apparent powers, the positive sequence power factor, … In the DIN norms only the power factor corresponding to the comparison of the real situation to the ideal situation where the current is proportional to the (possibly distorted and unbalanced) voltage, implicitly the impression is given that the load is responsible for obtaining that situation and is billed for deviations from it. The IEEE Standard at least defines other power factors (such as the fundamental frequency power factor and the positive sequence power factor) to avoid that impression and to provide the quantities which might be useful to characterize the power quality of the load.

VII. Final Remarks

One should keep in mind that the IEEE Standard 1459 is meant to propose the concepts and the definitions; it only marginally refers to the measurement issues themselves. It also does not go deeply into the question for which purpose a particular concept should be used instead of another. This is not an objection to the Standard, but a statement of the framework in which the Standard should be seen.

In this contribution to the special session "Barbagelata" on non-sinusoidal and unbalanced situations, the main ideas and the main proposed concepts of IEEE Standard 1459 are presented and commented upon. Some comparison is made with definitions proposed in the DIN Norm 40110.

Acknowledgment

For the preparation of this contribution ample use has been made of the papers on the Standard by A. E. Emanuel, who chaired the Working Group on Non-Sinusoidal Situations, as well during the preparation of the Trial Use Standard 1459 in 2000 as during the revision of the Standard in 2010. He undoubtedly was the main contributor to the discussion and the redaction of the Standard: The reader is referred to the papers he authored on the Standard (e.g. [5-7, 12]) for a further in-

depth discussion of the main ideas and the motivation of the proposed definitions as well as for a report on the historical context.

References

[1] L.S. Czarnecki, "What is wrong with the Budeanu concept of reactive and distortion power and why it should be abandoned," IEEE Trans. on Instrum. and Meas., Vol. 36, pp. 834-837, September 1987.

[2] L.S. Czarnecki, "Currents' Physical Components (CPC) in circuits with nonsinusoidal voltages and currents," EPQU Journal., Vol. XI (2), pp. 3-14, 2005.

[3] Deutsches Institut für Normung, Wechselstromgrössen: Zweileiter-Stromkreise (Quantities Used in Alternating Current Theory: Two-Line Circuits), DIN 40110-1, 1994.

[4] Deutsches Institut für Normung, Wechselstromgrössen: Mehrleiter-Stromkreise (Quantities Used in Alternating Current Theory: Multi-Conductor Circuits), DIN 40110-2, 2002.

[5] A.E. Emanuel, "IEEE Standard 1459: Questions and future direction – Quo vadis?" IEEE Power Engineering Society, July 2003.

[6] A.E. Emanuel, "Summary of IEEE Standard: Definitions for the measurement of electric power quantities under sinusoidal, nonsinusoidal, balanced, or unbalanced conditions," IEEE Trans. Ind. Appl., Vol. 40 (3), pp. 869-876, May/June 2004.

[7] A.E. Emanuel, "Optimum current compensation based on IEEE Standard 1549-2010 and DIN 40110," private communication, 2010.

[8] A. Ferrero, "Definitions of electrical quantities commonly used in nonsinusoidal conditions," Eur. Trans. Elect. Power, Vol. 8, pp. 235-240, 1998.

[9] IEEE PES Power System Instr. and Meas. Comm., IEEE Trial-Use Standard: Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions, IEEE Std 1459-2000, January 2000.

[10] IEEE PES Power System Instr. and Meas. Comm., IEEE Standard: Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions, IEEE Std 1459-2010, February 2010.

[11] IEEE Working Group on Non-Sinusoidal Situations, "Practical definitions for powers in systems with non-sinusoidal waveforms and unbalanced loads," IEEE Trans. Power Del., vol. 11 (1), pp. 79-101, Jan. 1996.

[12] S. Pajic, A.E. Emanuel, "Effect of neutral path power losses on the apparent power definitions: a preliminary study," IEEE Trans. Power Del., Vol. 24 (2), pp. 517-523, April 2009.

[13] H. Späth, Leitungsbegriffe für Ein- und Mehrphasensysteme, VDE Verlag, Berlin, 2000.

[14] J.L. Willems, J.A. Ghijselen, A.E. Emanuel, "The apparent power concept and the IEEE Standard 1459-2000," IEEE Trans. Power Del., Vol. 20 (2), pp. 876-884, April 2005.

[15] J.L. Willems, J.A. Ghijselen, A.E. Emanuel, "Addendum to the apparent power concept and the IEEE Standard 1459-2000," IEEE Trans. Power Del., Vol. 20 (2), pp. 885-886, April 2005.

[16] J.L. Willems, "Reflections on power theories for poly-phase nonsinusoidal voltages and currents," Przeglad Elektroteniczny (Electrical Review), Vol. 86, pp. 11-21, 2010.