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Ambiguity on the Definition of Power Quantities in Electrical system

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This paper aims at presenting a review of the definitions of power quantities in an electric system with distorted voltages and currents. This subject has been of interest for more than a century and over the years many definitions for reactive power and apparent power and compensation techniques have been developed. However none of these definitions characterize the distinguishing power quantities for all conditions of electrical circuit. A review of the ambiguities, confusion in the classical definition, power theories and difficulties in instrumentation, billing and compensation is presented in this paper.

Key words: *reactive power, definitions, distortion, power quality, apparent power, power factor*

1.0 INTRODUCTION

The concepts of active power (P), reactive power (Q), and apparent power (S) and power factor pf are well defined [1] and the power triangle given by $S^2=P^2+Q^2$ have been accepted without any reservations. These definitions are well understood in the situation of sinusoidal single-phase voltages and currents, and also in the case of balanced three-phase sinusoidal voltages and currents, but they fail when extended to non-sinusoidal situations [2-10].

The widespread use of power converters and other non-linear loads, generation of non-sinusoidal and non-periodic currents and voltages in power systems has increased which in turn has increased the demand for compensation. There is renewed attention given to the definitions [137],[141], [151],[152] for power quantities particularly to definitions for S and pf in order to design compensation optimally and maximize utilization of supply power.

Many researchers have proposed definitions and formulations of reactive power, but the attempts have so far been not very successful for all situations. As seen from the literature, the discussion on reactive power and the debate on this subject still persists even after a century. It is reported that the discussions for [4] have been very lengthy and did not result in any concrete conclusions. The classical definitions of IEEE followed religiously have been recently reviewed [82], [83], and revised [108]. Therefore there is a need to survey and understand the difficulties faced by academics in defining power quantities for practical non-sinusoidal situations and review the current practices followed in instrumentation. The current literature is surveyed and appended in this paper for quick reference.

This paper is presented in seven parts. Starting with an introduction highlighting the reasons for ambiguity in reactive power definition, the subsequent sections review different power theory formulations for single-phase and three-phase systems, with non-sinusoidal waveforms,

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measuring instrumentation, comments on revisions in IEEE Standards and the concluding remarks.

2.0 AMBIGUITY IN REACTIVE POWER DEFINITION

All textbooks define reactive power as being related to the oscillating power/energy between source and load. If (1) and (2) define the voltage v(t) across and current i(t) through a load [137], then the instantaneous power is given by (3)

$$v(t) = V_{max} \cos(\omega t) \quad (1)$$

$$i(t) = I_{max} \cos(\omega t - \theta) \quad (2)$$

$$p(t) = v(t)i(t) = V_{max} \cos(\omega t) I_{max} \cos(\omega t - \theta) \quad (3)$$

using trigonometric identities we get,

$$p(t) = \frac{V_{max} I_{max}}{2} \cos\theta\,(1+\cos(2\omega t)) + \frac{V_{max} I_{max}}{2} \sin\theta \sin 2\omega t \quad (4)$$

$$p(t)=p_p(t) + p_q(t)$$

The first part $p_p(t)$ of (4) is called the instantaneous active power and the second part $p_q(t)$ of (4), is the instantaneous reactive power. There is a fundamental difference observed between the two in that the active power oscillates around an arbitrary average value while the reactive power oscillates around a zero average power, as the average value of a cos and sin function is zero. This observation is valid under any conditions as long as the oscillations are sinusoidal. For a non-sinusoidal regime the problem is much more complicated and is not yet fully solved.

As is not practical to handle instantaneous quantities because they are difficult to measure, averaged values are introduced. The average value of $p_p(t)$ is called the active power and is given by

$$P = \frac{V_{max} I_{max}}{2} \cos\theta = V_{rms} I_{rms} \cos\theta \quad (5)$$

But the average value of $p_q(t)$ is zero and therefore of no practical significance. Instead, the maximum of the instantaneous reactive power is introduced to describe the instantaneous reactive power and this quantity is given by

$$Q = \frac{V_{max} I_{max}}{2} \sin\theta = V_{rms} I_{rms} \sin\theta \quad (6)$$

which is exactly the second part of (4) without the sin of the time.

The vector sum of active power and reactive power is defined as apparent power in (7)

$$S^2 = P^2 + Q^2 = V_{rms}^2 I_{rms}^2 \quad (7)$$

The power factor (pf) which determines the line efficiency is defined as

$$pf = \frac{P}{S} \quad (8)$$

It is obvious from equations (5) and (6) that the symmetry between the active and reactive power is broken and therefore *P* and *Q* do not have the same meaning as it is inferred in literature. This is the root of the misconceptions about reactive power and has led to ambiguities when they are extended to non-sinuoidal situations. It is shown in [137] that reactive power defined, as the magnitude of an oscillatory component of the instantaneous power cannot be determined in the frequency domain if Fourier transform are followed. The two concepts cannot be treated on equal foot while extending to non-sinusoidal situations.

Moreover non-linear elements such as thyristor controlled loads also cause phase shifts between voltage and current harmonics, but do not cause energy oscillations [28]. So it is not appropriate to presume that phase shift between voltage and current harmonics are caused only by reactive energy-storage devices, capacitors and inductors. In fact phase shift caused by a reactive element or a non-linear load are indistinguishable.

3.0 POWER THEORY IN SINGLE PHASE SYSTEMS WITH NON-SINUSOIDAL SUPPLY VOLTAGE AND NON-LINEAR LOADS

Two major models dominate today's approach to the definitions and components of reactive power. First is the school of Budeanu [2], Shephard and Zhakiani [12], Sharon [11] in frequency domain, which is accepted by the ANSI/IEEE Standard 100-1977. Second is the school of Fryze [5], Page[16], Kusters and Moore [15] in time domain which influenced the IEC standard.

The nonsinusoidal voltages and currents can be expressed using Fourier Series as,

$$v_n(t) = \sum_{1}^{n} \sqrt{2} V_n \sin(n\omega t) \tag{9}$$

$$i_n(t) = \sum_{1}^{n} \sqrt{2} I_n \sin(n\omega t - \phi_n) \tag{10}$$

The corresponding active power and reactive power are given by:

$$P_n = V_n I_n \cos\phi_n \qquad Q_n = V_n I_n \sin\phi_n \tag{11}$$

where V_n , I_n and j_n are the rms voltage and current and the phase angle difference of the n^{th} harmonic.

In 1927, Budeanu introduced an orthogonal decomposition of apparent power into active, reactive, and distortion power components. The total active and reactive powers are given by (12) and (13)

$$P_B = \sum P = \sum_{n} P_n = \sum_{n} V_n I_n \cos\phi_n \tag{12}$$

and

$$Q_B = \sum Q = \sum_{n} Q_n = \sum V_n I_n \sin\phi_n \tag{13}$$

The apparent power S is defined as the summation of the rms values of voltages and currents associated with all the harmonics. ie., the apparent power

$$S = \sum V_n \sum I_n \tag{14}$$

It is observed from equations (12) and (13) that the power triangle relation is not satisfied.

$$S^2 \neq P_B^2 + Q_B^2 . \tag{15}$$

So Budeanu has introduced another term in quadrature, called distortion power D_B to complete this inequality, as defined below

$$S^2 = P_B^2 + Q_B^2 + D_B^2 \tag{16}$$

Distortion power is calculated by cross product of different harmonic voltages and currents,

$$D_B^2 = S_B^2 - P_B^2 - Q_B^2$$
$$= \sum_{1}^{n=g} V_n^2 I_g^2 + V_g^2 I_n^2 - 2 V_n V_g I_n I_g \cos(\varphi_n - \varphi_g) \tag{17}$$

Budeanu's Q_B can be compensated by a simple capacitor. However this is not the case with D_B. For D_B to be zero, can show that

when $j_n = j_g$, then $(V_n I_g - V_g I_n)^2 = 0$

$$\text{if} \quad V_n I_g = V_g I_n \ \text{ie.,} \quad \frac{V_n}{I_n} = \frac{V_g}{I_g} \tag{18}$$

This implies that the distortion power is zero for resistive loads or for a load whose impedance is same under all frequencies. But this term has no physical meaning and also do not obey the law of energy conservation. IEEE has accepted this definition for Q_B and D_B and we find them in all electrical engineering textbooks despite some objections raised by experts for almost 60 years.

Researchers like Fryze [5], L S Czarnecki[28] have shown drawbacks in this definition. The objections have concerned mainly with the question whether these powers should be defined in frequency domain and whether they can be measured as defined. Budeanu's Q_B and D_B power turned out however to be very difficult to instrument and also they do not possess attributes which could be related to the power phenomenon of the circuit.

3.1 Load current splitting

Seeing the limitations of Budeanu's two-component decomposition, several definitions followed based on a concept of dividing the load current into two or more components, presumably responsible for different energy phenomena.

The load is represented in an equivalent form consisting of a linear equivalent $R_e=V^2/P$ (see Fig. 1) and a parallel combination of linear or non-linear components or current sources. The basic current is the active current flowing through equivalent resistor R_e dissipating active power P through the load.

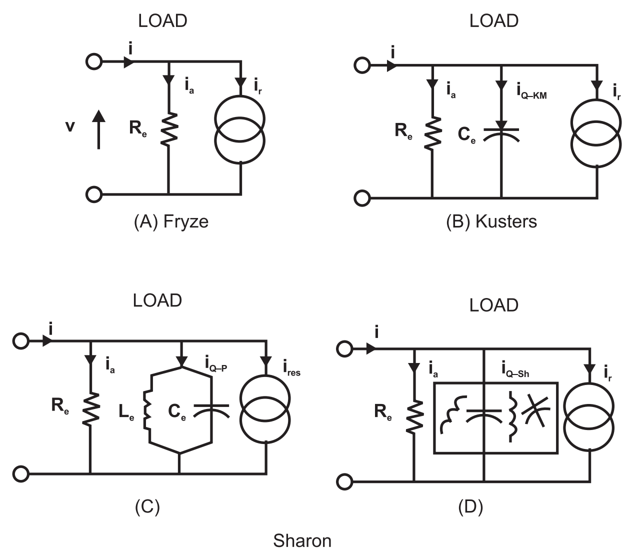

FIG. 1 LOAD-CURRENT SPLITTING

Fryze introduced reactive power as a single orthogonal component [5] accounting for the difference in apparent and average power. The load current is divided as active current i_a and reactive current i_r (Fig 1 A). The active, reactive and apparent powers are expressed in terms of rms values of voltages and these two currents, I, Ia

$$Q_F = VI_r = \sqrt{(VI)^2 - (VI_a)^2} = \sqrt{S^2 - P^2} \qquad (19)$$

Q_F can be calculated directly from S and P and there is no need for a separate reactive power meter. The magnitude of Q_F is seen as a useful quantity, because S=P corresponds unity power factor. Q_F is also given a sign convention to account for the difference between capacitive and inductive reactive power. Despite the sign convention, however, Fryze's definition does not obey conservation, meaning that a circuit with $Q_F= +1$ does not, in general, compensate a circuit with $Q_F= -1$

The main advantages of Fryze's decomposition are to provide accurate information on source efficiency and to be determined using ordinary phasor measurement devices. However calculated values are not suitable for reactive power compensator design.

Page in [16], defined capacitive reactive power and inductive reactive power–two components of Q_F that could be compensated by a parallel capacitor and inductor. But Page's projections failed to provide compensation for all circuits.

For this reason, Kusters and Moore [15] extended Fryze's decomposition theory for single phase systems based on whether the non-active current could be compensated by means of reactive elements C or L (capacitor or inductor) or not. The load current is decomposed as active, capacitive reactive and residual currents. The compensation by means of simple reactive elements doesn't eliminate all of the non-active power in electrical circuits under non-sinusoidal conditions. However, the optimal reactive compensator, i.e. the reactive compensator which provides the optimal current reduction can be found.

The capacitive reactive current $I_{Q\text{-}KM}$ has the same waveform and phase as 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. This capacitive reactive power is calculated as given in (20). If the capacitive reactive power is positive then no capacitive compensation is possible.

$$Q_{KM} = -\sum_h hV_h I_h \sin\phi_h \sqrt{\frac{\sum_h V_h^2}{\sum_h h^2 V_h^2}} \quad (20)$$

The possibility that the parameters of such reactive compensator might be determined has been discussed in these references [15]-[16].

Sharon [11]. generalized the reactive component of power equation proposed by Shepherd and Zand [14], as

$$S^2 = P^2 + S_Q^2 + S_C^2 \quad (21)$$

with Sharon's reactive apparent power

$$S_Q = V\sqrt{\sum_1^n I_n^2 \sin^2\varphi_n} \quad (22)$$

complimentary apparent power

$$S_C = \sqrt{S^2 - P^2 - S_Q^2} \quad (23)$$

Sharon's power equation give data about line loading conditions which is made by reactive load current and power factor easy to be calculated. Unfortunately Sharon did not manage to explain the physical meaning of introduced quantities.

Czamecki [26], [33] interpreted the above quantity using load current splitting concept. The current is divided into four components i.e. active, reactive, scattered and harmonic currents and expressed as

$$I^2 = I_A^2 + I_R^2 + I_S^2 + I_H^2 \quad (24)$$

with reactive current defined as

$$I_R = \sqrt{\sum_{n\in N} B_n^2 V_n^2} \quad (25)$$

generated harmonic current defined as

$$I_H = \sqrt{\sum_{n\in k} I_n^2} \quad (26)$$

and scattered current as

$$I_R = \sqrt{\sum_{n\in N} (G_n - G_e)^2 V_n^2} \quad (27)$$

where k represents current harmonic numbers not present in the set of voltage harmonic numbers N. The equivalent conductance defined as ;

$G_e = \frac{P}{V^2}$ and nth harmonic admittance of load as $Y_n = G_n + jB_n$

The power equation related to this decomposition as

$$S^2 = P^2 + D_S^2 + Q_R^2 + D_H^2 \quad (28)$$

with reactive power $Q_R = VI_R$

scattered power $D_S = VI_R$ and generated

harmonic power $D_H = VI_H$ (29)

Each of these approaches has its merits, discussed in the appropriate references. A comparison of these definitions is illustrated by Erhan Balci [141] using a simple single phase circuit with distorted voltages and currents and concludes that

1. Power decomposition according to Fryze, Shepherd and Zand, Sharon, Czamecki

could be used to accurately estimate source efficiency.

2. Reactive power calculated according to Fryze, Shepherd and Zand, Sharon, and Czamecki could not be completely compensated by a passive capacitance.

3. Optimum compensation capacitance could not be determined by using any of the power definitions directly.

4. On the other hand optimum compensation capacitance could be calculated by taking derivative of to Fryze, Shepherd and Zand, Sharon, Czamecki reactive powers.

4.0 POWER THEORY IN THREE PHASE SYSTEMS WITH NON-SINUSOIDAL SUPPLY VOLTAGE AND NON-LINEAR LOADS

From the engineering point of view, compensation usually takes place in the three phase systems. Many contributors [25], [32], [46], [55], [59], have attempted to redefine these quantities to deal with three-phase systems with unbalanced and distorted currents and voltages. They can be classified under two different concepts: one based on the average value concept an extension of Fryze definition to polyphase systems by Depenbrock [71] called the FBD method and the other on the instantaneous value concept, the so-called “pq theory” introduced by Akagi *et al.*

The p-q theory, or “Instantaneous Power Theory”, was initially developed with the objective of applying it to the control of active power filters in three-phase nonlinear systems without neutral wire [25], [59]. Subsequent efforts by Watanabe and Aredes [65], [67] modified this theory for three-phase four wires power systems.

The p-q theory is based on time-domain, that makes it valid for operation in steady-state or transitory regime, as well as for generic voltage and current power system waveforms, allowing to control the active power filters in real-time.

Another important characteristic of this theory is the simplicity of the calculations, which involves only algebraic calculation (exception done to the need of separating the mean and alternated values of the calculated power components).

The p-q theory performs a transformation (known as “Clarke Transformation”) of a stationary reference system of coordinates $a - b - c$ to a reference system of coordinates α–β-0, also stationary.

The voltages and currents in α–β-0 coordinates are calculated as follows :

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = T \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \text{ and } \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = T \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (30)$$

where

$$T = \sqrt{\tfrac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \quad (31)$$

The p-q theory power components are calculated as

1. instantaneous zero-sequence power

$$p_0 = v_0 i_0 \quad (32)$$

instantaneous Real power

$$p = v_\alpha i_\alpha + v_\beta i_\beta \quad (33)$$

instantaneous imaginary power

$$q = v_\beta i_\alpha - v_\alpha i_\beta \quad (34)$$

Rewriting the above equation in a-b-c coordinates the following expression is obtained,

$$q = \frac{[(v_a - v_b)i_c + (v_b - v_c)i_a + (v_c - v_a)i_b]}{\sqrt{3}} \quad (35)$$

which is used in the conventional reactive power meters in power systems without harmonics and balanced voltages. These instruments, of the electrodynamic type, display the mean value of equation (35). The instantaneous imaginary power differs from the conventional reactive power, because in the first case all the harmonics in voltage and current are considered.

The compensation of the p-q theory's undesired power components $(\tilde{p}, p_0, q)$ can be accomplished with the use of an active power filter also known as active power line conditioner APLC. Numerous control strategies for optimal compensation are found in literature. An extensive review on Active filters is found in [100] and hence not considered in this paper.

Towards the end of 1990s four other formulations of p-q theory along with control algorithms were proposed. They are the Park's transformation [153] or d-q coordinates; the modified or cross product theory [85]; new p-q-r reference frame [125] and the vector theory[154]. A comparison of their merits are discussed in [152]. The analysis shows that from the five formulations only the vectorial one is adequate to establish APLC compensation strategies with any kind of load and any kind of supply. Nevertheless the original formulation has a lot of advantages and has been used in real time compensation in APLC.

5.0 IEEE STD 1459-2000 AND REACTIVE POWER INSTRUMENTATION

It took almost forty years for IEEE to review their standard on power definitions. Recently the IEEE published a new standard IEEE 1459-2000 [108] in August 2002, giving definitions for power terms under conditions of non-sinusoidal, balanced or unbalanced conditions and non-linear loads. Still the standard is under trial use. Lot of research is ongoing to study its performance. Some work has been reported in [133-134], [138-140]. The powers, calculated using the IEEE 1459-2000 Standard in three circuits, are compared with the actual powers in [133]. Analysis of the results demonstrates the deficiency of the IEEE standard and the sources of the deficiency are identified. This implies that the validity of the non-active power, N, defined in IEEE standard is unknown at present, and its use is questionable.

With more and more non-linear loads in household appliances, measuring reactive energy accurately becomes a key issue for energy distributors. The question arises as to what method should an energy meter designer implement to accurately measure the reactive energy.

Traditional measurement methods like the Power triangle, Time delay and the Low pass filter which are based on classical power theories show limitations in the presence of harmonics or line frequency variation [146]. Over the years, Reactive power meters have been developed based on the several definitions discussed above [17], [55], but never adopted in practice.

On upgradation, IEEE Std 1459-2000 not only gives definitions for power and energy measurement, but also their decomposition for designing and using metering instrumentation under sinusoidal, non-sinusoidal , balanced or unbalanced conditions. [155 – 158]. Two basic approaches are used in implementing the Standard namely, the discrete Fourier transform DFT and Clarke-Park transformations. The implementation based on DFT generates accurate results but requires intensive computation effort. On the other hand, using Clarke-Park transformations the computation burden is reduced, but the obtained measurements under non-sinusoidal conditions can be erroneous due to low pass filters. Research efforts are continued to improve measurement accuracy and reduce the computation burden.

6.0 CONCLUSIONS

Because definitions and meaning for reactive power in non-sinusoidal conditions are being actively debated, a review on the subject is given in this paper for both single and three phase circuits. The mathematical expressions given for reactive power by various researchers either lack in giving physical meaning or in complete compensation or pose difficulties in instrumentation. In three phase circuits load assymmetry and non-linearities add to the complexity.

The IEEE standard suggests use of DFT or Clarke-Park transformations for implementation in active power filter design and measurement. But current research work on the adequacy of definitions and metering given in IEEE Std 1459-2000 indicate scope for an indepth study.

On the whole the debate on this subject is still open for researchers.

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