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Virtual Instrumentation Applied to Calculation of Electrical Power Quantities in Single-Phase Systems

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Abstract.

This paper presents a low cost virtual instrumentation platform. It is used in single-phase systems in order to calculate electric power quantities and indicators defined in IEEE Std. 1459-2010. The algorithm used to calculate the power quantities and indicators are based on synchronous reference frame, which is used to implement the definitions presented in IEEE Std. 1459-2010 under sinusoidal and nonsinusoidal utility conditions. To confirm the theoretical development, experimental results are presented by means of a versatile power monitoring system using a graphic platform, in which the apparent, active and nonactive powers can be viewed and analyzed, as well as the indicators.

Key words

Virtual Instrumentation, Power Calculation, Power Factor, Std. 1459-2010.

1. Introduction

The increasing demand in the use of nonlinear loads such as inverters, cycloconverters, switched-mode power supplies, uninterruptible power supplies, among others, has contributed to increase problems related to power quality (PQ). Such problems are occasioned by means of the harmonic currents drained from power system, which results in distorted voltage with high harmonic contents. The interaction of the harmonic currents with the line impedance, results in the utility voltage distortion that can contribute to cause PQ problems for consumers connected to the same point of common coupling (PCC).

In this context, estimating and monitoring harmonic sources in the power system are two of the main factors to keep the PQ within defined limits, as well as identifying the responsibilities of consumers and power suppliers through losses incurred in the system due to harmonic distortion. In practice, the electrical utility and load consumers can each be held responsible for harmonic distortion problems [1].

The IEEE Std. 1459-2000 [2] presents electric power definitions which allow performing power calculations under sinusoidal, nonsinusoidal, balanced, or unbalanced utility conditions. It has been subject of many discussions and applications [4-6]. Recently, the IEEE Std. 1459-2000 was reviewed originating the IEEE Std. 1459-2010 [3] with several corrections.

The IEEE Std. 1459-2010 is based on the effective apparent power resolution ($S_e = 3V_e I_e$), which is obtained from the determination of the effective current (I_e) and the effective voltage (V_e) [2–4]. The concept of effective apparent power (S_e), for three-phase systems, assumes a virtual balanced system that has the same power losses when compared to the actual unbalanced system [3]. For obtaining a correct computation of conventional electrical power quantities, such as active, reactive, and apparent powers, the apparent power resolution, conceived by the IEEE Std. 1459-2010, separates the fundamental power in its positive, negative and zero sequence components [5]. Besides, the nonfundamental apparent power (S_N) allows quantifying the real amount of harmonic pollution delivered or absorbed by the load [2, 3]. For single-phase systems the standard focuses the power calculations and indicators taking into account nonsinusoidal utility conditions.

To calculate the electric power quantities defined in the IEEE Std. 1459-2010 for single-phase systems, an algorithm based on synchronous reference frame (SRF) is employed in this paper. Despite the original description of the SRF is based on three-phase balanced system, it will be expanded to single-phase system, wherein each phase is treated independently, resulting in a fictitious balanced three-phase system. The SRF algorithm allows the determination of electrical quantities, such as active, nonactive, and apparent powers, and indicators, such as line utilization factor (power factor) and harmonic pollution factor. The electrical quantities can be easily viewed by means of a power monitoring system (PMS) using virtual instrumentation as an analysis tool [5-7].

2. SRF-Based Algorithm and Power Calculations for Single-Phase Systems

The PMS presented in this paper was implemented using SRF-based algorithm, in order to calculate the power quantities and indicators.

The SRF-based algorithm [8] is based on the transformation of the three-phase voltages/currents components from the *abc* stationary reference frame into continuous quantities in the *dq* synchronous frame. The corresponding voltage/current harmonic components in the *dq*-axes, which have different frequencies in the synchronous axes, are represented by oscillating waveforms superimposed on the fundamental continuous term. Thereby, the fundamental component can be easily obtained through the use of low-pass filters (LPFs). The required orthogonality for the operation of the SRF-based algorithm is obtained through generating the coordinates of the synchronous unit vector $sin\theta$ and $cos\theta$, using phase-locked loop (PLL) circuits synchronized with the utility frequency [9].

A. SRF-Based Algorithm Applied to Single-Phase System

In order to apply the SRF-based algorithm in the single-phase system, it is necessary to create a virtual three-phase system. The block diagram of the Fig. 1 shows the strategy adopted, in which the measured currents/voltages are phase delayed of 120 and 240 degrees, producing fictitious balanced three-phase system. Thus, it is possible using the SRF algorithm similarly to that used in conventional three-phase balanced system.

Since the single-phase system is treated as a fictitious balanced three-phase system, it is possible, using SRF algorithm, to extract the fundamental sequence components (V_1 and I_1) from the respective measured voltage and current, as follows:

$$V_1 = \frac{\sqrt{vd'^2_{dc} + vq'^2_{dc}}}{\sqrt{3}} \quad (1)$$

$$I_1 = \frac{\sqrt{id'^2_{dc} + iq'^2_{dc}}}{\sqrt{3}} \quad (2)$$

where vd'_{dc}, vq'_{dc}, id'_{dc} and iq'_{dc} are the fictitious DC components of voltage and current in *dq*-axes.

B. Calculation of Power Quantities Based on IEEE Std. 1459-2010 for Single-Phase Systems

Based on IEEE Std. 1459-2010, the apparent power S (VA) and the fundamental apparent power S_1 (VA) are defined as (3) and (4), respectively.

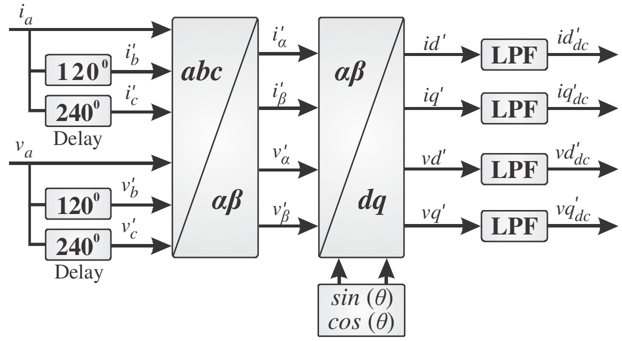


Fig. 1. Block diagram of SRF-based algorithm applied to single-phase systems.

$$S = VI \quad (3)$$

$$S_1 = V_1 I_1 \quad (4)$$

where V is the rms voltage and I is the rms current of the utility grid.

From Fig. 1, the fictitious three-phase instantaneous active power p' is defined by (5). It can be divided into average part ($\bar{p}'$), and alternate part ($\tilde{p}'$).

$$p' = vd'\,id' + vq'\,iq' = \bar{p}' + \tilde{p}' \quad (5)$$

Thus, the single-phase active power (P) and the fundamental active power P_1 can be found by (6) and (7), respectively.

$$P = \frac{\bar{p}'}{3} = P_1 + P_H \quad (6)$$

$$P_1 = \frac{vd'_{dc}\,id'_{dc} + vq'_{dc}\,iq'_{dc}}{3} = V_1 I_1 * cos\theta_1 \quad (7)$$

where P_H represents the nonfundamental active power (W), and $\theta_1 = \varphi_1 - \varphi_2$ represents the phase-angle between the fundamental phasors V_1 and I_1.
The phase-angles φ_1 and φ_2 can be achieved as follows:

$$\varphi_1 = arctg\left(\frac{id'_{dc}}{iq'_{dc}}\right) \quad (8)$$

$$\varphi_2 = arctg\left(\frac{vd'_{dc}}{vq'_{dc}}\right) \quad (9)$$

The fundamental reactive power Q_1 can be obtained by:

$$Q_1 = \sqrt{S_1^2 - P_1^2} = V_1 I_1 sen\theta_1 \quad (10)$$

The nonfundamental S_N (VA) and the harmonic S_H (VA) apparent powers can be calculated by (11) and (12), respectively.

$$S_N = \sqrt{S^2 - S_1^2} \tag{11}$$

$$S_H = V_H I_H \tag{12}$$

where the rms harmonic voltage V_H and the rms harmonic current I_H are given by (13) and (14).

$$V_H = \sqrt{V^2 - V_1^2} \tag{13}$$

$$I_H = \sqrt{I^2 - I_1^2} \tag{14}$$

From (3) and (6) the nonactive power N (var) can be obtained, and from (6) and (12) the harmonic distortion power D_H (var) can be calculated as follows:

$$N = \sqrt{S^2 - P^2} \tag{15}$$

$$D_H = \sqrt{S_H^2 - P_H^2} \tag{16}$$

The current distortion power D_I (var) and the voltage distortion power D_V (var) are defined by:

$$D_I = V_1 I_H \tag{17}$$

$$D_V = V_H I_1 \tag{18}$$

Thus, using (12), (17) and (18) the nonfundamental apparent power S_N (VA) can be rewritten as:

$$S_N = \sqrt{D_I^2 + D_V^2 + S_H^2} \tag{19}$$

The voltage and current total harmonic distortions are respectively defined as follows:

$$THD_V = \frac{V_H}{V_1} \tag{20}$$

$$THD_I = \frac{I_H}{I_1} \tag{21}$$

The power factor PF and the fundamental power factor PF_1 are given by (22) and (23) respectively:

$$PF = \frac{P}{S} \tag{22}$$

$$PF_1 = \frac{P_1}{S_1} = \cos\theta_1 \tag{23}$$

Table I summarizes the most important definitions of IEEE Std. 1459 for single-phase systems (apparent, active, nonactive powers and indicators, such as line utilization and harmonic pollution).

Table I – Summary and Grouping of IEEE Std. 1459 for Single-Phase Systems with Nonsinusoidal Waveforms.

Quantity or Indicator	**Combined**	**Fundamental Powers**	**Nonfundamental Powers**
Apparent (VA)	S	S_1	S_N S_H
Active (W)	P	P_1	P_H
Nonactive (var)	N	Q_1	D_I D_V D_H
Line Utilization	$PF=P/S$	$PF_1=P_1/S_1$	—
Harmonic Pollution	—	—	$F\_HP=S_N/S_1$

3. Experimental Results

The proposed PMS was implemented by means of virtual instrumentation (VI) using the LabVIEW graphic platform (National Instruments).

Figure 2 shows the block diagram of the implemented VI platform. The single-phase voltage and current quantities were measured and conditioned using a signal conditioning board. After that, they were acquired by a data acquisition board (PCI-6024E – National Instruments).

The fundamental and nonfundamental rms values of the utility voltage, which were generated using AC power supply equipment, are summarized in Table II, and the characteristics of the linear and nonlinear loads used in the tests are shown in Table III.

Table II - Characteristic of the Utility Voltage.

Fundamental Voltage (V)	**Harmonic Voltage (V)**	
	3th	**5th**
110	18.33	9.16

Table III – Characteristics of Linear and Nonlinear Loads for Single-Phase System.

Single-Phase Loads		**Linear**	**Nonlinear**
1	Resistive (R)	R= 37Ω	—
2	Resistive-Inductive (R-L)	R= 109Ω L= 480mH	—
3	Full-Bridge Rectifier (Load R-L)	—	R= 100Ω L= 500mH

The power quantities calculation and indicators are presented in Tables IV and V, following the summary and grouping of IEEE Std. 1459-2010 presented in Table I, which are considered the following utility conditions: i) Sinusoidal system: load 1 (Resistive load), load 2 (resistive-inductive load) and load 3 (full-bridge rectifier connected to R-L load); ii) Nonsinusoidal system: loads 1, 2 and 3.

Analysing all the results presented in Tables IV and V, it is possible to confirm the theoretical development presented in Section II.

Figure 3 shows the front panel of the PMS used to show the experimental results by means of both quantitative values and curves in the time domain. The Fig. 3(a) shows the results obtained for the load 1 (Table III), under nonsinusoidal voltage, and the Fig. 3(b) shows the results obtained for the load 3 (Table III), under sinusoidal voltage. Additionally the PMS allows to visualizing the rms values of voltage and current, the THDs of voltage and currents, and others.

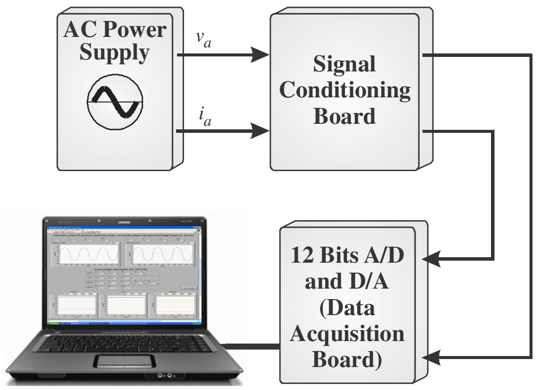


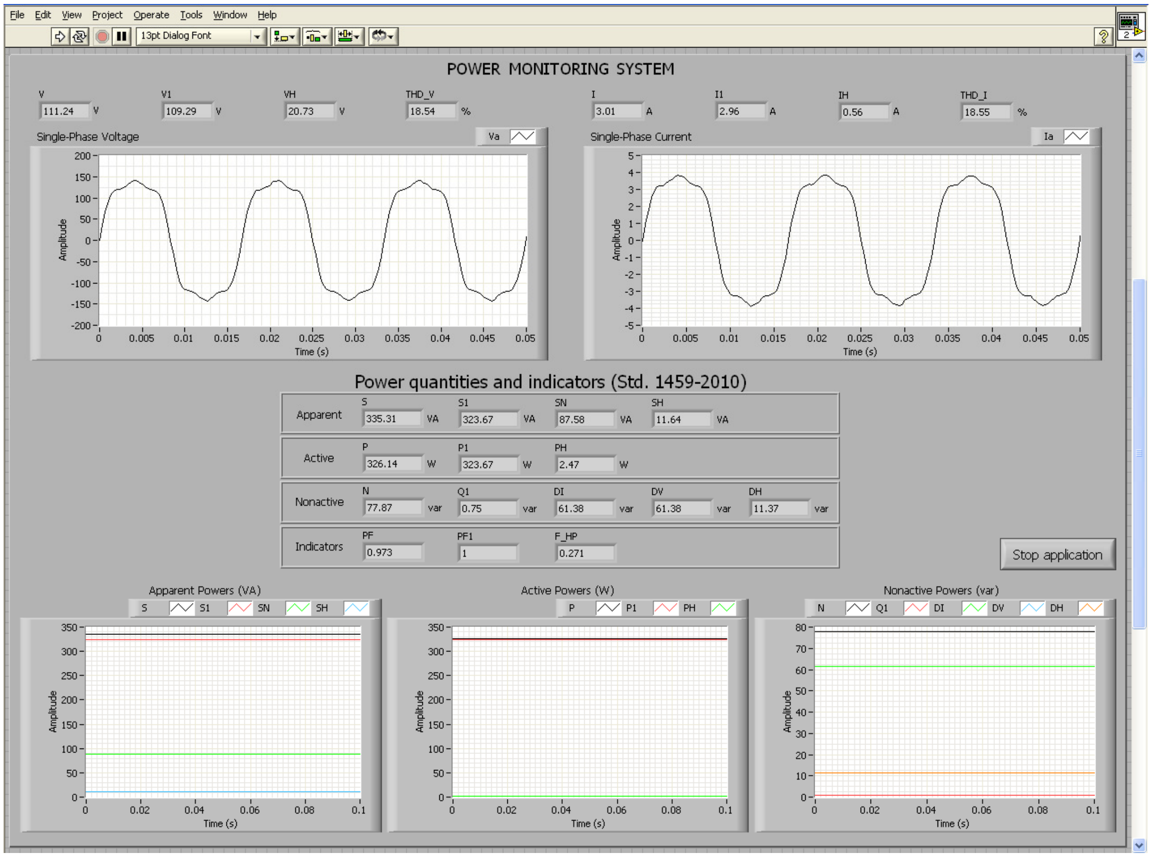
Fig. 2. Block diagram of the proposed PMS.

Table IV – Summary of Electrical Quantities for Sinusoidal Single-Phase System.

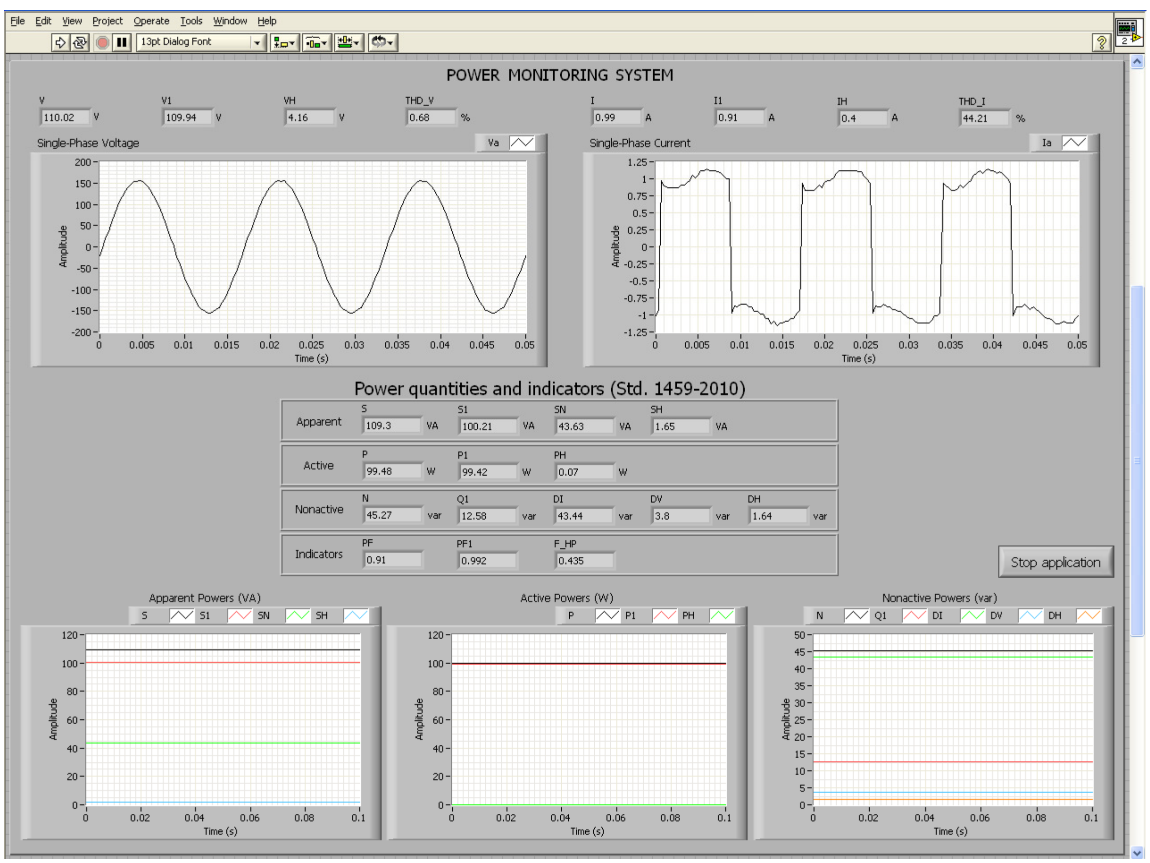
Quantity or Indicator	Combined	Fundamental Powers	Nonfundamental Powers
Sinusoidal system: Load 1 (Table III)			
Apparent (VA)	S= 327.27(VA)	S_1= 326.76(VA)	S_N= 18.32(VA) S_H= 0.51(VA)
Active (W)	P= 327.01(W)	P_1= 326.76(W)	P_H = 0.25(W)
Nonactive (var)	N= 13.1(var)	Q_1= 0.65(var)	D_1= 13.04(var) D_V= 12.85(var) D_H= 0.45(var)
Line Utilization	P_F= 0.999	P_{F1}= 1	—
Harmonic Pollution	—	—	S_N/S_1= 0.056
Sinusoidal system: Load 2 (Table III)			
Apparent (VA)	S= 56.03(VA)	S_1= 55.93(VA)	S_N= 3.49(VA) S_H= 0.1(VA)
Active (W)	P= 30.24(W)	P_1= 30.22(W)	P_H = 0.02(W)
Nonactive (var)	N= 47.17(var)	Q_1= 47.06(var)	D_1= 2.82(var) D_V= 2.06(var) D_H= 0.1(var)
Line Utilization	P_F= 0.54	P_{F1}= 0.54	—
Harmonic Pollution	—	—	S_N/S_1= 0.062
Sinusoidal system: Load 3 (Table III)			
Apparent (VA)	S= 109.3(VA)	S_1= 100.21(VA)	S_N= 43.63(VA) S_H= 1.65(VA)
Active (W)	P= 99.48(W)	P_1= 99.42(W)	P_H = 0.07(W)
Nonactive (var)	N= 45.27(var)	Q_1= 12.58(var)	D_1= 43.44(var) D_V= 3.8(var) D_H= 1.64(var)
Line Utilization	P_F= 0.91	P_{F1}= 0.992	—
Harmonic Pollution	—	—	S_N/S_1= 0.435

Table V – Summary of Electrical Quantities for Nonsinusoidal Single-Phase System.

Quantity or Indicator	Combined	Fundamental Powers	Nonfundamental Powers
Nonsinusoidal system: Load 1 (Table III)			
Apparent (VA)	S= 335.31(VA)	S_1= 323.67(VA)	S_N= 87.58(VA) S_H= 11.64(VA)
Active (W)	P= 326.14(W)	P_1= 323.67(W)	P_H =2.47(W)
Nonactive (var)	N= 77.87(var)	Q_1= 0.75(var)	D_1= 61.38(var) D_V= 61.38(var) D_H= 11.37(var)
Line Utilization	P_F= 0.973	P_{F1}= 1	—
Harmonic Pollution	—	—	S_N/S_1= 0.271
Nonsinusoidal system: Load 2 (Table III)			
Apparent (VA)	S= 56.64(VA)	S_1= 55.44(VA)	S_N= 11.59(VA) S_H= 0.9(VA)
Active (W)	P= 29.83(W)	P_1= 29.79(W)	P_H = 0.04(W)
Nonactive (var)	N= 48.14(var)	Q_1= 46.75(var)	D_1= 4.76(var) D_V= 10.53(var) D_H= 0.9(var)
Line Utilization	P_F= 0.527	P_{F1}= 0.537	—
Harmonic Pollution	—	—	S_N/S_1= 0.209
Nonsinusoidal system: Load 3 (Table III)			
Apparent (VA)	S= 118.24(VA)	S_1= 105.84(VA)	S_N= 52.71(VA) S_H= 9.08(VA)
Active (W)	P= 107.2(W)	P_1= 105.46(W)	P_H = 1.74(W)
Nonactive (var)	N= 49.87(var)	Q_1= 8.94(var)	D_1= 47.89(var) D_V= 20.06(var) D_H= 8.91(var)
Line Utilization	P_F= 0.907	P_{F1}= 0.996	—
Harmonic Pollution	—	—	S_N/S_1= 0.498



(a)



(b)

Fig. 3. Front panel of the PMS: (a) Nonsinusoidal input voltage: Linear Load (Load 1 – Table III); (b) Sinusoidal input voltage: Nonlinear Load (Load 3 – Table III).

4. Conclusion

This paper proposed SRF-based algorithm for calculation of electric power quantities defined in IEEE Std. 1459-2010. The determination of the power quantities was carried out under sinusoidal and nonsinusoidal utility conditions, taking into account a single-phase system.

The SRF-based algorithm was applied to single-phase systems with no loss of generalization. It was possible because the single-phase system was treated as a fictitious balanced three-phase system.

In the academic environment, the proposed PMS represents a possible tool for studying power quality problems due to the flexibility of implementing the algorithms and visualizing the results using graphics and curves.

To validate the SRF-based algorithm, by means a virtual instrumentation, experimental results were presented, in which the electrical quantities and indicators were determined, confirming the presented theoretical development.

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