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A New Improved Walsh Function Algorithm for Active and Reactive Power Measurement

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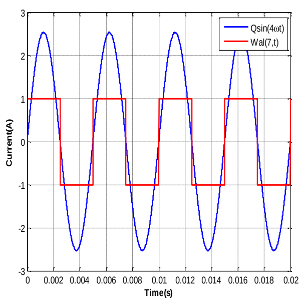
Graphical abstract



Abstract

This paper present improved Walsh function (IWF) algorithm as an alternative approach for active and reactive power measurement in linear and nonlinear, balanced and unbalanced sinusoidal three phase load system. It takes advantage of Walsh function unified approach and its intrinsic high level 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 algorithm. The IEEE standard 1459-2000 which is based on fast Fourier transform FFT approach was used as benchmark for the linear load system while a laboratory experiment using Fluke 435 power quality analyzer PQA which complies with IEC/EN61010-1-2001standards was 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.

Keywords: Walsh function; reactive power; nonlinear load; measurement; fast Fourier transform

Abstrak

Kertas ini membentangkan algoritma fungsi Walsh tertingkatkan sebagai pendekatan alternatif bagi pengukuran kuasa aktif dan reaktif dalam sistem beban sinus tiga fasa yang dan tak lelurus serta seimbang dan tidak seimbang. Kelebihan pendekatan fungsi Walsh adalah bersepadu dan ketepatannya bertahap tinggi yang hakiki yang disebabkan oleh ciri-ciri pekali dan perwakilan sifat tenaga. Algoritma yang dibina ini dimodelkan di perisian Matlab Simulink; jenis beban yang berlainan, linear dan tak linear juga dimodelkan berdasarkan gelombang voltan dan arus praktikal serta diuji dengan menggunakan algoritma Walsh tertingkatkan seperti yang dicadangkan. Standard IEEE 1459-2000 berasaskan pendekatan gubahan Fourier pantas FFT digunakan sebagai penanda aras bagi sistem beban lelurus manakala satu ujikaji makmal menggunakan Fluke 435 penganalisi kualiti kuasa PQA yang menepati standard IEC/EN61010-1-2001 telah digunakan untuk mengesahkan algoritma tertingkatkan ini bagi pengukuran beban tak lelurus. Hasil kajian menunjukkan bahawa algoritma ini mempunyai potensi untuk mengukur komponen kuasa tiga fasa bg keadaan beban berbeza secara berkesan.

Kata kunci: Fungsi Walsh; kuasa reaktif; tak lelurus; pengukuran; jelmaan Fourier pantas

1.0 INTRODUCTION

As the awareness of the problems associated with nonlinear devices and their influence on power components measurement increases, the use of these power electronics equipment and appliances with microprocessors have been proved to considerably contribute 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 negative effect on the power quality of the supply system. Accurate measurement and evaluation of energy consumption is of utmost importance for effective planning, billing, monitoring, maintenance and further development of the power supply system. The deregulation of the power sector and the increasing cost of fossil fuel have 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] Several companies are into design and manufacture of energy meter 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 distortion / asymmetrical voltages are billed not only for the useful energy but also for the energy which may have caused malfunction of their equipment.[6]

The IEEE working group on appropriate determination of billing system based on sinusoidal and non-sinusoidal situation defined distortion power in terms of total fundamental and harmonic constituents with less unwieldy theory.[7] The conventional or classical method of determining power consumption is to evaluate using measured values of the voltage, current and power factor. The apparent power, active power, and reactive power are defined as in reference.[8] This classical way of power evaluation needs 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. Precise determination of RMS values of voltage and current is complex and poses a serious challenge in electrical measurement.[9] For the classical method of power calculation to be effective in a three phase network the following has to be satisfied;

(i) Voltages and current RMS values on all the three phases must be identical.
(ii) Phase angles between voltage and current should always be 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 non-linear.[10]

This paper proposed improved algorithm as an alternative for power component measurement process 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 accuracy as a result of coefficient characteristics and energy behaviour representation.[11] The method can be used on any type of energy meter testing.

The remaining of this paper is organized as follows. Section two, presents Walsh function and its analytical expression, while section three highlights the steps involved in the development of the proposed improved algorithm for measurement using the Walsh function, section four has the modeling and simulation of the improved algorithm, five is the simulation and laboratory experiment results, Lastly, section six is the conclusions.

■2.0 WALSH FUNCTION (WF) ANALYTICAL EXPRESSION

The Walsh function method for the analysis and evaluation of nonlinear signals was presented as a mathematical tool to analyze energy parameters output behaviour for in-depth error detection; the method is faster when compared with other techniques like FFT. It does not require the phase shift between voltage and current and it has less computation requirement.[8] However, when the load becomes nonlinear the distorted voltage and current waveform produces harmonic which is a multiple of the fundamental frequency of the current and/or voltage. Harmonic current affects the reactive power measurement so another attempt using modified approach for power components measurement in both sinusoidal and non-sinusoidal 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.[12-14]

The attractions to Walsh function based technique for use in energy parameter evaluation are;

(i) The Walsh transforms analyzes signals into rectangular waveform rather than sinusoidal ones and is computed more rapidly when compared with Fourier transform FT.
(ii) Walsh function based algorithm contains addition and subtractions only and hence result in considerably simplified hardware implementation of power evaluation.
(iii) The IEEE/IEC definition of a phase shift between the voltage and the current signal mainly use for reactive power evaluation is eliminated from signal processing operation when using Walsh function.[15]

Generalized Walsh functions and transforms was 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 function considered. These functions can be applied 'inter alia', to develop algorithm that would be applicable to nonlinear load 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 related to measurement of power components and characteristics of power distribution system.

Analytically the Walsh function is expressed as;

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

Where;

n is the order of the function form $n = 1,2,3 \ldots n_m$ which is the m^{th} coefficients of the n represented in binary code i.e. $n = (n_{0,} n_{1,} n_{2,} n_3 \ldots . n_m)_2$, $n_m = 0,1$. With m being the highest-order WF serial number in the system, β is the argument of WF that defines the coefficients of β_k in binary code $\beta = (\beta_k, \beta_k \ldots \beta_k)_2$, $\beta_k = 0,1$ and $k = 1,2,3 \ldots m$. From equation (1) the graphical representation of the first fourth order Walsh function is generated as shown in Figure 1.

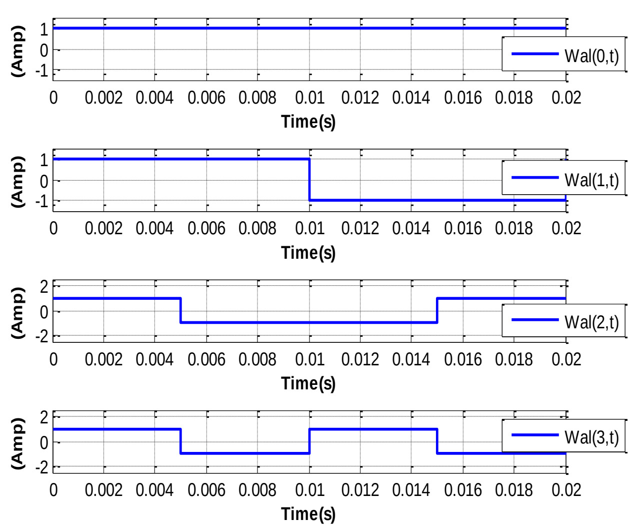


Figure 1 Graphical representation of first fourth order WF

3.0 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 loads is given as;[17] Instantaneous three phase sinusoidal voltages.

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

Instantaneous three phase currents

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

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 Hz, t = 1/f*. The instantaneous powers for the three phases represented with say p_a, p_b and p_c are given by;

$$p_a = v_a * i_a,\ p_b = v_b * i_b \text{ and } p_c = v_c * i_c \tag{4}$$

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

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

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.

The algorithm for measuring the reactive powers on these three-phase system says, Q_a, Q_b and Q_c using the Walsh function is obtained by multiplying both sides of equations (5) by the third order Walsh function $Wal(3,t)$ and integrating over the period T of power system frequency to obtain equations (6). The integral of the third order WF with a constant and a multiply of $\cos(2\omega t)$ is equal to zero. $\cos(2\omega t)$ is orthogonal with the Walsh function so the result is as shown in equations (6).

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

The algorithm for real or active powers in the three phase a, b and c is determined by multiplying equations (5) by the zero order Walsh function i.e. $Wal(0,t)$ and integrate over the period T. In Walsh algorithm the zero order function $Wal(0,t) = 1$, over the period of T as can be seen from Fig.1 so all the integral terms at the right hand side of equations (5) that involve product of $Wal(0,t)$ with the $\cos(2\omega t)$ and $\sin(2\omega t)$ approach to zero thus giving equations (7) as;

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

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

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

The modeling and simulation of equations (6) and (8) has been implemented earlier in[12] and it shows that current harmonic affects the reading of the simulation results. The algorithm has to be further improved as to be able to measure the power components in both linear and non-linear sinusoidal non-sinusoidal load conditions. It is worthy to note at this juncture, that in AC network source voltages are relatively pure sinusoidal waveforms. It is at the distribution that harmonic are introduced due to the increasing use of nonlinear load like computers, fluorescent lamps, adjustable speed drive motors, arc furnaces, arc welding machines, electronic control and power converters among others. Harmonic current causes overloading of neutral conductors, overheating of transformers, tripping of circuit breakers, power factor correction capacitors over stress and skin effects.[18] Also other research have shown that the effect of odd harmonic is more significant in power distribution system while that of even harmonic is negligible.[19-22]

3.1 Improved IWF Algorithm for Measurement

Harmonic in the power system does not have much effect on the active power measurement but has a great deal of influence on the reactive power which invariably affect 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 say, third order current harmonic denoted as i_{a3}, i_{b3} and i_{c3} with θ_{a3}, θ_{b3} and θ_{c3} being the phase angle 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;

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

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

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

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 equations (10) with the third order Walsh function i.e. $Wal(3,t)$ and integrate over the time T. According to the Walsh functions all the integrals of the right hand side terms of equation (10) that involves the multipliers of $\cos(2\omega t)$, $\cos(4\omega t)$, $\sin(4\omega t)$ the constant are all equal to zero. Hence equation (11) becomes;

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

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

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

Solving for Q_a, Q_b and Q_c

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

Q_{a3}, Q_{b3} and Q_{c3} in equations (13) are the reactive components of the distortion power in the phases, this indicates the influence of the third order current harmonics , and on the reactive power measurement algorithm. The third order Walsh function eliminates the effect of the third order harmonics of the nonlinear load. The final terms of equations (10) are the distortion power terms, i.e. $Q_{a3}\sin(4\omega t)$, $(Q_{b3} + P_b\sqrt{3})\sin(4\omega t)$ 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 WF, $Wal(7,t)$ as can be seen in the Figure 2.

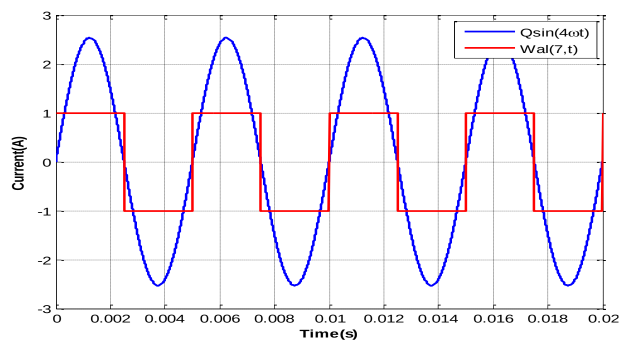


Figure 2 Oscillating frequency of $Q\sin(4\omega t)$ and . To estimate these distortions power terms we multiply both sides of equation (10) by the 7th order WF and then integrate over the period T and simplify to obtain equation (14)

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

The 7th order WF is the odd function with the frequency similar to the frequency of the distortion terms Figure 2. The product of the 7th order WF with the distortion terms results in their rectification. So taking cognizance of these rectifying effects, equations (14) is written as in equation (15).

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

Solving for Q_{a3}, Q_{b3} and Q_{c3} produces equations (16)

$$Q_{a3} = -\frac{\pi}{2T}\int_0^T p_a Wal(7,t)dt$$
$$Q_{b3} = \frac{\pi}{2T}\int_0^T p_b Wal(7,t)dt - P_b\sqrt{3} \qquad (16)$$
$$Q_{c3} = \frac{\pi}{2T}\int_0^T p_c Wal(7,t)dt - P_c\sqrt{3}$$

Equation (16) is the proposed improved Walsh function algorithm for measuring the distortion power in a three phase system. Substituting in equation (13) gives an algorithm for reactive powers shown in equations (17)

$$Q_a = -\frac{\pi}{2T}[\int_0^T p_a Wal(3,t)dt + \int_0^T p_a Wal(7,t)dt]$$
$$Q_b = [\int_0^T p_b Wal(3,t)dt + \int_0^T p_b Wal(7,t)dt] \qquad (17)$$
$$Q_c = [\int_0^T p_c Wal(3,t)dt + \int_0^T p_c Wal(7,t)dt]$$

This algorithm eliminates the effect of the 3rd and 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 a new improved algorithm. The analytical addition of the 3rd and 7th is represented in Figure 3.

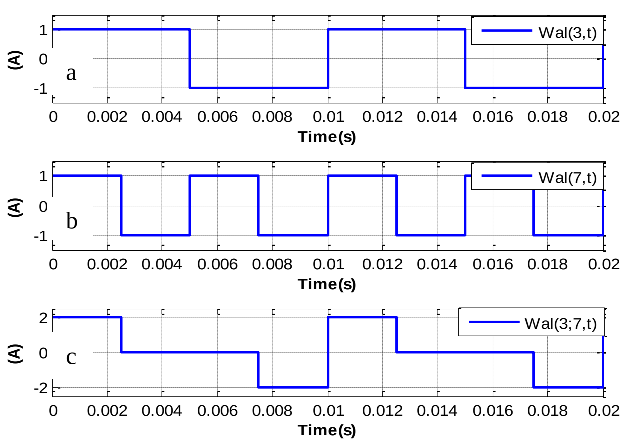


Figure 3 (a) $Wal(3,t)$ (b) $Wal(7,t)$ and (c) $Wal(3;7,t)$

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

$Wal(3;7,t)$ 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 is derived by multiplying equations (10), with $Wal(3;7,t)$ and takes the integral over the time T. Now considering the integrals after the equal sign, 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 sine functions waveform, so these integrals are not equal to zero. This equation is written as in equations (18);

$$\frac{1}{T}\int_0^T (p_a Wal(3;7,t))dt = \frac{1}{T}\int_0^T (\mathrm{Wal}(3;7,t))(Q_{a3} - Q_a)\sin 2\omega t dt - \frac{1}{T}\int_0^T Wal(3;7,t)Q_{a3}\sin 2\omega t dt.$$

$$\frac{1}{T}\int_0^T (p_b Wal(3;7,t))dt = \frac{1}{T}\int_0^T (\mathrm{Wal}(3;7,t))(P_b\sqrt{3} + Q_{b3} - Q_b)\sin 2\omega t dt + \frac{1}{T}\int_0^T (Wal(3;7,t))(Q_{b3} + P_b\sqrt{3})\sin 4\omega t dt. \qquad (18)$$

$$\frac{1}{T}\int_0^T (p_c Wal(3;7,t))dt = \frac{1}{T}\int_0^T (Wal(3;7,t))(P_c\sqrt{3} + Q_{c3} - Q_c)\sin 2\omega t dt + \frac{1}{T}\int_0^T (Wal(3;7,t))(Q_{c3} + P_c\sqrt{3})\sin 4\omega t dt.$$

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

$$Q_a = -\frac{\pi}{T}\int_0^T p_a Wal(3;7,t))dt$$
$$Q_b = -\frac{\pi}{T}\int_0^T p_b Wal(3;7,t)dt + (P_b\sqrt{3} + Q_{b3}) \qquad (19)$$
$$Q_c = -\frac{\pi}{T}\int_0^T p_c Wal(3;7,t)dt + (P_c\sqrt{3} + Q_{c3})$$

Equations (7) and (19) above are the proposed improved Walsh function algorithms that would be used to measure the active, distortion and reactive power 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.

■4.0 MODELING THE PROPOSED IWF ALGORITHM

Equations (7) and (19) are used to create the model for the active and reactive power measurement based on the proposed improved algorithm using the Matlab Simulink software tool. Some of the commonly used nonlinear domestic loads were modeled along and use in the simulation of the proposed improved Walsh function algorithm for active and reactive power measurement examples, compact fluorescent lamps (CFL) and computers, The loads can be resistive R, inductive L, capacitive C or a combination e.g. RL, RC, LC, RLC depending on the type of load being modeled. RL was used to model the loads used in this experiment.

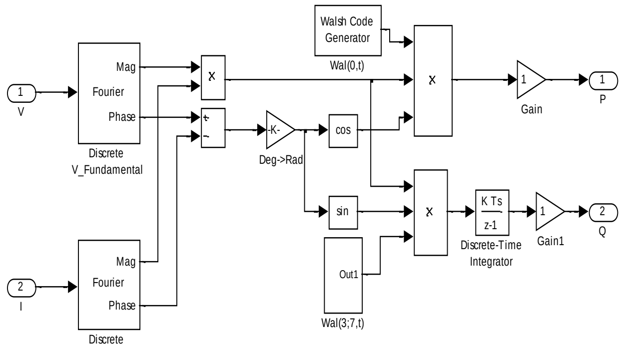


Figure 4 The Subsystem of the proposed model

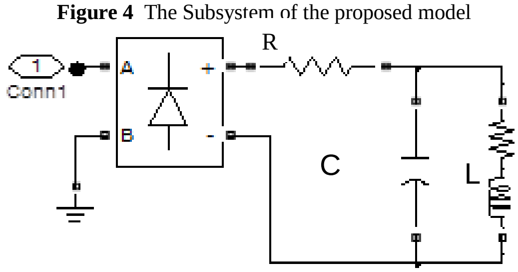


Figure 5 Model of nonlinear load

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

$R_s > 2T_s/C_s$ and $C_s < P_n \div 1000(2\pi f)V_n^2$

Where

P_n = nominal power of three phase converter VA

V_n = nominal line AC voltage V rms

f = fundamental frequency Hz

T_s = Sample time.

The R and L of an RL load is calculated using data recorded on the standard fluke power quality analyzer during the experiment.

5.0 SIMULATION AND EXPERIMENTAL RESULTS

For the simulation of the linear loads a synthetic line to neutral voltages (V phases) were chosen as follows;

$V_a = 220\angle 0^0$, $V_b = 220\angle 120^0$ and $V_c = 220\angle 120^0$

Load impedances for two different cases of unbalanced three phase system are chosen as shown in case 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 inductance (L) of each phase load was calculated and the obtained results for R and L was 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: $Z_a = 25 + j20\Omega; Z_b = 17 + j60\Omega; Z_c = 18 + j38\Omega$

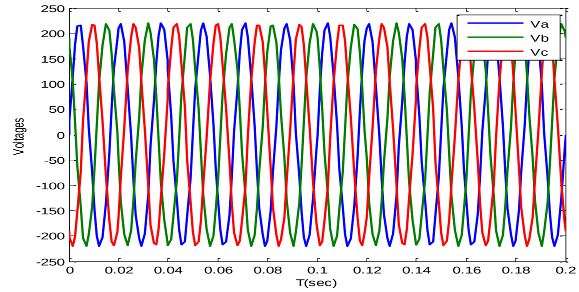


Figure 6 3-phase sinusoidal voltage waveform

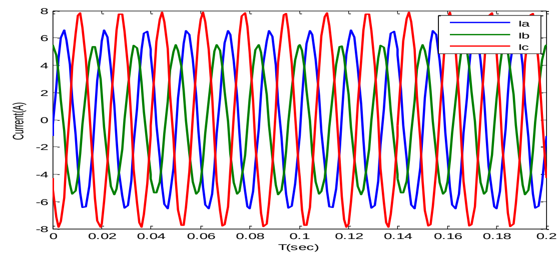


Figure 7 3-phase unbalanced load current waveform

Figure 6 and 7 shows the voltage and current waveform for the three phase sinusoidal linear unbalanced load system obtained from simulation with the new improved algorithm.

5.1 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 power of case (A) for the three phases and compared with the results using the proposed improved algorithms (7) and (19). The results are displayed in Table 1. Similarly for case (B) is 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 captured the active and reactive power with a high degree of accuracy.

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 P (watts)	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	2332.4

5.2 Nonlinear Harmonic Load

The modeling of the nonlinear loads was based on the readings recorded for the various nonlinear loads using the fluke PQA meter that is in compliances with IEC/EN61010-1-2001standards. The computer and CFL lamps were modeled as RL loads and simulated using both FFT approach and the proposed improved Walsh algorithm for the measurement of active and reactive power using the laboratory experimental results as benchmark. The non-linear load currents waveform for the experiment using the Fluke PQA meter and that of the model simulation is recorded as shown in Figure 8 and 9. The result of the simulations and experimental measurement of nonlinear loads are presented in the Table 3. It can be observed that the standard FFT approach recorded significant error which is 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 harmonic of the nonlinear harmonic load has been address by the proposed improved Walsh algorithm.

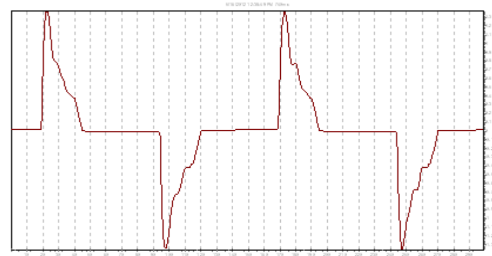


Figure 8 Nonlinear current waveform (experiment).

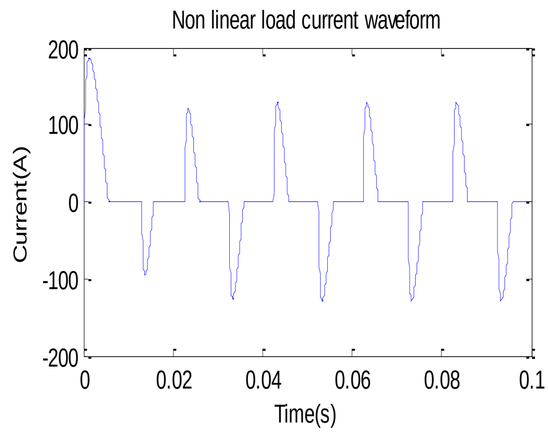


Figure 9 Nonlinear current waveform (simulation)

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 (15.8watts x 45)	711	364.5	710.8	363.4	711	364
2	Desktop computers (60.3watts x 70)	422.1	20.3	421.9	19.8	422	20
3	Laptop computers (54.6 watts x 8)	436.8	18.5	435.7	18.3	437	18
4	2ft. fluorescent lamps (27.8watt x 15)	417	934.5	416.3	933.8	417	934

■6.0 CONCLUSION

A new improved Walsh function algorithm for active and reactive power 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 measurement. The results shows that the proposed improved Walsh function has the potentials of accurately measuring power component under different load conditions. If the algorithm is integrated into measuring instrument it would be able to properly record the active and reactive power of consumers for proper billing purposes and maintenance planning. The research is continuing in the development of a model for measuring the distortion component of the power system.

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