A New Alternative Algorithm for Reactive and Distortion Power Measurement Using the Walsh Functions

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Abstract

This paper presents the use of the Walsh function based algorithm as an alternative for reactive and distortion power measurement. The algorithm provides a favorable method for calculating or measuring power components by simplifying the multiplication procedure that leads to the determination of the reactive and distortion power from instantaneous power signal. In comparison to the known existing fast Fourier transform FFT, it's faster and simple, the method does not require the phase shift of pi/2 between the voltage and current and its applicable both for stationary and nonstationary load conditions as it eliminate the effects of harmonics in measurement. Load harmonics affect the FFT algorithm and make its result of measurement unrealistic in the presence of harmonic distortion. A simulation tool developed on Matlab was used to validate the proposed Walsh function alternative algorithm.

1. Introduction

There has been astronomical increase in the number of nonlinear loads connected to the energy distribution networks. The nonlinear loads characteristics negatively impact on the voltage and current signals of the system, this affect the accurate measurement of power components. The definition of power components in power system analysis contained in IEEE 1459-2000 for power component signals consisting of harmonic is based on fast Fourier transform FFT algorithm, this definition which is in frequency domain implements power component measurement accurately if the system has stationary and sinusoidal current and voltage waveforms. When the system is made non-stationary and non-sinusoidal the reading recorded for the reactive power becomes unrealistic [1-3]. Research have shown that in a sinusoidal operating condition all known reactive energy measurement algorithms provide the same results, however, if the system becomes non-sinusoidal due to the presence of harmonic distortion the algorithms provide diverse results [4]. Meaning that, there is no global common definition yet for reactive power that takes into cognizance the operating environments that are not solely sinusoidal. Reactive power measurement is important in determining the reactive demand which assist in improving the voltage profile while reactive energy measurement is used by utility companies to fashion out suitable measures to reduce loss in revenue and increase the power supply capacity. Attempts to formulate a generally suitable algorithm for measurement of power components (reactive power in particular) in both sinusoidal and non-sinusoidal conditions have been ongoing for a while now [5]. Several authors have defined and formulated algorithms based on time-domain [6-9] while others used the frequency-domain [10-12] and lately a combination of time and frequency domain [13-15]. A careful look at the different approaches revealed that the time-domain approach is simple and easy to implement but then, cannot measure the fundamental and each harmonic component separately and it also lose frequency content information. The frequency domain approach though; it can accurately measure the fundamental and each harmonic component separately, certain reactive power quantities could lead to a result that have no physical meaning, it is difficult to apply for compensations and time information is lost since FFT gives only the amplitude frequency spectrum of the analyzed waveform. Afterward, the time-frequency domain approach for power component measurement using the Wavelet transform have been investigated and presented. It has the advantage of being able to effectively measure the power component in both stationary and non-stationary voltage and current waveform conditions, but the computation burden associated with Wavelet transform exposes the algorithm to errors, and it require the phase shift of pi/2 between the voltage and current signals [16-17].

This paper present the use of the Walsh function based algorithm as an alternative for reactive and distortion powers measurement. The advantages of the Walsh function based technique for use in energy components evaluation are;

- The Walsh transforms analyzes signals into rectangular waveform rather than sinusoidal ones and is computed more easily and rapidly when compared with fast Fourier transform FFT and Wavelet transform.
- Walsh function based algorithm contains addition and subtractions only and hence result in considerably simplified hardware implementation of power evaluation.
- A requirement of IEEE/IEC definition of a phase shift of pi/2 between the voltage and the current signal mainly use for reactive power evaluation is eliminated from signal processing operation when using Walsh function [18].

The remaining part of this paper is arranged as follows; section two is a review Walsh function analytical expression, section three describes the derivation of the Walsh function algorithm, while section four is the modeling, simulation of the algorithm, five is the conclusion.

2. Walsh Function Analytical Expression

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 [19] with some basic and enlightening properties of these function and transform considered. The Walsh function can be applied among others, to develop an algorithm that can be applied to non-linear loads problem analysis. It is a full orthogonal system with exciting distinctiveness, among which is that it has only two values i.e. +1 and -1 over stated normalized period T. This specificity greatly influences the effectiveness of signal processing operation as related to measurement of the components and characteristics of power distribution system. Analytically the Walsh function is expressed as [20];

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

Where; n is the order of the function from $n = 1,2,3 \dots n_m$ is the m^{th} coefficients of the n represented in binary code i.e. $n = (n_{0,}n_{1,}n_3 \dots n_m)_2$, $n_m = 0,1$. with m being the highest-order Walsh function 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 equation (1) the graphical representation of the first eight WF is generated as shown in figure (1)

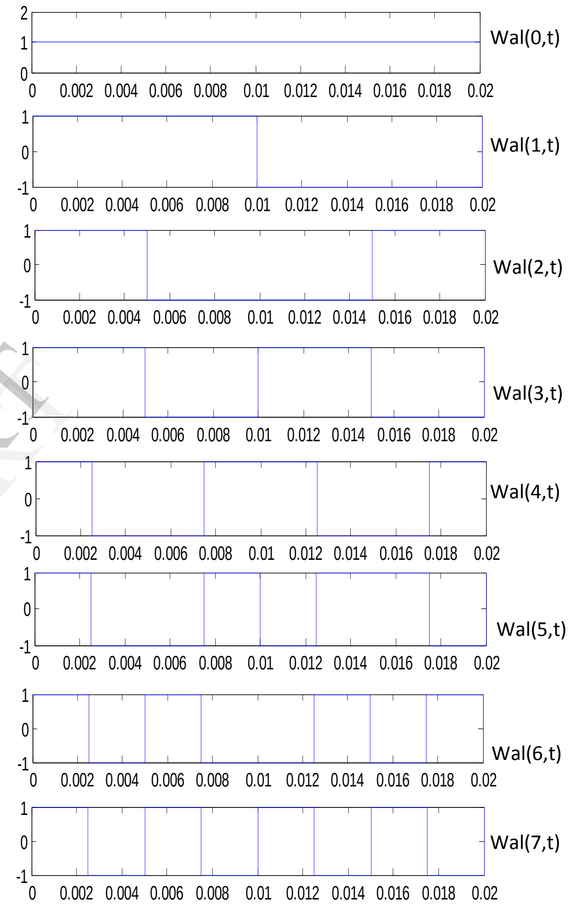


Figure 1: The first 8th order Walsh function

3. Proposed Walsh Function Algorithm for Power Measurements

The IEEE standard 1459-2000 for the instantaneous fundamental voltages (v_a, v_b, v_c) and currents (i_a, i_b, i_c) in a three phase sinusoidal distribution network is given as [21];

$$v_a = \sqrt{2}\, V_a \sin(wt)$$
$$v_b = \sqrt{2}\, V_b \sin(wt - 120°)$$
$$v_c = \sqrt{2} V_c \ \sin(wt + 120°) \qquad (2)$$

and

$$i_a = \sqrt{2} I_a \ \sin(wt - \emptyset_a)$$
$$i_b = \sqrt{2} I_b \ \sin(wt - \emptyset_b - 120°)$$
$$i_c = \sqrt{2} I_c \ \sin(wt - \emptyset_b + 120°) \qquad (3)$$

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.

$w = 2\pi f \qquad f = frequency\ (Hz) \qquad t = 1/f$

To derive the improved algorithm for measurement when the load current is contaminated with say, third orders 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;

$$i_{a3} = I_{a3} \sin(3wt - \theta_{a3})$$
$$i_{b3} = I_{b3} \sin(3wt - \theta_{b3} - 120)$$
$$i_{c3} = I_{c3} \sin(3wt - \theta_{c3} + 120) \qquad (4)$$

The instantaneous powers p_{a3}, p_{c3} and p_{c3} for the three phases a, b and c under this harmonic condition are; $p_{a3} = v_a * (i_a + i_{a3})$, $p_{b3} = v_b * (i_b + i_{b3})$ and $p_{c3} = v_c * (i_c + i_{c3})$

Substituting and solving yields,

$$p_{a3} = P_a + (P_{a3} - P_a)cos2wt + (Q_{a3} - Q_a)sin2wt - P_{a3}cos4wt - Q_{a3} \sin 4wt$$

$$p_{b3} = P_b + \left(P_{b3} + P_b - \sqrt{3}Q_b\right)cos2wt + (P_b\sqrt{3} + Q_{b3} - Q_b)sin2wt - (\sqrt{3}Q_{b3} - P_{b3})cos4wt + (Q_{b3} + P_b\sqrt{3})\sin 4wt$$

$$p_{c3} = P_c + \left(P_{c3} + P_c + \sqrt{3}Q_c\right)cos2wt + (P_c\sqrt{3} + Q_{c3} - Q_c)sin2wt - (\sqrt{3}Q_{c3} - P_{c3})cos4wt + (Q_{c3} + P_c\sqrt{3})\sin 4wt \qquad (5)$$

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

To find the reactive power we apply the Walsh function by multiplying equations (5) with the third order WF i.e. $Wal(3,t)$ and integrate over the period T. According to the Walsh functions all the integrals of the right hand side terms of equations (5) that involves the multipliers of $cos2wt$, $cos4wt$, $\sin 4wt$ and the constant P are all equal to zero. Hence;

$$\frac{1}{T}\int_0^T p_a\big(wal(3,t)\big)dt = \frac{1}{T}\int_0^T (Q_{a3} - Q_a)sin2wt\big(wal(3,t)\big)\,dt$$

$$\frac{1}{T}\int_0^T p_b\big(wal(3,t)\big)dt = \frac{1}{T}\int_0^T (P_b\sqrt{3} + Q_{b3} - Q_b)\,sin2wt\big(wal(3,t)\big)\,dt$$

$$\frac{1}{T}\int_0^T p_c\big(wal(3,t)\big)dt = \frac{1}{T}\int_0^T (P_c\sqrt{3} + Q_{c3} - Q_c)\,sin2wt\big(wal(3,t)\big)\,dt \qquad (6)$$

The product of the 3rd order WF by the $(Q_{a3} - Q_a)sin2wt$, $(P_b\sqrt{3} + Q_{b3} - Q_b)sin2wt$ and $(P_c\sqrt{3} + Q_{c3} - Q_c)sin2wt$ result in the full wave rectification of the terms.

$$\frac{1}{T}\int_0^T p_a\big(wal(3,t)\big)dt = \frac{1}{T}\int_0^T (Q_{a3} - Q_a)sin2wt\ dt$$

$$\frac{1}{T}\int_0^T p_b\big(wal(3,t)\big)dt = \frac{1}{T}\int_0^T (P_b\sqrt{3} + Q_{b3} - Q_b)\,sin2wt\ dt$$

$$\frac{1}{T}\int_0^T p_c\big(wal(3,t)\big)dt = \frac{1}{T}\int_0^T (P_c\sqrt{3} + Q_{c3} - Q_c)\,sin2wt\ dt \qquad (7)$$

Solving for Q_a, Q_b and Q_c respectively,

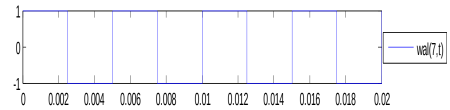
$$Q_a = -\frac{\pi}{2T}\int_0^T p_a\big(wal(3,t)\big)dt + Q_{a3}$$

$$Q_b = -\frac{\pi}{2T}\int_0^T p_b\big(wal(3,t)\big)dt + p_b\sqrt{3} + Q_{b3}$$

$$Q_c = -\frac{\pi}{2T}\int_0^T p_c\big(wal(3,t)\big)dt + p_c\sqrt{3} + Q_{c3} \qquad (8)$$

Q_{a3} , Q_{b3} and Q_{c3} are the reactive power components of the distortion power in the phases. It shows the influence of the third order current harmonics i_{a3} , i_{b3} and i_{c3} on the reactive power measurement algorithm. The final terms of equations (5) 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 of $4w$ which is similar to the oscillating frequency of the 7th order WF, $Wal(7,t)$ as can be seen in the figure 2.

(a)



(b)

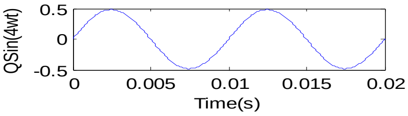


Figure 2: (a) 7th order Walsh function (b) Sin $4wt$ waveform

To estimate these distortions power terms we multiply the both sides of equation (5) by the 7th order WF and then integrate over the period T and simplify to obtain equation (9).

$$\frac{1}{T}\int_0^T p_a\left(Wal(7,t)\right)dt = -\frac{1}{T}\int_0^T Q_{a3}\ sin4wt\left(Wal(7,t)\right)dt$$

$$\frac{1}{T}\int_0^T p_b\left(Wal(7,t)\right)dt = \frac{1}{T}\int_0^T (Q_{b3}\ + P_b\sqrt{3})sin4wt\left(Wal(7,t)\right)dt$$

$$\frac{1}{T}\int_0^T p_c\left(Wal(7,t)\right)dt = \frac{1}{T}\int_0^T (Q_{c3} + P_c\sqrt{3})sin4wt\left(Wal(7,t)\right)dt \qquad (9)$$

The 7th order WF shown in the figure 2 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 rectification. So taking cognizance of these rectifying effects, equations (9) is written as in equation (10).

$$\frac{1}{T}\int_0^T p_a\left(wal(7,t)\right)dt = -\frac{1}{T}\int_0^T Q_{a3}\ sin4wt\ dt$$
$$\frac{1}{T}\int_0^T p_b\left(Wal(7,t)\right)dt = \frac{1}{T}\int_0^T (Q_{b3}\ + P_b\sqrt{3})sin4wt\ dt$$
$$\frac{1}{T}\int_0^T p_c\left(Wal(7,t)\right)dt = \frac{1}{T}\int_0^T (Q_{c3}\ + P_c\sqrt{3})sin4wt\ dt \qquad (10)$$

Solving for Q_{a3} , Q_{b3} and Q_{c3} respectively,

$$Q_{a3} = -\frac{\pi}{2T}\int_0^T p_a\left(wal(7,t)\right)dt$$

$$Q_{b3} = \frac{\pi}{2T}\int_0^T p_b\left(wal(7,t)\right)dt - P_b\sqrt{3}.$$

$$Q_{c3} = \frac{\pi}{2T}\int_0^T p_c\left(wal(7,t)\right)dt - P_c\sqrt{3}. \qquad (11)$$

Equation (11) is the Walsh function algorithm for measuring the distortion power in a three-phase load system. This distortion power occurs as a result of the effect of the reactive power resulting from the harmonic load condition.

Substituting in the equation (8)

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

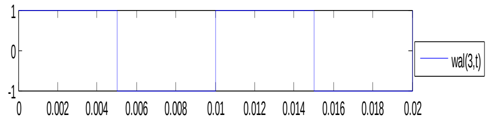
$$Q_b = \left[\int_0^T p_b\left(wal(3,t)\right)dt + \int_0^T p_b\left(wal(7,t)\right)dt\right]$$

$$Q_c = \left[\int_0^T p_c\left(wal(3,t)\right)dt + \int_0^T p_c\left(wal(7,t)\right)dt\right] \qquad (12)$$

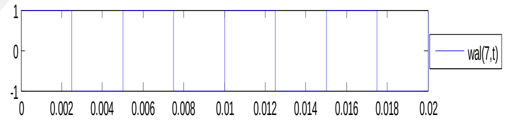
This algorithm eliminates the effect of the 3rd and 7th order harmonics on the reactive power measurement and also essentially reduced the effect of the higher order current harmonics. In other to overcome complex computation involved, the 3rd and 7th order Walsh function are added together which gives a new improved algorithm.

$$wal(3;7,t) = \frac{1}{2}\left(wal(3,t) + wal(7,t)\right)$$

(a)



(b)



(c)

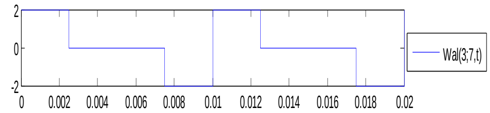


Figure 3: (a) $Wal(3,t)$, (b) $Wal(7,t)$
(c) $Wal(3;7,t)$

From Figure 3 it can be noticed that the proposed new Walsh function analytical graph as a result of the addition of standard 3rd and the 7th order WF is defined as $wal(3;7,t)$=

+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 proposed Walsh function is derived by multiplying equations (5), with $wal(3;7,t)$ and taking the integral over the period T. When done, the integrals after the equal sign, the first is a constant so is equal to zero because p_a , p_b and p_c are constants and the proposed Walsh function is a periodic function, 2nd and 4th integrals also equal to zero as they include cosine functions that are orthogonal with the proposed Walsh Function WF. The 3rd and 5th integrals comprise the rectification of the sin functions waveform, so these integrals are not equal to zero. They are written as in equations (13);

$$\frac{1}{T}\int_0^T \left(p_a wal(3;7,t)\right)dt = \frac{1}{T}\int_0^T \left(wal(3;7,t)\right)(Q_{a3} - Q_a)\ \sin 2wt\ dt - \frac{1}{T}\int_0^T wal(3;7,t)Q_{a3}\ sin4wt\ dt.$$

$$\frac{1}{T}\int_0^T \left(p_{b3} wal(3;7,t)\right)dt = \frac{1}{T}\int_0^T \left(wal(3;7,t)\right)(P_b\sqrt{3} + Q_{b3} - Q_b) sin2wt\ dt + \frac{1}{T}\int_0^T \left(wal(3;7,t)\right)(Q_{b3} + P_b\sqrt{3})\sin 4wt\ dt$$

$$\frac{1}{T}\int_0^T \left(p_{c3} wal(3;7,t)\right)dt = \frac{1}{T}\int_0^T \left(wal(3;7,t)\right)(P_c\sqrt{3} + Q_{c3} - Q_c) sin2wt\ dt + \frac{1}{T}\int_0^T \left(wal(3;7,t)\right)(Q_{c3} + P_c\sqrt{3})\sin 4wt\ dt \qquad (13)$$

Solving equations (13) and factorizing we obtain the new algorithm for measuring reactive power in sinusoidal and noise (harmonics) conditions as follow:

$$Q_{a,3,7} = -\frac{\pi}{T}\int_0^T p_a\left(wal(3;7,t)\right)dt$$
$$Q_{b,3,7} = -\frac{\pi}{T}\int_0^T p_b\left(wal(3;7,t)\right)dt + (p_b\sqrt{3} + Q_{b3})$$
$$Q_{c3,7} = -\frac{\pi}{T}\int_0^T p_c\left(wal(3;7,t)\right)dt + (p_c\sqrt{3} + Q_{c3}) \qquad (14)$$

Equations (14) above is the improved Walsh function algorithm that will measure the reactive power component in both sinusoidal and non-sinusoidal load system thereby eliminating the effect of harmonics in the three phase power measurement system. Suffice it to say that in actual cases only lower order harmonics are present in power system signal [22].

4. Modeling of the Proposed Algorithm for Power Measurement

Equations (11) and (14) are the proposed Walsh functions algorithm for measuring the reactive and distortion powers in a three-phase network. It is used to configure the model of the instrument for the measurement using the Matlab Simulink software tool.

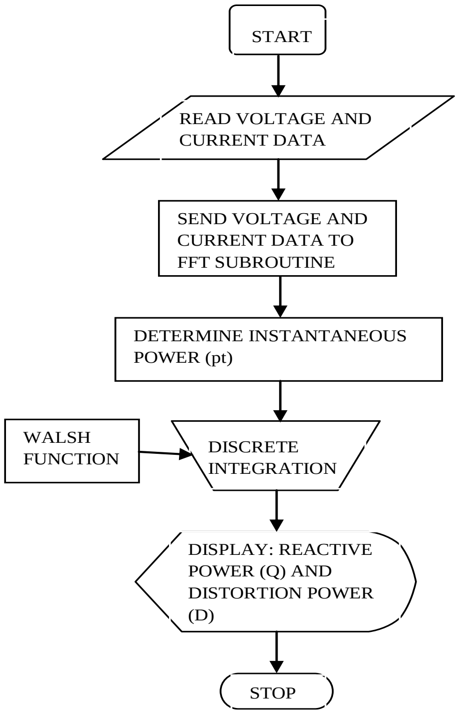


Figure 4: Flowchart for the implementation of the proposed Walsh function algorithm for reactive and distortion power measurement.

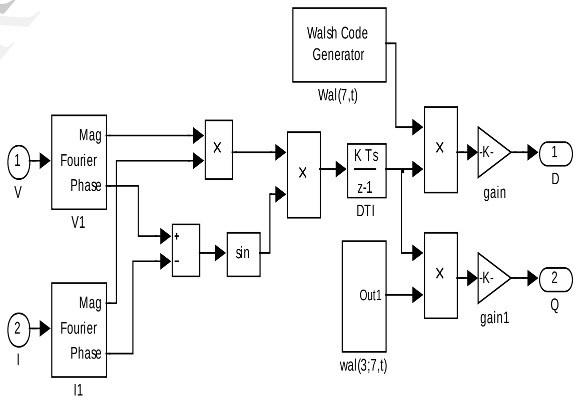


Figure 5: The model of the subsystems of the proposed measurement algorithm

4.1 Simulation of the Non-Harmonic load condition

For the purpose of this simulation the line to neutral voltages (V phases) were synthetically chosen as follows;

$Va = 50\llcorner 0°$, $Vb = 50\llcorner -120°$ and $Vc = 50\llcorner 120°$.

Two case studies 1 and 2 were considered as shown for linear sinusoidal unbalanced load system;

$Case\ 1$: $Z_a = 36 + j20\Omega$; $Z_b = 55 + j15\Omega$; $Z_c = 15 + j11\Omega$

$Case\ 2$: $Z_a = 25 + j20\Omega$; $Z_b = 17 + j60\Omega$; $Z_c = 18 + j38\Omega$

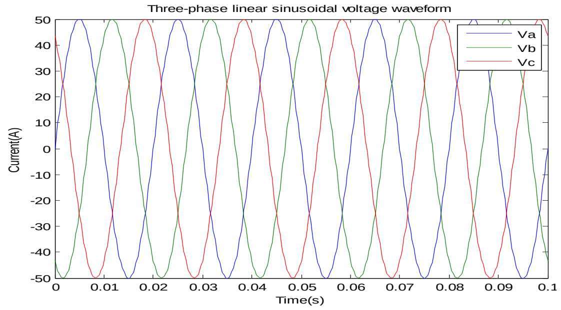


Figure 6: Three phase sinusoidal voltage waveform

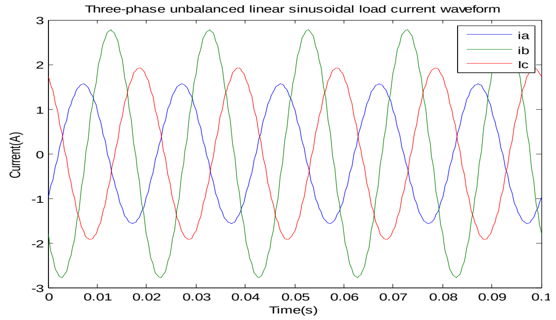


Figure 7: Three phase sinusoidal unbalance current waveform

Table 1: The result of case A

	Reactive Power Q (var)	Distortion Power D (var)
FFT Approach		
Phase a	569.5	285
Phase b	223.3	111.7
Phase c	1538.9	770
Total	**2331.7**	**1166.7**
Proposed Method		
Phase a	569.6	284.8
Phase b	223.8	112.0
Phase c	1539	769.5
Total	**2332.4**	**1165.2**

Table 2: The results of case B

	Reactive Power Q (var)	Distortion Power D (var)
FFT Approach		
Phase a	944.2	472
Phase b	762.8	381.9
Phase c	1039.8	520
Total	**2746.8**	**1373.9**
Proposed Method		
Phase a	944.5	472.2
Phase b	763.5	381.7
Phase c	1040.2	520.1
Total	**2731.4**	**1374.0**

The FFT analysis tool in Matlab Simulink tool analyzes and display the measured signal one phase at a time. Figure 8 shows the linear sinusoidal load waveform and the harmonic spectrum of one of the phases of the system under test and the same is applicable to the other two phases. Since it is a linear sinusoidal load system with no harmonic effect, the fundamental frequency becomes the only frequency, with no harmonic distortion as can be seen.

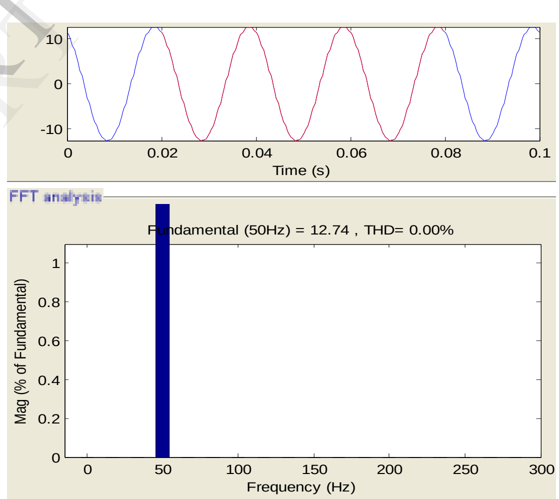


Figure 8: Linear sinusoidal load waveform and harmonic spectrum

From the simulation results shown in tables 1 and 2 it can be observed that the proposed algorithm practical validity is ascertained under linear sinusoidal unbalance load system. It accurately measures both the reactive and distortion powers of the system under test based on the linear sinusoidal unbalance load current conditions. The true values were determined using the IEEE standard 1459-2000 which is formulated using the fast Fourier transform approach for reactive and distortion powers measurement in AC circuits [23], while simulation of the model give the propose results for phase a, b and c respectively. A close looks at the results shows that the error or differences is negligible the result also shows the performance of the proposed algorithm over a wide variation of the unbalanced load conditions to be satisfactory.

4.2 Simulation of Harmonic Load Condition

Assuming that the fundamental voltage component is 50V sinusoidal and fundamental current component of 25A contaminated with a third order current harmonic of 10A that has time varying amplitude. The voltage component leads the current component by 40^o and the sampling frequency is 32 samples per 50Hz of fundamental frequency. The simulation is implemented for FFT with window of 10 cycles and the proposed Walsh function. The true values of the power component are computed using time domain formula. The FFT graphical user interface analyzes signal one phase at a time so the figure shown is for one of the phases and all other ones which are the same has been withheld for convenience, clarity and space.

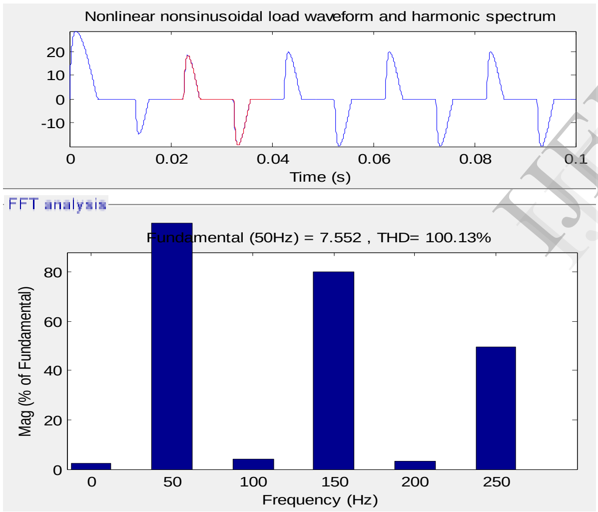


Figure 9: Nonlinear nonsinusoidal load waveform and harmonic spectrum.

Table 3: Nonlinear simulation result

	Reactive Power Q (var)	Distortion Power D (var)
Real Values		
Phase a	405.62	168.35
Phase b	521.35	127.20
Phase c	357.41	54.40
	1284.38	349.95
FFT Approach		
Phase a	400.72	166.30
Phase b	515.04	125.67
Phase c	353.11	53.74
Total	1268.87	**345.71**
Proposed Method		
Phase a	405.80	168.40
Phase b	521.50	127.50
Phase c	357.40	54.40
Total	**1284.70**	**350.30**

5. Conclusion

The results recorded from the simulations of the model using the IEEE standard 1459-2000 which is based on fast Fourier transform algorithm FFT have high accuracy rate when the load is linear sinusoidal with no harmonic effects, but shows significant error in an unstable nonsinusoidal harmonic load condition. On the other hand the proposed alternative algorithm using the Walsh function approach gives accurate measurement result both for the linear sinusoidal harmonic free scenario and the nonlinear nonsinusoidal load condition. This shows that the proposed algorithm has the potential to effectively measure reactive and distortion power components under different load conditions. The algorithm can be integrated into the circuitry of energy meter to improve on the efficiency and reliability of measurement reading.

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