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Review

A new IEEE Std 1459-2000—Compatible time-domain formulation for apparent power

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ABSTRACT

This paper presents the development of new time-domain equations related to the definition of apparent power. These equations are compatible with the IEEE Std 1459-2000 Standard. When the application of these formulations involves an adequate quantity of samples, thus obeying the Nyquist Criterion, they can be utilized without restrictions regarding distortion, imbalance and asymmetry. Thus, they may be used in numeric meters for power measurements. In addition, unlike the above-mentioned standard, they do not oversimplify with respect to the phase and neutral resistance ratio or the percentage of delta-connected and wye-connected loads.

This paper uses these formulations to present several illustrative examples regarding the apparent power definition. Simulated cases have confirmed that both approaches, American and European, lead to similar results, which differ only if the voltage homopolar component is present.

Contents

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1. Introduction

The definition of apparent power for unbalanced, asymmetric, and non-sinusoidal three-phase systems is still a controversial issue. Many papers on this topic [1–6] have been published during the last decades, but to date, only two approaches have prevailed: the American and the European. The first one, also called the practical approach [6], is presented in the Standard IEEE Std 1459-2000 [7]. The second approach is sometimes referred to as the theoretical approach [6] or FBD (Fryze–Buchholz–Dependrock) method [8]. Recently, many articles have been published trying to compare the two methods by focusing on their divergences and convergences [9–11].

This paper presents the development, in the time-domain, of equations compatible with the American approach [7]. Voltage and current samples were used to calculate power values and numerical examples are shown to illustrate the application of these new expressions.

It has been demonstrated [6,10] that for three-phase three wire electrical systems, both the American and the European approaches produce the same value in the calculation of apparent power. Thus, this paper focuses on three-phase four wire systems.

Though some recent works [6] have considered the resistances of the phases to be unequal, this paper considers the electrical resistances of the three phases to be equal. However, the neutral conductor may present a different resistance value. In this work, the skin effect was not been taken into consideration as it was in [10] and [12].

In the American approach, the apparent power is defined as the maximum active power that may be transmitted to a certain load under ideal conditions with the same voltage impact (on the insulation and on the no-load losses) and the same current impact (on line losses) [7,10]. These ideal conditions (sinusoidal and balanced voltages and currents) are found in balanced three-phase sinusoidal systems such as the one used in the IEEE Std 1459-2000 [7]. It is important to point out that in this approach, a combined action is necessary: the customer adjusts the current (load) and the utility adjusts the voltage. In order to justify this concept of apparent power, it is necessary to show customers that it is possible, with no active power injection, to achieve the ideal conditions for energy transmission with the same link losses. Thus convinced, the customer that causes imbalance and distortion in the system will be able to understand that it is fairer to be charged for the apparent power demanded from the network rather than the active power consumed.

This paper consists of five sections. Section 2 presents the development of the theoretical basis of the formulation. In Section 3, the theoretical results of this work are presented, including equation for effective apparent power S_e. Furthermore, expression for apparent power using the FBD method is presented to enable comparison between the two methods. In Section 4, some applications for these expressions of apparent power are shown. The conclusions are presented in Section 5 and list of symbols are presented in Appendix A.

2. Theoretical development

2.1. Basic concepts

The IEEE Std 1459-2000 definitions consider the apparent power to be the maximum active power which may be transmitted and supplied for the load under sinusoidal, balanced, and symmetrical conditions. In this way, a utility may minimize its investment and operating costs, while improving voltage regulation. The electrical system, originally fed by voltages represented by vector $\underline{v}(\boldsymbol{t})$ and conducting currents represented by vector $\underline{\boldsymbol{i}}(\boldsymbol{t})$, has its original load substituted by an optimized load. This optimized load is divided into two parts: one connected in delta (conductance per phase g_Δ) and the other in wye (conductance per phase g_Y). These parts of the optimized load consume the active powers $\boldsymbol{P}_\Delta$ and $\boldsymbol{P}_\mathbf{Y}$, respectively. The relation between $\boldsymbol{P}_\Delta$ and $\boldsymbol{P}_\mathbf{Y}$ is given by:

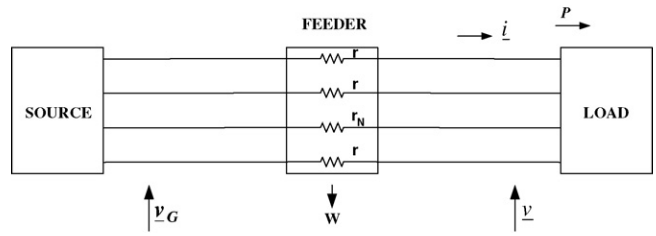

Fig. 1. Distribution original system.

$$\xi = \frac{\boldsymbol{P}_\Delta}{\boldsymbol{P}_\mathbf{Y}} = \frac{3\boldsymbol{g}_\Delta}{\boldsymbol{g}_\mathbf{Y}} \tag{1}$$

In the IEEE Std 1459-2000, ξ is considered to be equal to one, i.e., $\boldsymbol{P}_\Delta = \boldsymbol{P}_\mathbf{Y}$. In contrast, in this paper, any value of ξ can be used.

The next sub-sections will present a general set of equations deduced in the time-domain that provide the same results as the IEEE Std 1459-2000. These equations are obtained by considering the utilization of a hypothetical compensator of voltage and current without active power injection.

2.2. Original condition

Fig. 1 presents the original circuit. For simplicity, vector $\underline{v}(\boldsymbol{t})$ is represented by $\underline{v}$ and $\underline{\boldsymbol{i}}(\boldsymbol{t})$ by $\underline{i}$.

The problem to be solved is the maximization of the active power (P):

$$P = \mathrm{AVR}(\underline{v}^t \underline{i}) \tag{2}$$

where AVR is the mean value.

Subject to the feeder losses (W):

$$W = \mathrm{AVR}(\underline{i}^t \underline{\underline{R}}\, \underline{i}) \tag{3}$$

where $\underline{\underline{R}}$ is the feeder losses matrix, given by:

$$\underline{\underline{R}} = r\underline{\underline{B}} = r(dg\,\underline{1} + \rho\underline{1}\,\underline{1}^t) = r\begin{bmatrix} 1+\rho & \rho & \rho \\ \rho & 1+\rho & \rho \\ \rho & \rho & 1+\rho \end{bmatrix} = \begin{bmatrix} r+r_N & r_N & r_N \\ r_N & r+r_N & r_N \\ r_N & r_N & r+r_N \end{bmatrix} \tag{4}$$

where $\rho = r_N/r$ is the ratio between the neutral (return path) electrical resistance and the phase electrical resistance. In the IEEE Std 1459-2000, ρ is assumed to be equal to one. In this paper, any value of ρ can be used.

The following symbols are used:

One underline ($\underline{1}$) denotes a vector with all entries equal to one, two underlines ($\underline{\underline{A}}$) denote a matrix and $\underline{1}^t$ is the vector transpose of $\underline{1}$.

$dg\underline{1}$ is a unit matrix and $\underline{1}\,\underline{1}^t$ is a matrix with all entries equal to one.

2.3. Transforming the original load to an equivalent delta–wye load (optimized load)

The current is compensated by a current compensator (C.C.) for such that the feeder sees a fictitious load (represented in Fig. 2), i.e.,