An Improved Three-Phase Reactive Power Measurement Algorithm Using Walsh Functions Transform

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This paper proposes an improved algorithm for three-phase power component measurement using the Walsh function (WF), which takes into account the advantages offered by the algorithm in the analysis of nonlinear load problems to improve the accuracy and reliability of measurement. In the pricing of electricity based on the value of the integral of the load active power measured using a kilowatt-hour meter, the electric utility loses some revenue for the energy delivered to current harmonic generating customers and customers whose load causes current asymmetry. An improved algorithm based on the WF for measuring the active and reactive power of a network with linear and or nonlinear and sinusoidal or nonsinusoidal network is developed and tested, and the result compared with IEEE standard 1459–2000 which is based on fast Fourier transformation. The method does not require phase shifting of the phase current signals by π/2 with respect to the voltage signals. The proposed algorithm enables reactive power measurement for proper electricity billing to the consumer with nonlinear loads. © 2013 Institute of Electrical Engineers of Japan. Published by John Wiley & Sons, Inc.

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1. Introduction

The continuous development and increasing use of power electronic equipment and appliances with microprocessors have considerably contributed to the distortion of the waveform of the supply system at the distribution end [1]. These distortions increase the reactive power of the system and lower the power factor, which invariably has a negative effect on the power quality of the supply system. Accurate measurement and evaluation of the energy consumption is of utmost importance for effective planning, billing, monitoring, maintenance, and further development of the power supply system [2]. The deregulation of the power sector and the increasing cost of fossil fuel have led electricity operators to seek ways to make the best use of the supply systems [3]. Proper evaluation of the energy consumption is one of the important tasks in electric power industries, especially in electricity billing and the electrical energy quality estimation and control [2, 3]. Several companies are into the design and manufacture of energy meters to meet the increasing demand for smart metering [4]. In the pricing of electricity based on the value of the integral of the load active power measured using a kilowatt-hour meter, the electric utility board incurs loss in revenue for the energy delivered to current harmonic generating customers and also those that cause current asymmetry [5]. Ironically, customers that do not generate harmonics but are supplied with distorted and/or asymmetrical voltages are billed not only for the useful energy but also for the energy that may cause malfunctioning of their equipment [5].

The Walsh transform algorithm has a unique and essentially a high level of accuracy as a result of coefficient characteristics and energy behavior representation [6–8]. The conventional or classical method of determining power consumption is to evaluate using the measured values of the voltage (V), current (I), and power factor (pf). The apparent power S, active power P, and reactive power Q are defined in [9]. Precise determination of the root-mean-square (RMS) values of voltage and current is complex and poses a serious challenge in electrical measurements [10]. For the classical method of power calculation to be effective in a three-phase network, the voltages must be identical, currents must be equal, and the phase angles should be 120°. These conditions may not be attainable in the real practical world due to the nature of the loads, most of which are nonlinear [11].

This paper proposes an improved algorithm as an alternative for the power component measurement process using the Walsh function (WF). The rest of this paper is organized as follows. Section 2 gives a survey of the available methods for power component measurement, Section 3 presents the WF analytical expression, and Section 4 highlights the steps involved in the development of an alternative improved algorithm for the measurement using the WF. In Section 5, the modeling, six simulations, and discussion of results, are presented. Section 7 gives the conclusions.

2. Survey of Available Literature

The determination of the voltage, current, and phase factor of active power has been established but that for reactive power is still contentious. Several attempts have been made toward formulating an algorithm for reactive power measurement using different techniques.

2.1. Measuring algorithms

The authors in Ref. [12] compare the three main methods for measuring reactive power, i.e. power triangle, time delay, and low-pass filter. These methods...
show limitation in the presence of harmonics due to nonlinear loads. A Fourier transform (FT) based algorithm is used in Ref. [13]. It allows the evaluation of reactive power without the shifting operation. It is efficient under stationary frequency conditions. Though the computation of FT-based algorithms is complex and they lose accuracy under nonstationary conditions, practical data acquisition is usually noncoherent due to aliasing, spectral leakage, and the picket fence phenomenon. A Newton–Raphson type algorithm for active and reactive power measurements in both sinusoidal and nonsinusoidal circuits is presented in Ref. [14]. The process has fast convergence. It considers the system frequency as an unknown parameter of the model to be estimated, and in this way solves the problem of sensitivity to frequency variations over a wide range. It is not sensitive to the frequency changes of the input signal, and with the introduction of the power frequency in the vector of the unknown model parameters, the model itself becomes nonlinear, which requires that the strategies of nonlinear estimation must be used. In Refs [6] and [15], an algorithm is proposed for the measurement at a positive sequence of the fundamental power frequency under nonsinusoidal conditions, which allows the convenient computation of reactive power, reduces the volume of computation, and extracts a generalized positive sequence from a three-phase signal. A technique consisting of two phases using decoupled modules was presented in Ref. [16]; it presented an algorithm for the estimation of the energy parameters. The algorithm has a high level of robustness and high accuracy over a wide range of frequency changes. In the same vein, a method based on an interior point optimization, which combines powerflow-based load scaling and the weighted least algorithm (WLA), for v-state estimation is featured in [17]. However, the detection and identification of errors and load data posed a challenge to this method. Ref. [18] presents a design using the weighted least-squares method for energy parameter measurements. A mathematical model has been presented that transforms the problem of estimation into an overdetermined set of linear equations. The approach requires a phase shift of $\pi/2$ between the voltage and the current. While in Refs [11] and [19] the wavelet transform algorithm, which considers the energy parameter estimation in a stationary and nonstationary power quality PQ distortion, was adopted, the paper showed the use of orthogonal and biorthogonal wavelets for analysis. Error arises when the load becomes nonlinear, and it requires the phase shift of the input voltage signal. In Ref. [20], a multi-wavelet transform is used for energy component estimation. The paper implemented and tested a fuzzy product aggregation reasoning rule (FPARR) for various power quality events and suggested the use of a few symmetrical filters to test the response of the technique. Time and space complexity are challenges, and it requires the phase shift of the input voltage signal.

In Ref. [21], digital microprocessor technology was used in power measurement; the authors identified the condition for use of the classical algorithm. These conditions are difficult to satisfy in the real practical world and give rise to errors when the load becomes nonlinear. In Ref. [22], an algorithm for identifying and measuring the symmetrical components of distorted three-phase voltage or current waveform in electrical power system was presented, while Ref. [23] adopted the recursive averaging algorithm (RAA) for the simultaneous measurement of frequency, fundamental, and total active power.

### 2.2. Walsh function (WF)

In Refs [8] and [24], the WF method for the evaluation of the energy parameters was presented as a mathematical tool to analyze energy meter output behavior for in-depth error detection; the method is faster than other techniques such as FFT. It does not require the phase shift of $\pi/2$ between the voltage and the current. Further, an evaluation of three-phase power components from the instantaneous power signal using the peculiar properties of the WF was proposed in Ref. [25]. In all, the harmonic current affects the reactive power measurement, so another attempt using a modified approach for the measurement was made in Ref. [26]; the approach reduced the computational demand, though the influence of harmonics to the results, which was not accounted for, was the main drawback of the algorithms. Then, in Ref. [2], the WF algorithm was applied to a three-phase unbalanced system that did not require phase shift and had less computation requirement. The authors suggested the estimation and correction of the influence of the higher order harmonics on the evaluation algorithm as the next challenge for further study. An attempt on an advanced algorithm based on WF for harmonic elimination to obtain switching angles, which permits full regulation of the fundamental amplitude with only a switching interval vector for a single-phase system, was made in Ref. [27]. The technique had the drawback of obtaining a large number of solutions, which made the selection process of the better case difficult and took increased computation time.

Features of WF based technique are the following:

1. The Walsh transform analyzes signals into rectangular waveforms rather than sinusoidal ones and computes them more rapidly when compared with FT;
2. WF-based algorithm contains addition and subtractions only, which results in considerably simplified hardware implementation of the power evaluation.

The IEEE/IEC definition of a phase shift of $\pi/2$ between the voltage and the current signal mainly used for reactive power evaluation is eliminated from signal processing operation when using WF [24].

### 3. Analytical Expression of WF

Generalized WF and transforms were introduced in 1923 by J.L. Walsh, but their application to engineering and other fields did not happen until recently [24] when some basic and enlightening properties of these functions and transform were considered. These functions can be applied inter alia to develop an algorithm that would be applicable to nonlinear load problem analysis, which is the focus of the paper. It is a full orthogonal system with unique properties, which include that it has only two values (+1 and −1) over a specified normalized period $T$. This greatly influences the effectiveness of the signal processing operation as related to the measurement of energy components and characteristics of power distribution system. Analytically, the WF is expressed as

$$
\text{wal}(n, \beta) = (-1)^{\sum_{k=1}^{\beta} + \sum_{n=1}^{m} (\beta_n k + 1)} \beta_k
$$

where $n$ is the order of the function with $n = 1, 2, 3, \ldots, n_m$ which is the $m$th coefficients of $n$ represented in binary code, i.e. $n = (n_1, n_2, n_3, \ldots, n_m)_{2} n_m = 0, 1$. With $m$ being the highest order WF serial number in the system, $\beta$ is the argument of the WF that defines the coefficients of $\beta_k$ in binary code: $\beta = (\beta_1, \beta_2, \ldots, \beta_k), \beta_k = 0, 1, k = 1, 2, \ldots, m$. From (1), the graphical representation of the first eight WF is generated, as shown in Fig. (1).

### 4. Proposed WF Algorithm

The IEEE standard 1459–2000 for the instantaneous voltages ($v_a, v_b, v_c$) and currents ($i_a, i_b, i_c$) in a three-phase distribution
and solving the trigonometry, the instantaneous powers for phases network represented with

\[ Q_a(t) = \frac{1}{2} \int_0^T p_a \text{wal}(3,t) \, dt \]

\[ Q_b(t) = \frac{1}{2} \int_0^T p_b \text{wal}(3,t) \, dt - P_b \sqrt{3} \]

\[ Q_c(t) = \frac{1}{2} \int_0^T p_c \text{wal}(3,t) \, dt + P_c \sqrt{3} \]  

(6)

The algorithm for real or active powers in the three phases \( a, b, \) and \( c \) is determined by multiplying (5) by the zero-order WF, i.e. \( \text{wal}(0,t) \), and integrating over the period \( T \). In the Walsh algorithm, the zero-order function \( \text{wal}(0,t) = 1 \) over the period \( T \), so all the integral terms on the right hand-side of (5) that involve the product of \( \text{wal}(0,t) \) with the \( \cos(2wt) \) and \( \sin(2wt) \) approach zero, thus giving

\[ P_a = \frac{1}{T} \int_0^T \text{wal}(0,t)p_a(t) \, dt \]

\[ P_b = \frac{1}{T} \int_0^T \text{wal}(0,t)p_b(t) \, dt \]

\[ P_c = \frac{1}{T} \int_0^T \text{wal}(0,t)p_c(t) \, dt \]  

(7)

Solving the equations further, the active powers \( P_a, P_b, \) and \( P_c \) are obtained for a three-phase power system as shown in (8).

\[ P_a = \frac{1}{T} \int_0^T \text{wal}(0,t)p_a(t) \, dt \]

\[ P_b = \frac{1}{T} \int_0^T \text{wal}(0,t)p_b(t) \, dt \]

\[ P_c = \frac{1}{T} \int_0^T \text{wal}(0,t)p_c(t) \, dt \]  

(8)

The modeling and simulation of (6) and (8) has been presented earlier in [2], which shows that current harmonic affects the reading of the simulation results. The algorithm has to be further improved so as to be able to measure the power components in both linear and nonlinear sinusoidal load conditions. It is worth mentioning at this juncture that in an AC network the source voltages have relatively pure sinusoidal waveforms and that it is during distribution that harmonics are introduced due to the increased use of nonlinear loads such as computers, fluorescent lamps, adjustable speed drive motors, arc furnaces, arc welding machines, electronic control, and power converters, among others. Harmonic currents cause overloading of neutral conductors, overheating of transformers, tripping of circuit breakers, overstressing of power factor correction capacitors, and the skin effect [24]. Also, research has shown that the effect of odd harmonics is more significant in power systems than that of even harmonics which is negligible [28].

4.1. Improved WF algorithm

Harmonic in the power system does not affect the active power measurement but has a great deal of influence on the reactive power, which invariably affects the power factor and hence the quality of the supply system. To derive an alternative improved Walsh function (IWF) algorithm for the measurement when the load current is contaminated with, say, third-order current harmonic denoted as \( i_{a3}, i_{b3}, \) and \( i_{c3} \) with \( \theta_{a3}, \theta_{b3}, \) and \( \theta_{c3} \) being the phase angle between the fundamental voltages and the third-order current harmonic waveforms of the
The products of the third-order WF with the constant third-order WF, i.e. walharmonic condition, we apply WF by multiplying (10) with the phases,

\[ i_{a3} = I_{a3} \sin(3wt - \theta_{a3}) \]
\[ i_{b3} = I_{b3} \sin(3wt - \theta_{b3} - 120) \]
\[ i_{c3} = I_{c3} \sin(3wt - \theta_{c3} + 120) \]  

(9)

The instantaneous powers \( p_{a3}, p_{b3}, \) and \( p_{c3} \) for the three phases \( a, \ b, \) and \( c \) under this condition are as shown in (10):

\[ p_{a3} = P_{a} + (P_{a3} - P_{a}) \cos 2wt + (Q_{a3} - Q_{a}) \sin 2wt \]
\[ - P_{a3} \cos 4wt - Q_{a3} \sin 4wt \]
\[ p_{b3} = P_{b} + (P_{b3} + P_{b} - \sqrt{3}Q_{b3}) \cos 2wt \]
\[ + (P_{b3} + P_{b} - \sqrt{3}Q_{b3}) \sin 2wt - (\sqrt{3}Q_{b3} - P_{b3}) \cos 4wt \]
\[ + (Q_{b3} + P_{b} \sqrt{3}) \sin 4wt \]
\[ p_{c3} = P_{c} + (P_{c3} + P_{c} - \sqrt{3}Q_{c3}) \cos 2wt \]
\[ + (P_{c3} + P_{c} - \sqrt{3}Q_{c3}) \sin 2wt - (\sqrt{3}Q_{c3} - P_{c3}) \cos 4wt \]
\[ + (Q_{c3} + P_{c} \sqrt{3}) \sin 4wt \]  

(10)

where

\[ P_{a3} = V_{a}I_{a3} \cos \theta_{a3}, \]
\[ P_{b3} = V_{b}I_{b3} \cos \theta_{b3}, \]
\[ P_{c3} = V_{c}I_{c3} \cos \theta_{c3}, \]
\[ Q_{a3} = V_{a}I_{a3} \sin \theta_{a3}, \]
\[ Q_{b3} = V_{b}I_{b3} \sin \theta_{b3}, \]
\[ Q_{c3} = V_{c}I_{c3} \sin \theta_{c3}. \]

To obtain the improved algorithm for reactive power under this harmonic condition, we apply WF by multiplying (10) with the third-order WF, i.e. \( \text{wal}(3,t) \), and integrate over the time \( T \). According to the WFs, all the integrals of the right-hand side terms of (10), which involve the multipliers \( \cos 2wt, \cos 4wt, \sin 4wt, \) and the constant \( P \) and are all equal to zero. Hence, (11) becomes

\[ \frac{1}{T} \int_{0}^{T} p_{a}(\text{wal}(3,t))dt \]
\[ = \frac{1}{T} \int_{0}^{T} (Q_{a3} - Q_{a}) \sin 2wt(\text{wal}(3,t))dt \]
\[ = \frac{1}{T} \int_{0}^{T} p_{b}(\text{wal}(3,t))dt \]
\[ = \frac{1}{T} \int_{0}^{T} (P_{b} \sqrt{3} + Q_{b3} - Q_{b}) \sin 2wt(\text{wal}(3,t))dt \]
\[ = \frac{1}{T} \int_{0}^{T} p_{c}(\text{wal}(3,t))dt \]
\[ = \frac{1}{T} \int_{0}^{T} (P_{c} \sqrt{3} + Q_{c3} - Q_{c}) \sin 2wt(\text{wal}(3,t))dt \]  

(11)

The seventh-order Walsh function. (b) Sin 4wt waveform

Solving for \( Q_{a}, Q_{b}, \) and \( Q_{c} \) gives

\[ Q_{a} = -\frac{\pi}{2T} \int_{0}^{T} p_{a}(\text{wal}(3,t))dt + Q_{a3} \]
\[ Q_{b} = -\frac{\pi}{2T} \int_{0}^{T} p_{b}(\text{wal}(3,t))dt + P_{b} \sqrt{3} + Q_{b3} \]
\[ Q_{c} = -\frac{\pi}{2T} \int_{0}^{T} p_{c}(\text{wal}(3,t))dt + P_{c} \sqrt{3} + Q_{c3} \]  

(13)

where \( Q_{a3}, Q_{b3}, \) and \( Q_{c3} \) in (13) are the reactive components of the distortion power in the phases. This indicates the influence of the third-order current harmonics \( i_{a3}, i_{b3}, \) and \( i_{c3} \) on the reactive power measurement algorithm. The third-order WF eliminates the effect of the third-order harmonics of the nonlinear load. Harmonics affect only the reactive power measurement of the network. The final terms of (10) are the distortion power terms, i.e. \( Q_{a3} \) sin 4wt, \( Q_{b3} + P_{b} \sqrt{3} \) sin 4wt, and \( Q_{c3} + P_{c} \sqrt{3} \) sin 4wt. They are oscillating with the frequency 4w, which is similar to the oscillating frequency of the seventh-order WF, \( \text{wal}(7,t) \), as can be seen in the Fig. 2.

To estimate these distortion power terms, we multiply the both sides of (10) by the seventh-order WF and then integrate over the period \( T \) and simplify to obtain (14).

\[ \frac{1}{T} \int_{0}^{T} p_{a}(\text{wal}(7,t))dt \]
\[ = -\frac{1}{T} \int_{0}^{T} Q_{a3} \sin 4wt(\text{wal}(7,t))dt \]
\[ = -\frac{1}{T} \int_{0}^{T} p_{b}(\text{wal}(7,t))dt \]
\[ = -\frac{1}{T} \int_{0}^{T} (Q_{a3} + P_{b} \sqrt{3}) \sin 4wt(\text{wal}(7,t))dt \]
\[ = -\frac{1}{T} \int_{0}^{T} p_{c}(\text{wal}(7,t))dt \]
\[ = -\frac{1}{T} \int_{0}^{T} (Q_{c3} + P_{c} \sqrt{3}) \sin 4wt(\text{wal}(7,t))dt \]  

(14)

The seventh-order WF is an odd function with frequency similar to the frequency of the distortion terms. The product of the seventh-order WF with the distortion terms results in their rectification. So, taking cognizance of these rectifying effects, (14) is written as (15).

\[ \frac{1}{T} \int_{0}^{T} p_{a}(\text{wal}(7,t))dt = \frac{1}{T} \int_{0}^{T} Q_{a3} \sin 4wt \]
\[ \frac{1}{T} \int_{0}^{T} p_{b}(\text{wal}(7,t))dt = \frac{1}{T} \int_{0}^{T} (Q_{b3} + P_{b} \sqrt{3}) \sin 4wt \]
\[ \frac{1}{T} \int_{0}^{T} p_{c}(\text{wal}(7,t))dt = \frac{1}{T} \int_{0}^{T} (Q_{c3} + P_{c} \sqrt{3}) \sin 4wt \]  

(15)
The new improved WF is derived by multiplying (10) with when addition of standard third- and the seventh-order WF is defined analytically. Addition of the third and seventh orders is represented are added together, which gives a new improved algorithm. The integrals after the equal signs, powers in a three-phase system. Substituting in (13) produces an Equation (16) is the IWF algorithm for measuring the distortion waveform, so these integrals are not equal to zero. The equations cosine functions which are orthogonal with the IWF. The third and taking the integral over the period is in the shown intervals as follows:

\[ Q_a = \frac{-\pi}{2T} \int_0^T p_a(\text{wal}(3,t))dt + \frac{\pi}{2T} \int_0^T p_a(\text{wal}(7,t))dt \]

\[ Q_b = \int_0^T p_b(\text{wal}(3,t))dt + \frac{\pi}{2T} \int_0^T p_b(\text{wal}(7,t))dt \]

\[ Q_c = \int_0^T p_c(\text{wal}(3,t))dt + \frac{\pi}{2T} \int_0^T p_c(\text{wal}(7,t))dt \]

(17)

This algorithm eliminates the effect of the third- and seventh-order harmonics on the reactive power measurement and also essentially reduces the effect of the higher order current harmonics. In order to reduce the computation involved, the third- and seventh-order WFs are added together, which gives a new improved algorithm. The analytical addition of the third and seventh orders is represented in Fig. 3.

From Fig. 3, it can be visualized that the IWF as a result of the addition of standard third- and the seventh-order WF is defined when is in the shown intervals as follows:

\[ \text{wal}(3,7,t) = +1, \text{ if } t \text{ is in } [0, T/8], [T/2; 3T/8] \]
[0, 0.002, 0.004, 0.006, 0.008, 0.01, 0.012, 0.014, 0.016, 0.018, 0.02]

\[ \text{if } t \text{ is in } [T/8, 3T/8], [5T/8, 7T/8] \]

-1, if is in [3T/8, T/2], [7T/8, T] \]

The new improved WF is derived by multiplying (10) with wal(3, 7, t) and taking the integral over the period . Considering the integrals after the equal signs, , , and are constants so are equal to zero because the IWF is a periodic function and the second and fourth integrals are also equal to zero as they include cosine functions which are orthogonal with the IWF. The third and fifth integrals comprise the rectification of the sin functions waveform, so these integrals are not equal to zero. The equations are written as

\[ \frac{1}{T} \int_0^T (p_a \text{wal}(3,7,t))dt \]

\[ = \frac{1}{T} \int_0^T (\text{wal}(3,7,t))(Q_a - Q_c) \sin 2\omega dt \]

\[ - \frac{1}{T} \int_0^T \text{wal}(3,7,t)Q_{a3} \sin 2\omega dt \]

\[ = \frac{1}{T} \int_0^T (p_b \text{wal}(3,7,t))dt \]

\[ = \frac{1}{T} \int_0^T (\text{wal}(3,7,t))(P_b \sqrt{3} + Q_{b3} - Q_b) \sin 2\omega dt \]

\[ + \frac{1}{T} \int_0^T (\text{wal}(3,7,t))(Q_{b3} + P_b \sqrt{3}) \sin 4\omega dt \]

\[ \frac{1}{T} \int_0^T (p_c \text{wal}(3,7,t))dt \]

\[ = \frac{1}{T} \int_0^T (\text{wal}(3,7,t))(P_c \sqrt{3} + Q_{c3} - Q_c) \sin 2\omega dt \]

\[ + \frac{1}{T} \int_0^T (\text{wal}(3,7,t))(Q_{c3} + P_c \sqrt{3}) \sin 4\omega dt \]

(18)

Solving the right-hand side integrals of (18) yields the new improved algorithm as in (19).

\[ Q_{a3,3} = -\frac{\pi}{T} \int_0^T p_a(\text{wal}(3,7,t))dt \]

\[ Q_{b3,3} = -\frac{\pi}{T} \int_0^T p_b(\text{wal}(3,7,t))dt + (P_b \sqrt{3} + Q_{b3}) \]

\[ Q_{c3,3} = -\frac{\pi}{T} \int_0^T p_c(\text{wal}(3,7,t))dt + (P_c \sqrt{3} + Q_{c3}) \]

(19)

Equations (8), (16), and (19) constitute the IWF algorithms that should be used to measure the active, distortion, and reactive power, respectively, of a network and also eliminate the effect of higher order harmonics in the three-phase reactive power measurement system. Suffices it to say that in actual cases only lower order harmonics are present in power system signal [19].

5. Modeling of the Proposed Algorithm

Equations (8) and (19) were used to create the model for the active and reactive power measurement based on the proposed improved algorithm using the MATLAB Simulink software tool. The flowchart for the implementation is shown in Fig. 4 and the model of the nonlinear load system in Fig. 5. The subsystem of the model of the measuring instrument (Fig. 6) shows the various units in the model. Some of the commonly used nonlinear loads modeled and used in the simulation of the improved WF algorithm for active and reactive power measurement are compact fluorescent lamps (CFLs), computers, adjustable-speed drives, etc. The loads can be resistive , inductive , capacitive , or their combination, e.g. , , , depending on the type of load being modeled. was used to model the loads presented in this experiment. The models for nonlinear loads were modeled using a universal diode bridge rectifier. To avoid numerical oscillation, the snubber resistance and snubber capacitance were specified. The values of and were determined for each simulation using the expressions [29]:

\[ \frac{Rs}{Cs} > \frac{2\pi}{5} \quad \text{and} \quad Cs < \frac{P_{\text{max}}}{1000(2\pi f)V_{\text{m}}^2} \]

where
6. Discussion of the Simulation

6.1. Linear load system For the simulation of linear loads, synthetic line-to-neutral voltages \( V \) phases were chosen as follows:

\[
\begin{align*}
V_a &= 220 \angle 0^\circ, \\
V_b &= 220 \angle -120^\circ, \\
V_c &= 220 \angle 120^\circ
\end{align*}
\]

The IEEE standard 1459-2000 for the measurement of power component, which is based on the FFT algorithm, was used as benchmark for this simulation.

Load impedances for two different cases of unbalanced three-phase systems are chosen as shown in cases A and B below for the simulation to verify the algorithm. Knowing the supply voltage and the impedance of the loads \( Z \), the resistance \( R \) and inductive reactance \( X_L \) of each phase load were computed and the obtained results for \( R \) and \( X_L \) were used to configure a standard \( RLC \) load taken from the MATLAB Simpower blocks and used as load for the simulation.

Case A. \( Z_a = 36 + j20 \) /\( \Omega \), \( Z_b = 55 + j15 \) /\( \Omega \), \( Z_c = 15 + j11 \) /\( \Omega \)

Case B. \( Z_a = 25 + j20 \) /\( \Omega \), \( Z_b = 17 + j60 \) /\( \Omega \), \( Z_c = 18 + j38 \) /\( \Omega \)

Figures 7 and 8 show the voltage and current waveform for the three-phase sinusoidal, linear, unbalanced load system obtained from simulation with the new algorithm. Both the FFT algorithm and the proposed IWF algorithm \((8)\) and \((19)\) were used to simulate case A for the three phases. The results are shown in Table I. Similarly, for case B the results are shown in Table II. From the results, it can be observed that using the IEEE standard 1459-2000, which is based on FFT algorithm as reference, the proposed improved algorithm has a near-accurate result, the little difference being mainly due to approximation being within the negligible limit.

6.2. Nonlinear load system The Fluke 435 three-phase power quality analyzer (PQA), which complies with IEC/EN61010-1-2001, was used as benchmark for this test to compare the improved algorithm and the FFT algorithm used in the IEEE standard 1459-2000 for measurement under nonlinear,
The effect of harmonics has been addressed in the algorithm. The power system. The IWF algorithm records more accurate results as the FFT algorithm has significant error, resulting from spectral leakage and the picket fence effect that occurs in the FFT spectrum when used in a distorted power measurement. On the other hand, the proposed improved algorithm gives a near-accurate result since the effect of harmonic distortion has been eliminated by the improved algorithm implemented in the simulation. Therefore, the IEEE standard 1459-2000 based on FFT for measuring power components is only appropriate for linear waveform and not suitable for nonlinear waveforms, while the proposed algorithm can be effectively applied for both linear and nonlinear waveform measurements. The research is continuing toward the estimation of the distortion power and discretization of the algorithm.

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Table I. Results of Case A

<table>
<thead>
<tr>
<th>FFT Approach IEEE standard 1459-2000</th>
<th>Active power P (W)</th>
<th>Reactive power Q (var)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase a</td>
<td>1027.5</td>
<td>569.5</td>
</tr>
<tr>
<td>Phase b</td>
<td>819.3</td>
<td>223.3</td>
</tr>
<tr>
<td>Phase c</td>
<td>2098.8</td>
<td>1538.9</td>
</tr>
<tr>
<td>Total</td>
<td>3945.6</td>
<td>2331.7</td>
</tr>
</tbody>
</table>

**Proposed Walsh algorithm**

| Phase a | 1028 | 569.6 |
| Phase b | 818.6 | 223.8 |
| Phase c | 2099 | 1539 |
| Total   | 3945.6 | 2332.4 |

Table II. Results of Case B

<table>
<thead>
<tr>
<th>FFT Approach IEEE standard 1459-2000</th>
<th>Active power P (W)</th>
<th>Reactive power Q (var)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase a</td>
<td>1181.1</td>
<td>944.8</td>
</tr>
<tr>
<td>Phase b</td>
<td>214.1</td>
<td>746.2</td>
</tr>
<tr>
<td>Phase c</td>
<td>492.6</td>
<td>1039.1</td>
</tr>
<tr>
<td>Total</td>
<td>1887.8</td>
<td>2731.1</td>
</tr>
</tbody>
</table>

**Proposed Walsh Algorithm**

| Phase a | 1180 | 945 |
| Phase b | 215 | 747 |
| Phase c | 494 | 1040 |
| Total   | 1889 | 2732 |

Table III. Simulation and experimental results

<table>
<thead>
<tr>
<th>S/N</th>
<th>Load name</th>
<th>Fluke 435 PQA meter reading</th>
<th>FFT Approach (Reference)</th>
<th>Proposed Walsh algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>P (W)</td>
<td>Q (var)</td>
<td>P (W)</td>
</tr>
<tr>
<td>1</td>
<td>CFL Lamps</td>
<td>710.8</td>
<td>363.4</td>
<td>703.7</td>
</tr>
<tr>
<td>2</td>
<td>Desktop Comp.</td>
<td>421.9</td>
<td>19.8</td>
<td>417.7</td>
</tr>
<tr>
<td>3</td>
<td>Laptop Comp.</td>
<td>435.7</td>
<td>18.3</td>
<td>431.3</td>
</tr>
<tr>
<td>4</td>
<td>2 ft. F. Lamp</td>
<td>416.3</td>
<td>933.8</td>
<td>412.1</td>
</tr>
</tbody>
</table>

Fig. 9. Nonlinear current waveform (experiment)

Fig. 10. Nonlinear current waveform (simulation)

7. Conclusion

A new IWF algorithm for three-phase active and reactive power measurement was presented. From the simulation of the synthesized load results in Tables I and II, it could be seen that, when compared with the IEEE standard 1459-2000 which is based on FFT algorithm, the proposed improved Walsh algorithm gives near-accurate results when used for measurements. In the nonlinear load with the Fluke power analyzer experimental results used as benchmark, the simulation of the modeled load with FFT approach introduced significant error which made the result unrealistic due to the spectral leakage and picket fence effect that occurs in the FFT spectrum when used in a distorted power measurement. On the other hand, the proposed improved algorithm gives a near-accurate result since the effect of harmonic distortion has been eliminated by the improved algorithm implemented in the simulation. Therefore, the IEEE standard 1459-2000 based on FFT for measuring power components is only appropriate for linear waveform and not suitable for nonlinear waveforms, while the proposed algorithm can be effectively applied for both linear and nonlinear waveform measurements. The research is continuing toward the estimation of the distortion power and discretization of the algorithm.

References


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