Research Article

An Improved Walsh Function Algorithm for Use in Sinusoidal and Nonsinusoidal Power Components Measurement

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Received 11 December 2012; Revised 12 March 2013; Accepted 14 March 2013

Academic Editor: Antonio Moreno-Munoz

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This paper presents an improved Walsh function IWF algorithms as an alternative approach for active and reactive powers measurement in linear and nonlinear, balanced and unbalanced sinusoidal three-phase load system. It takes advantage of Walsh function unified approach, simple algorithm and its intrinsic high level of accuracy as a result of coefficient characteristics and energy behaviour representation. The developed algorithm was modeled on the Matlab Simulink software; different types of load, linear and nonlinear, were also modeled based on practical voltage and current waveforms and tested with the proposed improved Walsh algorithms. The IEEE standard 1459–2000 which is based on fast Fourier transform FFT approach was used as benchmark for the linear load system. The data obtained from laboratory experiment to determine power components in harmonic load systems using Fluke 435 power quality analyzer PQA which complies with IEC/EN61010-1-2001 standard was modeled and used to validate the improved algorithm for nonlinear load measurement. The results showed that the algorithm has the potential to effectively measure three-phase power components under different load conditions.

1. Introduction

The awareness of the problems associated with nonlinear devices and their effects on power components measurement algorithms has considerably increased. The use of these power electronics equipment and appliances with microprocessors has been shown to contribute to the distortion of the voltage and current waveforms of the supply system at the distribution end [1]. This distortion affects the smooth operation of most algorithms use for power components measurement and invariably has negative effect on the quality of the power supply system. Accurate measurement and evaluation of energy consumption are of utmost importance for effective planning, billing, monitoring, maintenance, and further development of the electricity supply system. The deregulation of the power sector has led electricity operators to seek for ways to make the best use of the supply systems. Proper evaluation of the energy consumption is one of the

important tasks in electric power industries, especially in electric bill and the electrical energy quality estimation and control [2, 3]. Therefore, several companies are into design and manufacture of energy meters using different algorithms to meet the increasing demand of smart metering [4]. In the pricing of electric bill based on the value of the integral of the load active power measured using kilowatt-hour meter, the electric utility board incurs losses in revenue for energy delivered to current harmonic generating customers and also those that cause current asymmetry [5]. Most times, customers that do not generate harmonics but are supplied with distorted or asymmetrical voltages are made to pay not only for the useful energy but also for the energy which may have caused malfunction of their equipment [6]. There is no universally accepted definition for the measurement of reactive power component in the presence of nonlinear and nonsinusoidal waveform [7, 8]. The IEEE working group on appropriate determination of billing system based

on sinusoidal and nonsinusoidal situation defined distortion power in terms of total fundamental and harmonic constituents with less unwieldy theory [8].

The conventional method of determining power consumption is to evaluate using 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 as in [9]. This way of power evaluation requires accurate measurement of the root mean square (RMS) values of the voltage and current before performing the multiplication operation so as to determine the apparent power S . Precise determination of RMS values of voltage and current is complex and poses a serious challenge in electrical measurement [10]. For this method of power calculation to be effective in a three phase network the following has to be satisfied.

- (i) The RMS voltages and current on all the three phases must be identical.
- (ii) Phase angles between voltage and current must be maintained at 120° and are time invariant.

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 proposed an improved algorithm as an alternative for power components measurement/estimation using the Walsh function which has the advantage of better accuracy and reliability in energy measurement as it takes into consideration among others, elimination of the effect of harmonic on reactive power measurement. Walsh function transform algorithm has a unique and essentially high level of accuracy as a result of coefficient characteristics and energy behaviour representation [12]. This proposed algorithm might be integrated into any type of energy meter for measurement.

The remaining of this paper is organized as follows. Section 2 presents Walsh function and its analytical expression, while Section 3 highlights the steps involved in the development of the proposed improved algorithms for measurement using the Walsh function, Section 4 has the modeling and simulation of the improved algorithms, and Section 5 is the simulation with laboratory experiment results. Lastly, Section 6 is the conclusions.

2. Walsh Function (WF) Analytical Expression

The Walsh function method for the evaluation of energy parameters was presented as a mathematical tool to analyze energy meter output behaviour for indepth error detection [9]. The method is faster when compared with other techniques like FFT. It does not require the phase shift of $\pi/2$ between voltage and current and it has less computation requirement. However, when the load becomes nonlinear and nonsinusoidal the voltage and current waveforms become distorted. This leads to harmonic which is a multiple of the fundamental frequencies of the current and/or voltage. The authors exert that harmonic current affects the reactive power measurement so another attempt using modified approach for power components measurement in both sinusoidal and

nonsinusoidal condition was made; the approach reduced computational demand, though the influence of harmonics to the measurement results which was not accounted for, was the main setback of the algorithms [13–15].

The attractions to Walsh-function-based technique for use in energy parameter evaluation are the following.

- (a) The Walsh transform analyzes signals into rectangular waveform rather than sinusoidal ones and is computed more rapidly when compared with Fourier transform FT.
- (b) Walsh-function-based algorithm contains addition and subtractions only and hence results in considerably simplified hardware implementation of power evaluation process.
- (c) 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 Walsh function [8].

Generalized Walsh functions and transforms were introduced in 1923 by J. L. Walsh, but their application to engineering and other fields did not happen until recently [16] with some basic and enlightening properties of these functions and transforms considered. This function can be applied among other uses to develop an algorithm that would be applicable to nonlinear loads problem analysis. It is a full orthogonal system with unique properties, which include that it has only two values $+1$ and -1 over specified normalized period T . This greatly influences the effectiveness of signal processing operation as being related to measurement of power components and characteristics of power distribution system. Analytically the Walsh function is expressed as

$$\text{Wal}(n, \beta) = (-1)^{\sum_{k=1}^m (n_{m-k+1} \oplus n_{m-k}) \beta_k}, \quad (1)$$

where n is the order of the function form $n = 1, 2, 3, \dots, n_m$ which is the m th coefficients of the n represented in binary code, that is, $n = (n_0, n_1, n_2, n_3, \dots, n_m)_2$, $n_m = 0, 1$. With m being the highest order WF serial number in the system, β is the argument of WF that defines the coefficients of β_k in binary code $\beta = (\beta_k, \beta_k, \dots, \beta_k)_2$, $\beta_k = 0, 1$, and $k = 1, 2, 3, \dots, m$. From (1) the graphical representation of the first sixteenth order Walsh function is generated as shown in Figure 1.

3. Walsh Function 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 network with linear balanced or unbalanced load is given as [17]. Instantaneous three-phase sinusoidal voltages are

$$\begin{aligned} v_a &= \sqrt{2}V_a \sin(\omega t), \\ v_b &= \sqrt{2}V_b \sin(\omega t - 120), \\ v_c &= \sqrt{2}V_c \sin(\omega t + 120). \end{aligned} \quad (2)$$

FIGURE 1: The first 16th order of Walsh function.

Instantaneous three-phase currents are

$$\begin{aligned} i_a &= \sqrt{2}I_a \sin(\omega t - \theta_a), \\ i_b &= \sqrt{2}I_b \sin(\omega t - \theta_b - 120), \\ i_c &= \sqrt{2}I_c \sin(\omega t - \theta_c + 120), \end{aligned} \quad (3)$$

where V_a, V_b, V_c and I_a, I_b, I_c are the RMS values of the line to neutral voltages and currents for the phases a, b , and c , respectively. θ_a, θ_b and θ_c are the phase angles between the respective voltage and current. $\omega = 2\pi f$, f = frequency in Hertz, $t = 1/f$.

The instantaneous reactive powers for the three phases represented with say p_a, p_b , and p_c are given by

$$p_a = v_a \times i_a, \quad p_b = v_b \times i_b, \quad p_c = v_c \times i_c. \quad (4)$$

Substituting for (v_a, v_b, v_c) and (i_a, i_b, i_c) in the previous expressions and solve trigonometrically the instantaneous powers for phases a, b , and c of the three-phase linear balanced and unbalanced load network are derived as in (5):

$$\begin{aligned} p_a &= P_a - [P_a \cos(2\omega t) - Q_a \sin(2\omega t)], \\ p_b &= P_b + P_b - \sqrt{3}Q_b \cos(2\omega t) + (P_b \sqrt{3} + Q_b) \sin(2\omega t), \\ p_c &= P_c + (P_c + Q_c \sqrt{3}) \cos(2\omega t) + (Q_c - P_c \sqrt{3}) \sin(2\omega t), \end{aligned} \quad (5)$$

where $P_a = V_a I_a \cos \theta_a$, $P_b = V_b I_b \cos \theta_b$, $P_c = V_c I_c \cos \theta_c$, $Q_a = V_a I_a \sin \theta_a$, $Q_b = V_b I_b \sin \theta_b$, and $Q_c = V_c I_c \sin \theta_c$, respectively.

From the instantaneous power of (5) the algorithms for measuring the reactive powers on these three-phase systems say, Q_a, Q_b , and Q_c , using the Walsh function are obtained by multiplying both sides of the equations by the third-order Walsh function, that is, $Wal(3, t)$ and integrate over the period T of power system frequency. The integral of the third order Walsh function with a constant and also a multiplier of $\cos(2\omega t)$ is equal to zero. Because $\cos(2\omega t)$ is orthogonal (right angled) with the third Walsh function so the result is obtained as follows:

$$\begin{aligned} Q_a &= -\frac{\pi}{2T} \int_0^T p_a Wal(3, t) dt, \\ Q_b &= \frac{\pi}{2T} \int_0^T p_b Wal(3, t) dt - P_b \sqrt{3}, \\ Q_c &= \frac{\pi}{2T} \int_0^T p_c Wal(3, t) dt + P_c \sqrt{3}. \end{aligned} \quad (6)$$

The algorithms for real or active powers in the three phases a, b , and c are determined by multiplying (5) by the zero-order Walsh function, that is, $Wal(0, t)$ and integrate over the period T . In Walsh algorithm the zero-order function is a constant $Wal(0, t) = 1$, over the period of T as can be seen from Figure 1, so all the integral terms on the right-hand side

of (5) that involve product of $\text{Wal}(0, t)$ with either $\cos(2\omega t)$ or $\sin(2\omega t)$ approach to zero thus giving (7) as

$$\begin{aligned}\frac{1}{T} \int_0^T p_a \text{Wal}(0, t) dt &= \frac{1}{T} \int_0^T \text{Wal}(0, t) P_a dt, \\ \frac{1}{T} \int_0^T p_b \text{Wal}(0, t) dt &= \frac{1}{T} \int_0^T \text{Wal}(0, t) P_b dt, \\ \frac{1}{T} \int_0^T p_c \text{Wal}(0, t) dt &= \frac{1}{T} \int_0^T \text{Wal}(0, t) P_c dt.\end{aligned}\quad (7)$$

Solving the equations further active powers P_a , P_b , and P_c are obtained for three-phase power system as follows:

$$\begin{aligned}P_a &= \frac{1}{T} \int_0^T \text{Wal}(0, t) p_a dt, \\ P_b &= \frac{1}{T} \int_0^T \text{Wal}(0, t) p_b dt, \\ P_c &= \frac{1}{T} \int_0^T \text{Wal}(0, t) p_c dt.\end{aligned}\quad (8)$$

The modeling and simulation of (6) and (8) have been presented earlier in [12] and the authors showed that current harmonic affects the reading of the simulation results. The algorithms have to be further improved as to be able to measure the power components in both linear and nonlinear, sinusoidal nonsinusoidal load conditions. It is worthy to mention, at this juncture, that in AC network source voltages are relatively pure sinusoidal waveforms and that it is mostly at the transmission and distribution end that harmonic and other forms of distortions are introduced. The use of statistical estimators to detect distortions like sags and swells using synthetics analysis that allowed the identification of the variance, skewness, and kurtosis associated with normal sinusoidal waveforms was proposed in [18]. The increase use of nonlinear loads like computers, fluorescent lamps, adjustable speed drive motors, arc furnaces, arc welding machines, electronic control and power converters among others cause harmonics. This lead to overloading of neutral conductors, overheating of transformers, tripping of circuit breakers, power factor correction capacitors over stress and skin effect [19]. Also research has shown that the effect of odd harmonic is more significant in power distribution system while that of even harmonic is negligible [20].

4. Proposed Improved Walsh Function Algorithm for Measurement

Harmonic in the power system does not affect the active power measurement but has a great deal of influence on reactive power measurement which invariably affects the power factor and hence the quality of the supply system. To derive the improved Walsh function IWF algorithm for measurement we assume that the load current is contaminated with third-order current harmonic denoted as i_{a3} , i_{b3} , and i_{c3} , with θ_{a3} , θ_{b3} , and θ_{c3} being the phase angles between the fundamental voltages, and the third-order current harmonic

waveforms of the phases, I_{a3} , I_{b3} , and I_{c3} are the RMS values of the third-order current harmonic as given below:

$$\begin{aligned}i_{a3} &= I_{a3} \sin(3\omega t - \theta_{a3}), \\ i_{b3} &= I_{b3} \sin(3\omega t - \theta_{b3} - 120), \\ i_{c3} &= I_{c3} \sin(3\omega t - \theta_{c3} + 120).\end{aligned}\quad (9)$$

The instantaneous powers p_{a3} , p_{b3} , and p_{c3} for the three phases a , b , and c under this condition are derived as follows:

$$\begin{aligned}p_{a3} &= P_a + (P_{a3} - P_a) \cos(2\omega t) + (Q_{a3} - Q_a) \sin(2\omega t) \\ &\quad - P_{a3} \cos(4\omega t) - Q_{a3} \sin(4\omega t), \\ p_{b3} &= P_b + (P_{b3} + P_b - \sqrt{3}Q_b) \cos(2\omega t) \\ &\quad + (P_b \sqrt{3} + Q_{b3} - Q_b) \sin(2\omega t) \\ &\quad - (\sqrt{3}Q_{b3} - P_{b3}) \cos(4\omega t) + (Q_{b3} + P_b \sqrt{3}) \sin(4\omega t), \\ p_{c3} &= P_c + (P_{c3} + P_c - \sqrt{3}Q_c) \cos(2\omega t) \\ &\quad + (P_c \sqrt{3} + Q_{c3} - Q_c) \sin(2\omega t) \\ &\quad - (\sqrt{3}Q_{c3} - P_{c3}) \cos(4\omega t) + (Q_{c3} + P_c \sqrt{3}) \sin(4\omega t),\end{aligned}\quad (10)$$

where $P_{a3} = V_a I_{a3} \cos \theta_{a3}$, $P_{b3} = V_b I_{b3} \cos \theta_{b3}$, $P_{c3} = V_c I_{c3} \cos \theta_{c3}$, $Q_{a3} = V_a I_{a3} \sin \theta_{a3}$, $Q_{b3} = V_b I_{b3} \sin \theta_{b3}$, and $Q_{c3} = V_c I_{c3} \sin \theta_{c3}$, respectively.

To obtain the improved algorithm for reactive power under this harmonic condition we apply the Walsh function by multiplying (10) with the third-order WF, that is, $\text{Wal}(3, t)$ and integrate over the time T . According to the Walsh functions all the integrals of the right-hand side terms of (10) that involves the multipliers of $\cos(2\omega t)$, $\cos(4\omega t)$, and $\sin(4\omega t)$ and the constant P are all equal to zero [14]. Hence (11) become

$$\begin{aligned}\frac{1}{T} \int_0^T p_a \text{Wal}(3, t) dt &= \frac{1}{T} \int_0^T (Q_{a3} - Q_a) \sin(2\omega t) \times \text{Wal}(3, t) dt, \\ \frac{1}{T} \int_0^T p_b \text{Wal}(3, t) dt &= \frac{1}{T} \int_0^T (P_b + \sqrt{3}Q_{b3} - Q_b) \sin(2\omega t) \times \text{Wal}(3, t) dt, \\ \frac{1}{T} \int_0^T p_c \text{Wal}(3, t) dt &= \frac{1}{T} \int_0^T (P_c + \sqrt{3}Q_{c3} - Q_c) \sin(2\omega t) \times \text{Wal}(3, t) dt.\end{aligned}\quad (11)$$

FIGURE 2: (a) 7th order WF, (b) $\sin(4\omega t)$ waveforms.

The product of the 3rd-order WF the expressions, $(Q_{a3} - Q_a) \sin(2\omega t)$, $(P_b \sqrt{3} + Q_{b3} - Q_b) \sin(2\omega t)$, and $(P_c \sqrt{3} + Q_{c3} - Q_c) \sin(2\omega t)$, results in the full-wave rectification of the terms:

$$\begin{aligned} \frac{1}{T} \int_0^T p_a Wal(3, t) dt &= \frac{1}{T} \int_0^T (Q_{a3} - Q_a) \sin(2\omega t) dt, \\ \frac{1}{T} \int_0^T p_b Wal(3, t) dt &= \frac{1}{T} \int_0^T (P_b \sqrt{3} + Q_{b3} - Q_b) \sin(2\omega t) dt, \\ \frac{1}{T} \int_0^T p_c Wal(3, t) dt &= \frac{1}{T} \int_0^T (P_c \sqrt{3} + Q_{c3} - Q_c) \sin(2\omega t) dt. \end{aligned} \quad (12)$$

Solving for Q_a , Q_b , and Q_c

$$\begin{aligned} Q_a &= -\frac{\pi}{2T} \int_0^T p_a Wal(3, t) dt + Q_{a3}, \\ Q_b &= -\frac{\pi}{2T} \int_0^T p_b Wal(3, t) dt + P_b \sqrt{3} + Q_{b3}, \\ Q_c &= -\frac{\pi}{2T} \int_0^T p_c Wal(3, t) dt + P_c \sqrt{3} + Q_{c3}. \end{aligned} \quad (13)$$

Q_{a3} , Q_{b3} , and Q_{c3} in (13) are the reactive components of the distortion power in the phases; these indicate the influence of the third-order current harmonics i_{a3} , i_{b3} , and i_{c3} on the reactive power measurement algorithms. The third-order Walsh function eliminates the effect of the third-order harmonics of the nonlinear load. Harmonics affect the reactive power measurement of a network. The final terms of (10) are the distortion power terms, that is, $Q_{a3} \sin(4\omega t)$, $(Q_{b3} + P_b \sqrt{3}) \sin(4\omega t)$, and $(Q_{c3} + P_c \sqrt{3}) \sin(4\omega t)$. They are oscillating with the frequency of 4ω which is similar to the oscillating frequency of the 7th-order Walsh function, $Wal(7, t)$, as can be seen in Figure 2.

FIGURE 3: (a) $Wal(3, t)$, (b) $Wal(7, t)$, and (c) $Wal(3; 7, t)$.

To estimate these distortions power terms both sides of (10) are multiplied by the 7th-order WF and then integrated over the period T and simplified to obtain the following:

$$\begin{aligned} \frac{1}{T} \int_0^T p_a Wal(7, t) dt &= -\frac{1}{T} \int_0^T Q_{a3} \sin(4\omega t) \times Wal(7, t) dt, \\ \frac{1}{T} \int_0^T p_b Wal(7, t) dt &= \frac{1}{T} \int_0^T (Q_{b3} + P_b \sqrt{3}) \sin(4\omega t) \times Wal(7, t) dt, \\ \frac{1}{T} \int_0^T p_c Wal(7, t) dt &= \frac{1}{T} \int_0^T (Q_{c3} + P_c \sqrt{3}) \sin(4\omega t) \times Wal(7, t) dt. \end{aligned} \quad (14)$$

The 7th-order WF is the odd function with the frequency similar to the frequency of the distortion terms. The product of the 7th-order WF with the distortion terms results in their

FIGURE 4: The model of the proposed improved Walsh function algorithm.

FIGURE 5: Model of nonlinear load.

rectification. So taking cognizance of these rectifying effects, (14) is rewritten as follows:

$$\begin{aligned} \frac{1}{T} \int_0^T p_a \text{Wal}(7, t) dt &= -\frac{1}{T} \int_0^T Q_{a3} \sin(4\omega t) dt, \\ \frac{1}{T} \int_0^T p_b \text{Wal}(7, t) dt &= \frac{1}{T} \int_0^T (Q_{b3} + P_b \sqrt{3}) \sin(4\omega t) dt, \\ \frac{1}{T} \int_0^T p_c \text{Wal}(7, t) dt &= \frac{1}{T} \int_0^T (Q_{c3} + P_c \sqrt{3}) \sin(4\omega t) dt. \end{aligned} \quad (15)$$

Solving for Q_{a3} , Q_{b3} , and Q_{c3} produces the following:

$$\begin{aligned} Q_{a3} &= -\frac{\pi}{2T} \int_0^T p_a \text{Wal}(7, t) dt, \\ Q_{b3} &= \frac{\pi}{2T} \int_0^T p_b \text{Wal}(7, t) dt - P_b \sqrt{3}, \\ Q_{c3} &= \frac{\pi}{2T} \int_0^T p_c \text{Wal}(7, t) dt - P_c \sqrt{3}. \end{aligned} \quad (16)$$

Equations (16) are the improved Walsh function algorithms for measuring the distortion power in a three-phase system. Substituting in (13) algorithms for reactive powers are obtained as follows:

$$\begin{aligned} Q_a &= -\frac{\pi}{2T} \left[\int_0^T p_a \text{Wal}(3, t) dt + \int_0^T p_a \text{Wal}(7, t) dt \right], \\ Q_b &= \left[\int_0^T p_b \text{Wal}(3, t) dt + \int_0^T p_b \text{Wal}(7, t) dt \right], \\ Q_c &= \left[\int_0^T p_c \text{Wal}(3, t) dt + \int_0^T p_c \text{Wal}(7, t) dt \right]. \end{aligned} \quad (17)$$

These algorithms eliminate the effect of the 3rd- to 7th-order harmonics on the reactive power measurement and also essentially reduced the effect of the higher order current harmonics. In other to reduce the computation involved, the 3rd- and 7th-order Walsh are added together which gives the new improved algorithms. The analytical addition of the 3rd and 7th is represented in Figure 3.

From Figure 3 it can be observed that the IWF as a result of the addition of standard 3rd- and the 7th-order WF is defined as follows.

$\text{Wal}(3; 7, t)$ is

+1, if t is in the interval $[0; T/8], [T/2; 5T/8]$

0, if t is in the interval $[T/8; 3T/8], [5T/8; 7T/8]$

-1, if t is in the interval $[3T/8; T/2], [7T/8; T]$.

The new improved WF algorithms are derived by multiplying (10), with $\text{Wal}(3; 7, t)$ and then integrate over the time T . Now considering the integrals after the equal sign, the p_a , p_b , and p_c are constants so are equal to zero because IWF is a periodic function; 2nd and 4th integrals are also equal to zero as they include cosine functions that are orthogonal with the IWF. The 3rd and 5th integrals comprise the rectification of the sin

FIGURE 6: (a) 3-phase voltage waveform and (b) 3-phase unbalance current waveform.

functions waveform, so these integrals are not equal to zero. Thus equations are written as follows:

$$\begin{aligned}
 & \frac{1}{T} \int_0^T p_a \text{Wal}(3; 7, t) dt \\
 &= \frac{1}{T} \int_0^T \text{Wal}(3; 7, t) (Q_{a3} - Q_a) \sin(2\omega t) dt \\
 &\quad - \frac{1}{T} \int_0^T \text{Wal}(3; 7, t) Q_{a3} \sin(2\omega t) dt, \\
 & \frac{1}{T} \int_0^T p_b \text{Wal}(3; 7, t) dt \\
 &= \frac{1}{T} \int_0^T \text{Wal}(3; 7, t) (P_b \sqrt{3} + Q_{b3} - Q_b) \sin(2\omega t) dt \\
 &\quad + \frac{1}{T} \int_0^T \text{Wal}(3; 7, t) \times (Q_{b3} + P_b \sqrt{3}) \sin(4\omega t) dt, \\
 & \frac{1}{T} \int_0^T p_c \text{Wal}(3; 7, t) dt \\
 &= \frac{1}{T} \int_0^T \text{Wal}(3; 7, t) \times (P_c \sqrt{3} + Q_{c3} - Q_c) \sin(2\omega t) dt \\
 &\quad + \frac{1}{T} \int_0^T \text{Wal}(3; 7, t) \times (Q_{c3} + P_c \sqrt{3}) \sin(4\omega t) dt.
 \end{aligned} \tag{18}$$

Solving the right-hand side integrals of (18) yields the new improved algorithms in the following:

$$\begin{aligned}
 Q_{a,3;7} &= -\frac{\pi}{T} \int_0^T p_a \text{Wal}(3; 7, t) dt, \\
 Q_{b,3;7} &= -\frac{\pi}{T} \int_0^T p_b \text{Wal}(3; 7, t) dt + (P_b \sqrt{3} + Q_{b3}), \\
 Q_{c,3;7} &= -\frac{\pi}{T} \int_0^T p_c \text{Wal}(3; 7, t) dt + (P_c \sqrt{3} + Q_{c3}).
 \end{aligned} \tag{19}$$

Equations (7), (16), and (19) are the proposed improved Walsh function IWF algorithms that would be used to measure the active, distortion, and reactive powers, respectively, of a network and also eliminate the effect of higher order harmonic in the three-phase reactive power measurement system. Suffice it to say that in actual cases only lower order harmonics are present in power system signal.

5. Modeling the Proposed IWF Algorithm

Equations (7) and (19) are used to create the model for the active and reactive powers measurement based on the proposed improved algorithms using the Matlab Simulink software tool. Then some of the commonly used nonlinear domestic and industrial loads were modeled along and used in the simulation of the improved Walsh function algorithms for active and reactive powers measurement. Examples are compact fluorescent lamps (CFL) and computers. Loads can be resistive R , inductive L , capacitive C , or a combination, for example, RL , RC , LC , RLC depending on the type of load being modeled. RL was used to model the loads used in this simulation (see Figures 4 and 5).

FIGURE 7: (a) Nonlinear current waveform and (b) harmonic spectrum (experiment).

TABLE 1: The result of case A.

FFT approach	Active power P (watts)	Reactive power Q (var)
Phase a	1181.1	944.8
Phase b	214.1	746.5
Phase c	492.6	1039.1
Total	1887.8	2730.4
Proposed IWF method		
Phase a	1180.7	944.5
Phase b	214.8	746.7
Phase c	493.5	1040.2
Total	1889	2731.4

TABLE 2: The result of case B.

FFT approach	Active power P (watts)	Reactive power Q (var)
Phase a	1027.5	569.5
Phase b	819.3	223.3
Phase c	2098.6	1538.9
Total	3945.4	2331.7
Proposed IWF method		
Phase a	1028	569.6
Phase b	818.6	223.8
Phase c	2099	1539
Total	3945.6	2332.4

The RL nonlinear loads were modeled using universal bridge rectifier; the values for the R_s and C_s were determined using the expressions

$$R_s > \frac{2T_s}{C_s}, \quad C_s < \frac{P_n}{1000(2\pi f)V_n^2}, \quad (20)$$

where P_n = nominal power of three phase converter VA, V_n = nominal line AC voltage V rms, f = fundamental frequency Hertz, and T_s = sample time.

The R and L of an RL load on dc side of the universal bridge rectifier are calculated using data recorded on the standard 435 fluke power quality analyzer PQA during the laboratory experiment involving measurement of power components of harmonic generating loads.

5.1. Simulation and Discussion of Results. For the simulation of the linear loads a synthetic line to neutral voltages (V phases) is chosen as follows:

$$V_a = 220\angle 0^\circ, \quad V_b = 220\angle -120^\circ, \quad V_c = 220\angle 120^\circ. \quad (21)$$

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 algorithms. Knowing the supply voltage and the impedance of the loads (Z) the resistance (R) and inductive reactance (X_L) of each phase load were calculated and the obtained results for R and X_L were used to configure standard RLC load taken from the Matlab simulink power blocks.

Case A: $Z_a = 36 + j20\Omega$, $Z_b = 55 + j15\Omega$, $Z_c = 15 + j11\Omega$.

Case B: $Z_a = 25 + j20\Omega$, $Z_b = 17 + j60\Omega$, $Z_c = 18 + j38\Omega$.

Figure 6 shows the voltage and current waveform for the three-phase sinusoidal linear unbalanced load system obtained from simulation with the new improved algorithms.

5.2. Linear Load System. For the linear sinusoidal load system, IEEE standard 1459-2000 which is based on FFT approach was used as benchmark for measurement of active and reactive powers of case A for the three phases

TABLE 3: Simulation and experimental results.

S/N	Load type	Fluke 435 PQA meter readings		FFT approach		Proposed IWF algorithm	
		P (watts)	Q (var)	P (watts)	Q (var)	P (watts)	Q (var)
1	CFL lamps (15.8 watts $\times$ 45)	711	364.5	710.8	363.4	711	364
2	Desktop computers (60.3 watts $\times$ 70)	422.1	20.3	421.9	19.8	422	20
3	Laptop computers (54.6 watts $\times$ 8)	436.8	18.5	435.7	18.3	437	18
4	2 ft. fluorescent lamps (27.8 watt $\times$ 15)	417	934.5	416.3	933.8	417	934

FIGURE 8: (a) Nonlinear current waveform and (b) harmonic spectrum (Simulation).

and compared with the results using the proposed improved algorithms (7) and (19). The results are displayed in Table 1. Similarly for case B results are shown in Table 2. From the results using the IEEE standard 1459-2000 which is based on FFT as reference it can be observed that the proposed Walsh function algorithm has the potential to measure the active and reactive powers with a high degree of accuracy. In terms of computational complexity the proposed Walsh function algorithm has less computational requirement than the FFT.

5.3. Nonlinear Harmonic Load. Experimental results using harmonic load bank and other harmonic generating loads in the laboratory as recorded by fluke PQA meters were used in modeling of the nonlinear loads. The computer and CFL lamps were modeled as RL loads and simulated using both FFT approach and the proposed improved Walsh algorithms for the measurement of active and reactive powers. The laboratory experimental results were used as benchmark. The nonlinear load currents waveform for the experiment using the Fluke PQA meter and that of the model simulation is recorded as shown in Figures 7 and 8. The results of the simulations and experimental measurement of nonlinear loads are presented in Table 3. It can be observed that the standard FFT approach recorded significant error which could be due to the spectral leakage and picket fence effect phenomenon of the FFT approach when used for measurement in nonlinear harmonic load system. On the other hand, the proposed improved Walsh function algorithm for

measurement gave a near accurate result as the influence of the harmonics of the nonlinear load has been address in the improved Walsh algorithms. The Fluke power quality analyzer and FFT graphical user interface analyze signals of one phase at a time so the figure shown is for one of the phases and the same is applicable to the other two phases but has been withheld for convenience, clarity, and space. Walsh function transform is a special form of the Fourier transforms [21, 22]. So it is sometimes called Walsh Fourier.

6. Conclusion

A new improved Walsh function algorithm for active and reactive powers measurement was presented. The IEEE standard 1459-2000 fast Fourier transform approach was used as benchmark to validate the algorithm when the load system is linear and sinusoidal. The Fluke 435 power quality analyzer PQA meter was used as reference for nonlinear harmonic load system simulation and measurement. The results show that the proposed improved Walsh function has the potentials of accurately measuring power components under different load conditions. If the algorithm is integrated into measuring instrument it would be able to properly record the active and reactive powers components under sinusoidal and non-sinusoidal load system for proper monitoring, management, and maintenance planning. The approach is simpler with less computation when compared with Fourier transform. The

research is continuing in the development of a model for measuring the distortion component of the power system.

Acknowledgments

The authors wish to acknowledge the Ministry of Higher Education, Malaysia (MOHE), for funding of project and Universiti Teknologi Malaysia and Universiti Kebangsaan Malaysia for providing infrastructure and moral support for the research work.

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