

On the Definition of Apparent Power

S. CANTURK¹, M.E. BALCI², M.H. HOCAOGLU³

1) *Sindirgi Vocational School, Balikesir University, Balikesir, Turkey*

2) *Electrical and Electronics Engineering Dept., Balikesir University, Balikesir, Turkey*

3) *Electronics Engineering Dept., Gebze Technical University, Kocaeli, Turkey*

Summary: In this paper, the widely recognised apparent power definitions, which are Arithmetic, Vector, IEEE standard, DIN standard apparent power definitions and the apparent power definition of Mayordomo and Usaola, are rigorously reviewed, and their abilities on the measurement of the system's power transfer efficiency are analysed by using a specially derived apparent power, which is calculated in terms of the total line losses of the system with and without the reactive power compensation. In the analyses, two major compensation strategies, namely the minimum line loss (MLL) and sinusoidal and balanced current (SBC) compensation strategies, are considered to determine the total line loss of the system with the compensation. Therefore, in a representative nonsinusoidal and unbalanced test system, the results are simulated by taking into account unbalance among the resistances of neutral and phase lines. The simulated results show that under nonsinusoidal and unbalanced conditions, the unbalance among the resistances of neutral and phase lines highly affects the system's power transfer efficiency. Additionally, Mayordomo and Usaola's apparent power definition can be used for proper measurement of the power transfer efficiency in the nonsinusoidal and unbalanced systems. On the other hand, the accuracies of the rest of the reviewed definitions considerably depends on unbalance among the resistances of neutral and phase lines. It should also be mentioned that the accuracies of the apparent power definitions are considerably not affected by the type of compensation strategy.

Key Words:
*Apparent power;
 Power factor;
 Unbalanced
 and non-sinusoidal
 conditions*

1. BACKGROUND

Hitherto, in sinusoidal single-phase systems, with the aim of to provide a tool for the sizing of the system's equipment and the measurement of system's power transfer efficiency the classical apparent power was defined as the product of rms values of voltage and current, and it is also decomposed as the vector sum of the active power, which transports the net energy from the source to the load, and rest is the reactive power. The classical apparent power is conventionally calculated for three-phase systems by treating each phase individually. According to this approach, Arithmetic and Vector apparent powers were defined in the literature [2,13]. Vector apparent power is the vector sum of active and reactive powers of each phase:

$$S_V = \sqrt{\left(\sum_{m=a,b,c} P_m\right)^2 + \left(\sum_{m=a,b,c} Q_m\right)^2} = \sqrt{P^2 + Q^2} \quad (1)$$

where the active and reactive powers measured at phase m are $P_m = V_m I_m \cos\theta_m$ and $Q_m = V_m I_m \sin\theta_m$, respectively. Other definition is the Arithmetic apparent power that is the arithmetic sum of phase apparent powers ($S_m = V_m I_m$):

$$S_{Ar} = \sum_{m=a,b,c} S_m \quad (2)$$

For balanced and sinusoidal systems, both apparent powers are equal to $S = \sqrt{3} V_{pp} I_p$ where V_{pp} and I_p are the rms values of the phase-to-phase voltage and phase current.

Consequently the index of the system's power transfer efficiency, conventionally named as power factor, was expressed as the ratio of active power to apparent power:

$$pf = \frac{P}{S} \quad (3)$$

For sinusoidal and balanced three-phase systems with identical line resistances (r), total line loss (ΔP) can be written as a function of the apparent power (S):

$$\begin{aligned} \Delta P &= 3rI_p^2 \\ &= 3r \left(\frac{S}{\sqrt{3}V_{pp}} \right)^2 = r \frac{S^2}{V_{pp}^2} \end{aligned} \quad (4)$$

One can see from (3) and (4) for the considered systems that power factor can effectively be employed to measure total line loss or system's power transfer efficiency due to the fact that the square of apparent power is linearly related with total line loss when the voltage is constant. However, for unbalanced three-phase systems, Arithmetic and Vector apparent powers have nonlinear parts with respect to total line losses. As a result, they do not give true information on the system's power transfer efficiency. This matter can basically be explained for a three-phase and three-line system, which consists of linear-unbalanced load, sinusoidal-balanced voltage source and identical line resistances. In this case, Arithmetic apparent power (S_{Ar}) and total line loss (ΔP) can be written as:

$$S_{Ar} = V_a I_a + V_b I_b + V_c I_c = V_p (I_a + I_b + I_c) \quad (5)$$

$$\Delta P = r(I_a^2 + I_b^2 + I_c^2) \quad (6)$$

and the square of Arithmetic apparent power is calculated:

$$S_{Ar}^2 = V_p^2 \left[\underbrace{(I_a^2 + I_b^2 + I_c^2)}_{\text{linear part with } \Delta P} + \underbrace{2(I_a I_b + I_b I_c + I_a I_c)}_{\text{nonlinear part with } \Delta P} \right] \quad (7)$$

where the voltage drop on the line resistances are negligible and phase-to-neutral voltages are assumed as balanced ($V_a = V_b = V_c = V_p$). On the other hand, the relation between Vector apparent power (S_V) and total line loss (ΔP) can be investigated using similar approach. The total active and total reactive powers are expressed as in (8) and (9):

$$P = V_p (I_a \cos \theta_a + I_b \cos \theta_b + I_c \cos \theta_c) \quad (8)$$

$$Q = V_p (I_a \sin \theta_a + I_b \sin \theta_b + I_c \sin \theta_c) \quad (9)$$

Thus, the square of Vector apparent power is found as:

$$S_V^2 = V_p^2 \left[(I_a \cos \theta_a + I_b \cos \theta_b + I_c \cos \theta_c)^2 + (I_a \sin \theta_a + I_b \sin \theta_b + I_c \sin \theta_c)^2 \right] \quad (10)$$

And then, (10) can be arranged as:

$$S_V^2 = V_p^2 \left[\underbrace{(I_a^2 + I_b^2 + I_c^2)}_{\text{linear part with } \Delta P} + \underbrace{2(I_a I_b \cos \theta_a \cos \theta_b + I_b I_c \cos \theta_b \cos \theta_c + I_a I_c \cos \theta_a \cos \theta_c)}_{\text{nonlinear part with } \Delta P} + \underbrace{2(I_a I_b \sin \theta_a \sin \theta_b + I_b I_c \sin \theta_b \sin \theta_c + I_a I_c \sin \theta_a \sin \theta_c)}_{\text{nonlinear part with } \Delta P} \right] \quad (11)$$

This simple qualitative analysis shows that the square of both apparent powers are not linearly related with the total line loss for unbalanced conditions. Due to this lack of Vector and Arithmetic apparent powers, qualitatively illustrated above, apparent power was redefined for poly-phase systems in Buchholz's studies [5,6]. He proposed an apparent power definition, which treats the system as a single unit, by using "collective rms voltage" and "collective rms current" definitions. At the present time, the resolution of Buchholz's apparent power, which is based on the current relations presented by FBD (Fryze-Buchholz-Depenbrock)

theory [7], took place in German standard DIN 40110 [10]. The DIN power resolution approximates Buchholz's apparent power as the maximal active power that can be transmitted for the given voltage waveform and the given current rms value. On the other hand, Buchholz's apparent power is linearly related to the total line loss only for the systems with identical line resistances. However, the line resistances are not identical that is the case for most of the practical power systems. In order to fulfil this gap, Mayordomo and Usaola and S.J. Jeon redefined Buchholz's apparent power for such systems [14,15].

In addition to the apparent powers mentioned above, IEEE std. 1459 [13] working group defined apparent power in terms of "equivalent rms voltage" and "equivalent rms current". It treats three-phase system as a single unit like Buchholz's apparent power. However, it should be noted that IEEE apparent power gives the maximal active power, which can be transmitted under ideal conditions (sinusoidal and balanced) with the same rms voltage and current.

On the other hand, a completely different view took place in Ghassemi's works [11,12]. He proposed an apparent power definition, which is the magnitude of "complex instantaneous power". It is clearly understood from his derivations that his apparent power definition is related with the proper sizing of the system and its equipment but not the loss of the system.

In this study, firstly the milestone studies on the apparent power definitions are summarized in section II. Secondly, the outlines of the widely recognized apparent power definitions are given in section III. Finally, for an unbalanced and non-sinusoidal test system, the abilities of the apparent power definitions on the measurement of the system's power transfer efficiency are investigated by taking into account the unbalance among the resistances of neutral and phase lines and giving particular emphasis to the compensation strategies. It should be noted that a part of this study was previously presented and discussed in [4].

2. LITERATURE SUMMARY

The philosophy of apparent power was explained and interpreted in many engineering publications, accessible important ones of these studies are summarised below to show apparent power's evolution.

One of these studies [9] that is a milestone work on the way of present IEEE standard definition presents that the resolution of Buchholz's apparent power contains active and non-active powers calculated by using symmetrical components theory for a sinusoidal but unbalanced three-phase system. It also shows that the negative and zero sequence powers cause additional power losses in the network and they should be viewed as useless powers unless they are generated purposely with the goal of cancelling these powers of another load. Therefore, author concluded that power factor should be defined as the ratio of positive sequence active power to Buchholz's apparent power.

In another study [8], the same author concludes that the power loss of the system is not linearly related with the square of Arithmetic and Vector apparent powers under unbalanced and nonsinusoidal conditions. Only the apparent power defined by Buchholz holds this property for the same conditions.

Williems et al. [19,20] discussed the relationships and differences between two apparent power definitions that took place in DIN and IEEE standards. The main conclusion of these studies is that two apparent power definitions give different results only if zero sequence voltage exists in the system.

In [17], Pajic and Emanuel provided comparative evaluation of the apparent power definitions placed in DIN and IEEE standards. They pointed out that DIN definition uses a pure mathematical approach to obtain unity power factor case that implies the currents in-phase with the voltages. Thus, in unity power factor case of DIN definition (Buchholz's definition), negative and zero-sequence currents may be present. IEEE definition uses a practical approach to obtain unity power factor case that implies perfectly sinusoidal and balanced voltages and currents in-phase with each other. In addition, the evaluation results show that for the networks, where the differences among the supplying lines resistances are small and the zero-sequence voltage is kept low, DIN and IEEE definitions yield the results that are nearly overlapping.

[16] summarizes several apparent power definitions and their resolutions, which have frequency and time domain calculations, and shows that none of the definitions and resolutions can be used to solve all of the non-sinusoidal and/or unbalanced power system's problems, i.e. compensation, metering and billing.

Finally, a recent study [3] evaluated different apparent power definitions using the simulation of a typical power network that supplies linear and non-linear loads, and analysed the effects of several methods of non-active power compensation on the power factor, unbalance, harmonic distortion, motor power losses and converters voltage ripple. Therefore, it advocated the idea that the apparent power should quantify an ideal situation that represents optimum energy flow conditions not only for the energy supplier, but for the consumers as well.

Above literature summary shows that apparent power is still a controversial topic in the non-sinusoidal and unbalanced systems despite the fact that it is the core for design and operation of the power systems. Accordingly, the evaluation studies on the apparent power definitions should continue to understand their capabilities and limitations.

3. EXPRESSIONS OF APPARENT POWER DEFINITIONS

In this section, the apparent power definitions other than Arithmetic apparent power, which is given in the background, Ghassemi's apparent power [11,12], which is not in the scope of this study due to the fact that it does not aim to measure the losses, and S. J. Jeon's apparent power [14], which is identical with Mayordomo and Usaola's apparent power [15], are briefly summarised:

3.1. Vector Apparent Power

This is one of the oldest [2] and probably the most common definition [18]. According to the definition, under nonsinusoidal or harmonically distorted system conditions

the powers are measured individually for each of the three phases $m = a, b, c$:

Active powers,

$$P_m = \sum_h V_{mh} I_{mh} \cos(\theta_{mh}) \quad (12)$$

Reactive powers,

$$Q_m = \sum_h V_{mh} I_{mh} \sin(\theta_{mh}) \quad (13)$$

Apparent powers,

$$S_m = \sqrt{\left(\sum_h V_{mh}^2\right)\left(\sum_h I_{mh}^2\right)}, \quad m = a, b, c \quad (14)$$

and the calculated distortion powers,

$$D_m = \sqrt{S_m^2 - P_m^2 - Q_m^2} \quad (15)$$

giving the vector apparent power:

$$\begin{aligned} S_V &= \sqrt{\left(\sum_{m=a,b,c} P_m\right)^2 + \left(\sum_{m=a,b,c} Q_m\right)^2 + \left(\sum_{m=a,b,c} D_m\right)^2} = \\ &= \sqrt{P^2 + Q_V^2 + D_V^2} \end{aligned} \quad (16)$$

where h denotes the harmonic number of voltages and currents.

Since each phase is treated as an independent single-phase system in this definition, it proposes the compensation of the each phase separately.

3.2. Buchholz's (or DIN standard) Apparent Power

For three-phase systems (a, b, c phases) with neutral line (n), Buchholz's apparent power definition [6,7,10] can be expressed as:

$$\begin{aligned} S_\Sigma &= V_\Sigma I_\Sigma = \sqrt{V_{a0}^2 + V_{b0}^2 + V_{c0}^2 + V_{n0}^2} \times \\ &\times \sqrt{I_a^2 + I_b^2 + I_c^2 + I_n^2} \end{aligned} \quad (17)$$

where the line-to-virtual star point rms voltages ($V_{a0}, V_{b0}, V_{c0}, V_{n0}$) can be calculated in terms of the positive-, negative- and zero- sequence voltage harmonics of order h (V_h^+, V_h^-, V_h^0) [3]:

$$V_{m0} = \sqrt{\sum_h (V_h^+)^2 + \sum_h (V_h^-)^2 + \frac{1}{16} \sum_h (V_h^0)^2} \quad \text{for } m = a, b, c \quad (18)$$

$$V_{m0} = \sqrt{\frac{9}{16} \sum_h (V_h^0)^2} \quad \text{for } m = n \quad (19)$$

In DIN standard 40110 [10], by taking into account the current decomposition defined in FBD theory [7], the apparent power is separated into active (or average power) and two non-active power components:

$$S_{\Sigma} = \sqrt{P^2 + Q_{tot\Sigma IIv}^2 + Q_{tot\Sigma\perp}^2} \quad (20)$$

The non-active power drawn due to the difference between the conductance of the line m , $G_m = P_m / V_{m0}^2$, and equivalent conductance, $G = P / V_{\Sigma}^2$, can be calculated as:

$$Q_{tot\Sigma IIv} = V_{\Sigma} \sqrt{\sum_{m=a,b,c,n} (G_m - G)^2 V_{m0}^2} \quad (21)$$

Thus, the non-active power drawn by the component of the collective rms current orthogonal with the voltage, can be found as:

$$Q_{tot\Sigma\perp} = V_{\Sigma} \sqrt{\sum_{m=a,b,c,n} [I_m^2 - G_m^2 V_{m0}^2]} \quad (22)$$

According to this power decomposition, in unity power factor case; the load should react to the lines as a symmetric load consisting of four identical star connected ohmic resistors. Thus, it can be mentioned that Buchholz's apparent power definition treats the neutral wire (n) as a fourth phase. In addition to that, for the unity power factor case of this apparent power, some imbalance and distortion may persist in the line currents [3].

3.3. IEEE Apparent Power

IEEE standard 1459 [13] proposed apparent definition relies on equivalent rms voltage,

$$V_e = \sqrt{\frac{1}{18} [3(V_a^2 + V_b^2 + V_c^2) + V_{ab}^2 + V_{bc}^2 + V_{ca}^2]} \quad (23)$$

and equivalent rms current,

$$I_e = \sqrt{\frac{I_a^2 + I_b^2 + I_c^2 + I_n^2}{3}} \quad (24)$$

giving apparent power as below;

$$S_e = 3V_e I_e \quad (25)$$

The IEEE definition has two main power components: first is fundamental effective apparent power;

$$S_{e1} = 3V_{e1} I_{e1} \quad (26)$$

where V_{e1} and I_{e1} are the fundamental harmonic equivalent rms voltage and current values, which are calculated by substituting only fundamental harmonic voltages and currents in (23) and (24), and second is non-fundamental apparent power;

$$S_{eN}^2 = S_e^2 - S_{e1}^2 \quad (27)$$

Fundamental effective apparent power is decomposed into fundamental harmonic positive sequence apparent power and fundamental harmonic unbalanced apparent power:

$$S_{e1} = \sqrt{(S_1^+)^2 + S_{U1}^2} \quad (28)$$

Fundamental harmonic-positive sequence apparent power can be calculated as:

$$S_1^+ = \sqrt{(P_1^+)^2 + (Q_1^+)^2} \quad (29)$$

by means of fundamental harmonic-positive sequence active power ($P_1^+ = 3V_{1+} I_1^+ \cos \theta_1^+$) and fundamental harmonic positive sequence reactive power ($Q_1^+ = 3V_{1+} I_1^+ \sin \theta_1^+$)

In addition, non-fundamental apparent power is decomposed into the power components as follows:

$$S_{eN}^2 = D_{eI}^2 + D_{eV}^2 + S_{eH}^2 \quad (30)$$

where:

$$D_{eI} = 3V_{e1} I_{eH} \quad (31)$$

is the current distortion power,

$$D_{eV} = 3V_{eH} I_{e1} \quad (32)$$

is the voltage distortion power,

$$S_{eH} = 3V_{eH} I_{eH} = \sqrt{P_H^2 + D_{eH}^2} \quad (33)$$

is the harmonic apparent power, which is the vector sum of the total harmonic active power (P_H) and the harmonic distortion power (D_{eH}). Note that V_{eH} and I_{eH} are the non fundamental components of the equivalent rms voltage and current $V_{eH} = \sqrt{V_e^2 - V_{e1}^2}$, $I_{eH} = \sqrt{I_e^2 - I_{e1}^2}$.

Therefore, IEEE apparent power is decomposed as:

$$S_e = \sqrt{(P_1^+)^2 + (Q_1^+)^2 + S_{U1}^2 + D_{eI}^2 + D_{eV}^2 + S_{eH}^2} \quad (34)$$

It can be concluded from (34) that IEEE apparent power approximates the powers other than fundamental harmonic positive sequence active power as non-active powers. Consequently, voltage and current must have in phase sinusoidal and balanced wave shapes for the unity power factor case of the IEEE definition.

3.4. Apparent Power Defined By Mayordomo and Usaola

In [15], Mayordomo and Usaola modified Buchholz's apparent power as:

$$S_{MU} = V_{MU} I_{MU} \quad (35)$$

Table 1. The main properties of the summarised apparent powers.

Apparent Powers (AP)	Properties
Arithmetic AP	It is defined as the sum of each phase's apparent power. So, it handles three-phase systems by treating each phase individually.
Vector AP	Vector apparent power is defined as the vector sum of total active, total reactive and total distortion powers, which are the sum of respective values for each phase. It treats each phase as an independent single phase system like Arithmetic apparent power.
Buchholz's (or DIN standard) AP	It is the maximal active power that can be transmitted for the given voltage waveform and the given current rms value. It treats three-phase system as a unit.
Mayordomo and Usaola's AP	This is the modified version of Buchholz's apparent power for the systems with different line resistances.
IEEE standard AP	It is the maximal active power that can be transmitted under sinusoidal and balanced conditions with the same voltage and current rms values. It treats three-phase system as a unit like the apparent powers defined by Buchholz and Mayordomo and Usaola.

by redefining collective rms voltage,

$$V_{MU} = \sqrt{\sum_{m=a,b,c,n} 1/\beta_m V_{m0}^2} \quad (36)$$

and collective rms current,

$$I_{MU} = \sqrt{\sum_{m=a,b,c,n} \beta_m I_m^2} \quad (37)$$

where V_{m0} denotes the rms value of line m -to-virtual star point voltage ($v_{m0}(t)$);

$$V_{m0} = \sqrt{\frac{1}{T} \int_0^T [v_{m0}(t)]^2 dt}, \quad v_{m0}(t) = \left[\begin{array}{c} \sum_{m=a,b,c,n} \frac{v_m(t)}{\beta_m} \\ \sum_{m=a,b,c,n} \frac{1}{\beta_m} \end{array} \right] \quad (38)$$

In the equations from (36) to (38), β_m is the ratio among the resistance of respective line (r_m) and a reference resistance value (r_L), which can be one of the resistances of the lines.

The main properties of the above summarised apparent power definitions are given in Table 1.

4. APPLICATION

Table 1 shows that there are five different apparent power definitions proposed for the effective utilisation of the system. In order to quantitatively analyse their abilities on the measurement of the system's power transfer efficiency, the power factor and apparent power definitions related with total line loss is taken as the reference in the analysis. The reference definition of the power factor used in the analysis has the meaning of the power factor well expressed for sinusoidal and balanced three-phase systems with identical line resistances. The power factor for sinusoidal and balanced

systems with identical line resistances can be expressed in terms of the total line loss as below:

Firstly, power factor is written as;

$$pf_T = \frac{P}{S} = \frac{I_{pmin}}{I_p} \quad \text{for } S = \sqrt{3}V_{pp}I_p \quad (39)$$

$$\text{and } P = \sqrt{3}V_{pp}I_{pmin}$$

where I_{pmin} and I_p are the minimum and actual rms phase currents, which transport the same active power (P), with keeping same phase-to-phase voltage rms value (V_{pp}).

Second, the ratio among the minimum (ΔP_{min}) and actual (ΔP) total line losses is expressed as;

$$\frac{\Delta P_{min}}{\Delta P} = \frac{3rI_{pmin}^2}{3rI_p^2} = \left(\frac{I_{pmin}}{I_p} \right)^2 \quad (40)$$

where r denotes line resistance. It should be kept in mind that active power has the same value for the both cases i.e. the minimum and actual line losses.

And then; the equivalent of I_{pmin} / I_p found in (39) is substituted in (40):

$$pf_T^2 = \frac{\Delta P_{min}}{\Delta P} \quad (41)$$

Finally, (41) can be arranged as;

$$pf_T = \sqrt{\frac{\Delta P_{min}}{\Delta P}} \quad (42)$$

Thus, a fictitious apparent power (S_T) could be calculated with respect to the definition of the power factor (pf_T), which is driven for sinusoidal and balanced three-phase systems with identical line resistances:

$$S_T = \frac{P}{pf_T} = \frac{P}{\sqrt{\frac{\Delta P_{min}}{\Delta P}}} \quad (43)$$

However, for unbalanced and non-sinusoidal systems, S_T depends on compensation strategy due to the fact that in practice ΔP_{min} is related with the compensation strategy. The active compensation strategies can mainly be classified as the minimum line loss (MLL) and the sinusoidal and balanced current (SBC) compensations [1]. It is well known that the transferring of the same active power under same voltage wave shapes with the minimum line loss (MLL) can be achieved via the line currents, which are the perfect replicas of their respective line-to-a virtual neutral point voltages. On the other hand, SBC compensation, which is useful for the power quality improvement, the compensated phase currents contain only the active portion of the fundamental harmonic positive-sequence current that is in phase with the fundamental harmonic positive-sequence voltage.

Therefore, to show the abilities of the reviewed apparent power definitions on the measurement of the power transfer efficiency, they are evaluated against the fictitious apparent power (S_T), which is calculated for MLL and SBC compensation strategies. During the comparison, the variation of the ratio among the resistances of neutral and phase lines ($\alpha = R_n/R_p$) is also taken under consideration. The results of the analyses are obtained for the test system given in Figure 1. For $\alpha = 0.1$, the wave shapes of the phase-to-neutral voltages and the phase currents, which are measured when the active compensator is not activated, are given in Figure 2.

It is shown from Figure 2 (a) and (b) that both load voltages and phase currents are non-sinusoidal and unbalanced. In the system without compensation, $THDV_{a,b,c}$, V_1^- / V_1^+ and V_1^0 / V_1^+ of the phase-to-neutral voltages are 8%, 2.05% and 10.25% respectively. In addition to that, for the same case of the system, $THDI_{a,b,c}$, I_1^- / I_1^+ and I_1^0 / I_1^+ of the phase currents are 35.00%, 22.30% and 36.30%, respectively.

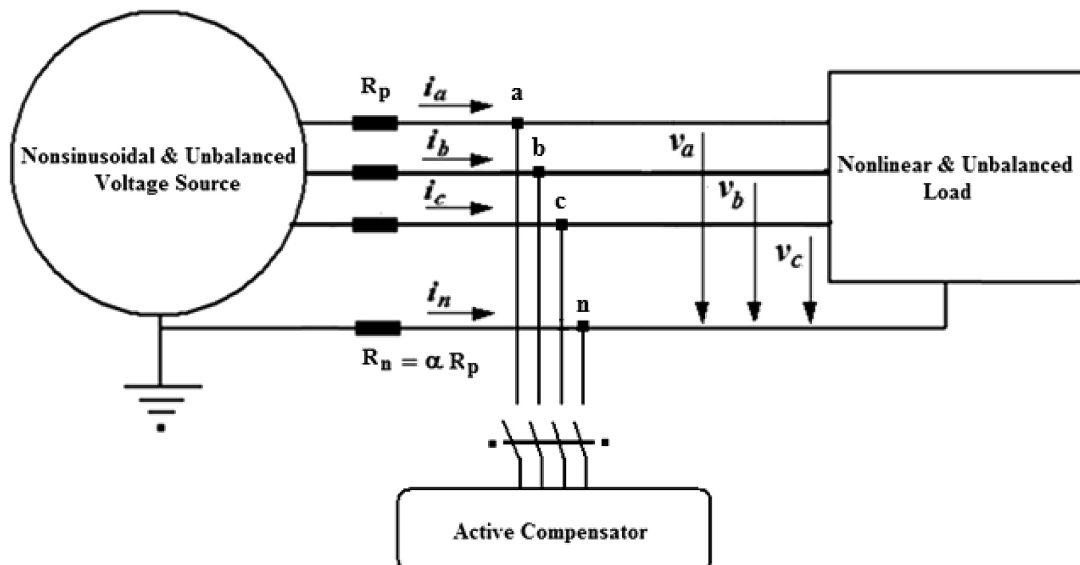


Figure 1. Test system.

To analyse the ability of the reviewed apparent power definitions on the measurement of the power transfer efficiency, the relative differences between them and the apparent power definition derived in terms of the line loss (S_T) are calculated in two steps:

- **Measurements on the system without compensation:** S_{Ar} , S_V , S_Σ , S_e and S_{MU} are calculated at the load terminal of the system without compensation. Additionally, P and ΔP are calculated for the same case of the system.
- **Measurements on the system with the compensation:** Active compensator is activated regarding the respected compensation strategy (MLL or SBC compensations). It should be underlined for the test system that the variations of P and phase-to-neutral voltages measured at the load terminal are negligible when active compensator is activated. ΔP_{min} is found for the system with the active compensation.

Consequently, pf_T is calculated by substituting ΔP_{min} and ΔP in (42), and S_T is found by substituting P and pf_T in (43). Thus, the relative differences (RD_{Ar} , RD_V , RD_e , RD_Σ and RD_{MU}) between S_T and the reviewed apparent power definitions are obtained using (44):

$$RD_X (\%) = \frac{S_X - S_T}{S_T} \cdot 100 \quad X: Ar, V, e, \Sigma, MU \quad (44)$$

Case I: Evaluation of the reviewed apparent powers against the S_T calculated for MLL compensation

For the MLL compensation strategy, S_{MU} and S_T give the same numerical value [4,15]. Thus, RD_{MU} is nil for the same case. Due to this, for α values between 0.1 and 3, the variations of P , S_{MU} and pf_{MU} ($= P/S_{MU}$) are plotted in Figure 3 (a). For the same α interval, RD_{Ar} , RD_V , RD_e and RD_Σ are plotted in Figure 3 (b). It should be noted that the

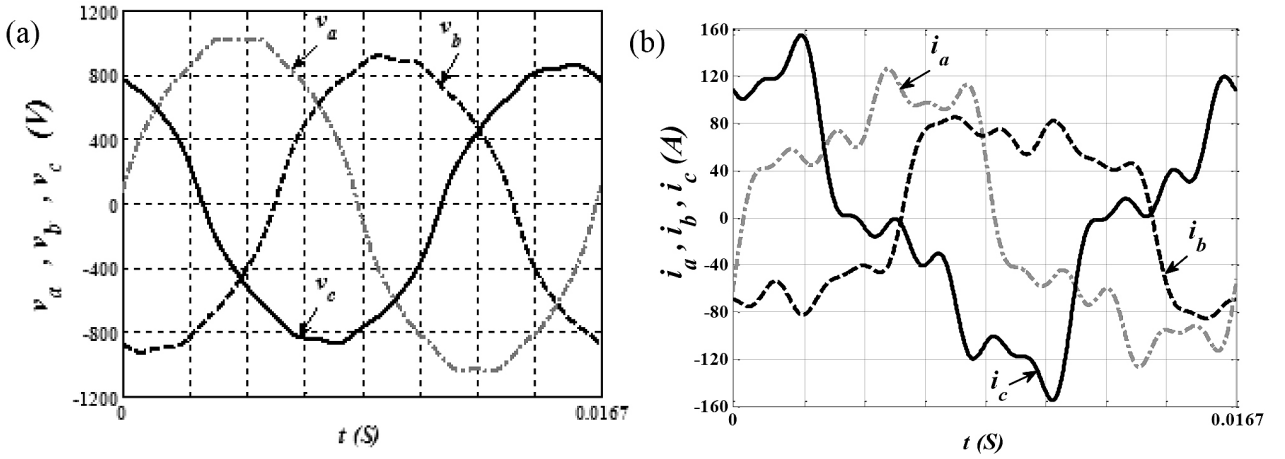


Figure 2. (a) The wave shapes of phase-to-neutral voltages and (b) the phase currents.

voltage and the active power (P) are almost constant during the variation of α value.

Figure 3 (a) shows that P is measured as 0.8104 pu for all α values. However, S_{MU} increases from 1.0000 pu to 1.5122 pu, and pf_{MU} decreases from 0.8104 to 0.5359. These results point out that the ratio among the resistances of neutral and phase lines highly influences S_{MU} and pf_{MU} (or the true power transfer efficiency). It is shown from Figure 3 (b) that RD_{Ar} varies from -3.0538 to -35.8956 , RD_V varies from -7.2031 to -38.6391 , RD_e varies from 18.3815 to -21.7347 , and RD_Σ varies from 18.1541 to -21.8841 with the increment of α .

It is seen from the figure that RD_e and RD_Σ is nil for $\alpha=1$ due to the fact that S_Σ gives the same numerical value with S_{MU} when all line resistances are equal. It is also seen from the figure that RD_e and RD_Σ are very close to each other for all α values. It is one of the most important results that RD_{Ar} and RD_V are smaller than the relative differences of two major definitions (RD_e and RD_Σ) for $\alpha < 0.4$ and $\alpha \leq 0.3$, respectively. Thus, one can see that S_{Ar} and S_V give much accurate results on the power transfer efficiency than S_Σ and S_e for the system, which has the neutral line's resistance considerably smaller than phase line's resistance. However, for the system, which has the neutral line's resistance close to or higher than phase line's resistance, S_Σ and S_e have higher accuracy on the power transfer efficiency when compared to S_{Ar} and S_V .

Case II: Evaluation of the reviewed apparent powers against the ST calculated for SBC compensation

For the α values from 0.1 to 3, the variations of P , S_T and pf_T are plotted in Figure 4 (a). In addition to that, RD_{Ar} , RD_V , RD_e , RD_Σ and RD_{MU} are plotted in Figure 4 (b). Figure 4 (a) shows that P has the same value measured as 0.8104 pu for all α values, S_T increases from 0.9924 pu to 1.5099 pu, and pf_T decreases from 0.8166 to 0.5367 with the increment of α . Thus, it can be seen from Figure 3 (a) and Figure 4 (a) that the specially derived power factor has almost the same values for both compensation strategies. It is also obvious from Figure 4 (b) that RD_{MU} has very small values, which

are between 0.7653 and 0.1519 for all α values. In addition to these results, RD_{Ar} varies from -2.3119 to -35.7982 , RD_V varies from -6.4930 to -38.5459 , RD_e varies from 19.2874 to -21.6158 , and RD_Σ varies from 19.0583 to -21.7655 with the increment of α . Therefore, it can be seen from Figure 3 (b) and Figure 4 (b) that the trends of the variation of RD_{Ar} , RD_V , RD_e and RD_Σ are the same for both compensation strategies.

5. CONCLUSION

In this paper, the literature on three-phase apparent power definitions is carefully reviewed. The reviewed literature shows that the apparent power definition is still

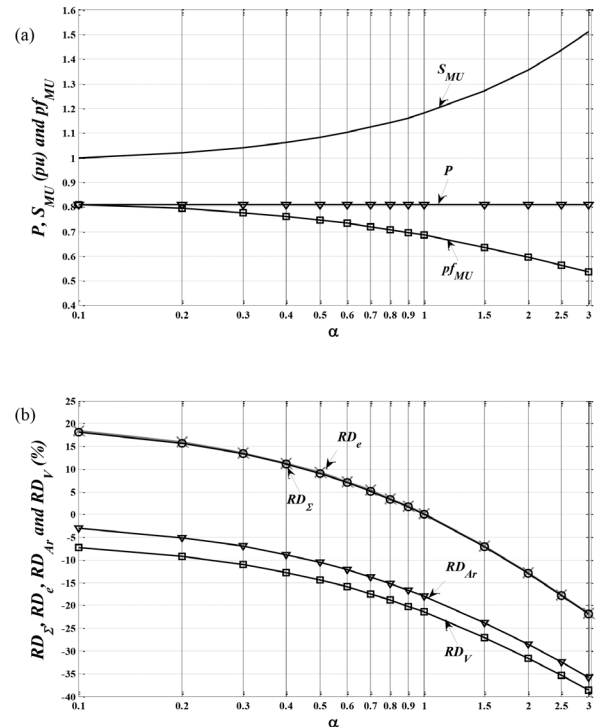


Figure 3. For Case I, the variations of (a) P , S_{MU} and pf_{MU} , and (b) RD_{Ar} , RD_V , RD_e and RD_Σ with the increment of α .

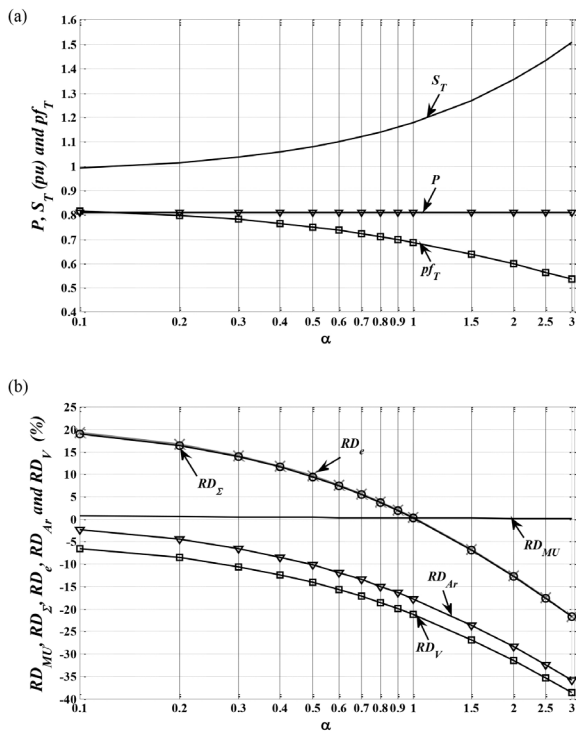


Figure 4. For Case II, the variations of (a) P , S_T and pf_T , and (b) RD_V , RD_{Ar} , RD_e , RD_{Σ} and RD_{MU} with the increment of α .

a controversial subject for unbalanced and non-sinusoidal systems. Therefore, it is figured out that the studies on the analysis of the apparent powers should continue to understand their capabilities and limitations.

Accordingly, in a non-sinusoidal and unbalanced three-phase system, the abilities of the widely known apparent power definitions on the measurement of the power transfer efficiency are quantitatively analysed by considering the apparent power definition, which is specially derived in terms of the total line loss of the system with and without compensation. In the analysis, two main compensation strategies, which are called as the minimum line loss (MLL) and sinusoidal and balanced current (SBC) compensations, are taken into account for the calculation of the specially derived apparent power definition. Thus, regarding two compensation strategies, the comparative evaluation of the specially derived and the widely known apparent powers are studied in the test system for several values of the unbalance ratio between neutral and phase lines resistances (α). The obtained results reveal that:

- Arithmetic and Vector apparent powers give much accurate results on the system's power transfer efficiency than DIN standard and IEEE standard apparent powers for the systems, which have the neutral line's resistances considerably smaller than the phase line's resistances. However, this is not the case for the systems with the value of the neutral line's resistance close to or higher than the value of the phase line's resistances. It should also be mentioned that the apparent power definitions' accuracies on the measurement of the power transfer efficiency

are considerably not affected with the type of compensation.

- The unbalance among the resistances of neutral and phase lines highly influences the power factor (or the power transfer efficiency). Due to the fact that the normalized values of all line resistances are taken into account by the apparent power definition of Mayordomo and Usaola, it is the most accurate definition to measure the power transfer efficiency under unbalanced and non-sinusoidal conditions. However, its practical implementation is very difficult at the present time unless the system consists of a few transmission or distribution lines. Nevertheless, as the acceptance of smart energy metering and energy management systems will increase in the future, their apparent power definition can successfully be implemented for proper measurement of the power transfer efficiency.

ACKNOWLEDGEMENTS

This work was supported by the Scientific and Technological Research Council of Turkey (TUBITAK) under project number 112E222.

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Mehmet Hakan Hocaoglu

received the B.Sc. and M.Sc. degrees from Marmara University, Turkey. He obtained the Ph.D. degree in 1999 from Cardiff School of Engineering, UK. From 1988 to 1993, he worked at Gaziantep University, Turkey as a Lecturer. Since 1999, he has been with the Electronics Engineering Department of Gebze Technical University, Turkey . He is, currently, a full Professor at the same University.

Address:

Gebze Technical University, Department of Electronics Engineering, Kocaeli, 41400, TURKEY

Tel.: (+90 262) 605 2440, Fax: (+90 262) 653 84 90

E-mail: hocaoglu@gtu.edu.tr



Sevket Canturk

received B.Sc. degree from Marmara University and M.Sc. degree from Suleyman Demirel University, Turkey. Since 2008, he has been a lecturer in Sındırgı Vocational School of Balıkesir University, Turkey. In addition, he currently continues Ph.D. Programme at Electric and Electronics Engineering Department of Balıkesir University.

Address:

Balıkesir University, Sındırgı Vocational School, Sındırgı, 10330, Balıkesir, TURKEY

Tel: (+90 266) 516 17 03, Fax: (+90 266) 516 48 01

E-mail: scanturk@balikesir.edu.tr



Murat Erhan Balci

received B.Sc. degree from Kocaeli University, M.Sc. and Ph.D. degrees from Gebze Institute of Technology, Turkey in 2001, 2004 and 2009, respectively. During 2008, he was a visiting scholar at Worcester Polytechnic Institute, USA. Since 2009, he has been with the Electrical and Electronics Engineering Department of Balıkesir University, Turkey as Professor. He is working in the field of electric machines, power electronics, power quality, power system analysis and wind power.

Address:

Balıkesir University, Department of Electrical and Electronics Engineering Cagis Campus, 10145, Balıkesir, TURKEY

Tel: (+90 266) 612 11 94, Fax: (+90 266) 612 12 57

E-mail: mbalci@balikesir.edu.tr

