Power system frequency control: instantaneous discrete testing for numerical relay using wavelet transform

Emad Awada[1], Akram Al-Mahrouk[2], Eyad Radwan[3], Tareq A. Alawneh[1], Aws Al-Qaisi[4]
[1]Department of Electrical Engineering, Faculty of Engineering Technology, Al-Balqa Applied University, Amman, Jordan
[2]Department of Electrical Engineering, Faculty of Engineering and Technology, Philadelphia University, Jerash, Jordan
[3]Department of Electrical Engineering, Faculty of Engineering and Technology, Applied Science Private University, Amman, Jordan
[4]Department of Electrical Engineering, College of Engineering and Technology, American University of the Middle East, Eqaila, Kuwait

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ABSTRACT

With today's advanced technology and rapidly growing energy demands, the reliability of electrical power systems has reached an important level. With extensive monitoring and protection, system issues like voltage drops, power irregularities, and frequency variations can have destructive consequences on the power network. Therefore, as frequency relays play a critical role in protecting power generators and load equipment from power frequency shifts, relays have evolved from electromechanical to solid-state devices with ongoing optimization to handle integrated modern networks. Traditional numerical relays use Fourier transform to identify frequency changes, which necessitates numerous data samples and has limitations with transient waveform data. To address these challenges, this work proposes a new relay algorithm based on instantaneous discrete testing and wavelet transform for frequency analysis, aimed at enhancing relay performance. This new approach demonstrates promising advantages, including significant reductions in data sample requirements, compilation complexity, decision-making time, and improved handling of transient waveforms.

Corresponding Author:

Emad Awada
Department of Electrical Engineering, Faculty of Engineering Technology, Al-Balqa Applied University
Amman 11134, Jordan
Email: emad.awada@bau.edu.jo

1. INTRODUCTION

Because of today's technology revolution, rapid population expansion, and the significant rise in energy consumption, demand for electrical power systems has increased. Therefore, as electrical power is essential in all daily tasks, the protection of power generation, distribution, and electrical load is one of the main tasks of the power company [1]–[3]. In accordance with IEEE Standard C37.106-2003 (R2009), for power generation plant abnormal frequency protection, IEEE Standard C37.117-2007 (guide for the application of protective relays used for abnormal frequency load shedding and restoration), and IEEE Standard C37.102-2006 (AC generator protection), the protective relay role is to trigger a system withdrawal from service when it experiences abnormality in a manner that could damage the network. When disruption occurs due to a large load added or taken off, the frequency of the grid may alter quickly due to the inertia presented in the grid. Therefore, it is vital to preserve the frequency of the grid within tolerable ranges, mainly in islanded mode. Therefore, utilizing frequency relays assists in continuing and stabilizing the frequency efficiently.

As protective relays were invented to offer the last line of defense in an electrical network, they can be one of the most vulnerable to power system disturbances [4]. Yet, due to power quality, improper relay operations may occur based on flawed input values [5]. Therefore, these protective devices have advanced significantly from electromechanical to solid-state devices to achieve the highest level of speed, accuracy, and reliability [6]. As power frequency variation occurs due to variance among power generation and load consumption, a growing number of power feeders (renewable resources) or a sudden increase in consumption load removal will lead to an unbalanced power system frequency with an over-frequency phenomenal [7]. On the other hand, as the power system experiences heavy load effects or losses from other generating sources, an under-frequency phenomenon will be observed. In either case, power generators are protected by the prime mover speed governor. In fact, an accurate frequency estimation is very essential for correct phasor assessment where a frequency error creates a phasor fault and causes failure in frequency detection, which leads to failure in protection and control functions. In case of failure and due to the compilation of power sources, distributed generation, and renewable energy sources connected to the power grid, an active guard such as a frequency relay must accurately perform to isolate the power system in case of frequency deviation beyond the tolerated limit and prevent a blackout by islanding [8]. Several papers have focused on the approaches and design of frequency relays to enhance fault detection.

Numerical relays revolve around power system protection and control to provide advanced reliability in [9]. However, as in [3], [10], [11], continuous monitoring is required over a long period. That is, as many power failures may occur in microseconds to hours, a large amount of data will be collected, stored, compiled, and transmitted to the circuit breaker. It was suggested to adjust the fault threshold at which disturbances occur to prevent relay memory overload and expedite response time in [10]. Yet, as power systems continuously expand in size and configuration and a variety of input resources are attached to the overall power system, such as photovoltaics and windmills, protection devices must be optimized to handle the massive effect of potential frequency changes. On the other hand, in [12]–[17], the microgrid was proposed as a promising structure to advance fault performance. Yet, as microgrids scaled for small distribution and load systems, large-scale distribution networks could not be implemented as a result of technical difficulty and were extremely expensive [15], [18]. It was proposed to set a shedding predetermine load as a frequency drop under a threshold called under frequency load shedding (UFSL) in [19]. However, such a technique may lead to the destruction of power plants (turbines and generators) since auxiliaries cannot sustain such a low frequency [19]–[21]. While other works had a focus on islanding detection using the phase-space technique [22]–[24], some works proposed algorithms by fuzzy logic to detect UFLS [25]. Yet, as these solutions can be applied to improve network frequency stability, blackouts are still subject to occurrence [18]. Therefore, early detection of power network frequency deviation could give the best indication of power system conduct and determine the best action. However, these strategies have shown limitations based on relay conventional algorithms due to dynamic transient waveform changes and a large number of analyzed data samples [3]. As a result, a massive storage area is required, and complicated algorithms are used. Meanwhile, this paper will discuss the further enhancement that can be made to the numerical frequency algorithm to improve response time, precision measurement, and compiling process by implementing a new analysis algorithm and increasing fault detection.

This work uses the discrete wavelet transform (DWT) to improve the performance of modern numerical relays. This technique will allow for the analysis of frequency components before numerical relay computation. By eliminating noise interference and reducing computational processes, unexpected changes in the waveform frequency data can be detected. Numerous DWTs will be considered in distinct operating to define the dependability of the system in extracting and characterizing power system frequency faults. The proposed technique exploits the special capabilities of the wavelet transform’s decomposition, dilation, filtering, and translation into the power frequency analysis [26]–[30]. As an ultimate goal, this approach will facilitate a faster, simpler, and more efficient power frequency fault detection algorithm, embedded into a digital power frequency relay to differentiate between normal and faulty conditions for instantaneous testing without changing relay settings.

2. POWER SYSTEM FREQUENCY EFFECT AND PROTECTION MODEL

As power system frequency control allows the flow of generated power waveforms by numerous generators, system frequency could be subject to variations due to load and generator mismatches [31]. That is, in the event of generator failure, severe overload demands will occur, driving the power line system frequency to drop, as illustrated in Figure 1. Meanwhile, in the event of an unexpected load drop, a rise in power system frequency will result, as shown in Figure 2.

Therefore, in either case, frequency parameters are the main element in power system classification [32], where the characterization of the power system must be maintained within a predefined frequency level. As frequency variations occur in the power system, a severe failure could arise on the generation, distribution, and consumer sides. The effect of frequency variation can be drastic in both long-term and instantaneous consequences. That is, on the load side, the apparatus is designed to work at a standard frequency (50 Hz or 60 Hz) for safety. As frequencies distort, the effectiveness and life span of apparatus and electrical power cables will decline. While frequency spikes will lead to cable insulation damage and catastrophic motor speed, frequency drops cause transformers and motors to overload and have a high potential for short circuits over some time.

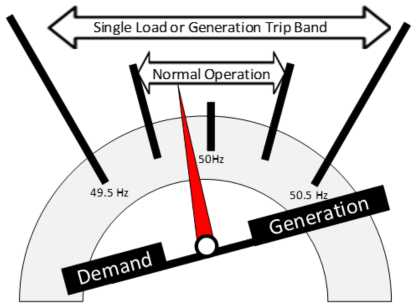

Figure 1. Frequency drop due to severe overload demands

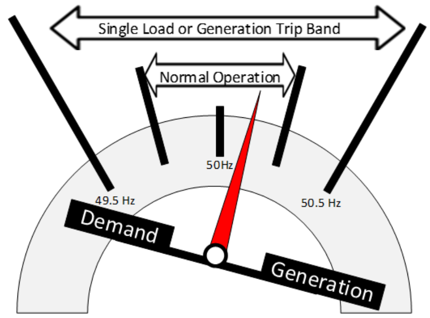

Figure 2. Frequency rise in power system

3. FREQUENCY RELAY

To maintain a healthy power system, any deviation in system frequency must be detected as a sign of an imbalance between load and generation. However, due to the rise of power generation by renewable energy sources such as wind, solar, and water flow, the distribution system is now subject to frequency alteration due to various intermittent inputs [1], [2], [33]. As a result, frequency relays play a critical role in sensing power system frequency alteration and initiating load shedding to preserve and restore balance to parts of the network in cases of under-frequency phenomena or disconnecting generators in cases of over-frequency. As frequency is defined as a number of recurrences over a precise period, the power system frequency is the number of completed voltage or current signals series per second. However, as in conventional synchronous generator power systems, the power frequency source is regularly based on the synchronous generator rotation speed as in (1):

$$f_e = f_m \times \frac{p}{2} \tag{1}$$

where f_e is electrical frequency (voltage/current signal frequency); f_m is mechanical frequency; and P is number of poles.

Yet, with the rapid increase of renewable energy generation and transient dynamics, power grids must be maintained in steady operation despite the potential variations in frequency that can cause network failure [34]. Renewable integration influences grow into substantial stability issues at larger size penetrations [35], [36]. Therefore, conventional frequency relays based on the performance of conventional transmission systems need to be replaced with digital relays, as frequency rapid changes are likely. Since numerical power relays rely on digital analysis using frequency measurement algorithms, analog power waveforms are converted into numerical data for processing. This involves steps like digitization (via an analog-to-digital converter), relay algorithm processing, and digital output based on pre-set thresholds [18], [30], as illustrated in Figure 3.

Generally, as the fundamental frequency of a power network is predefined as 50 Hz or 60 Hz (based on the network configuration), the main role of the frequency relay is to define and detect the network emergency condition. However, to detect power system frequency dynamic changes, a relative frequency deviation (RFD) for instantaneous frequency is applied to measure the difference between the fundamental frequency f_n and the system frequency f_s, and in (2):

$$RFD = \frac{\Delta f}{f_n} = \frac{f_s - f_n}{f_n} \quad (2)$$

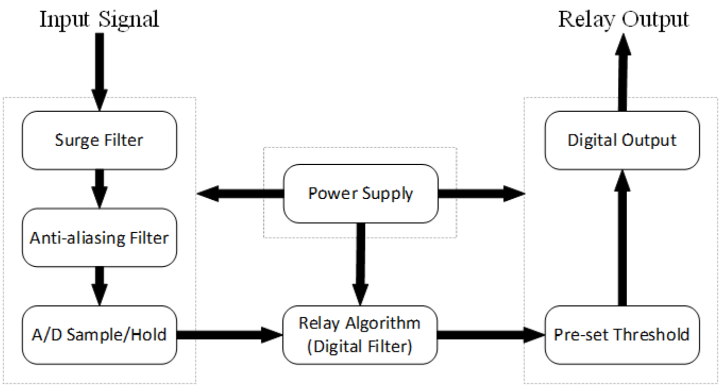

Figure 3. Numerical frequency relay work scheme

The analyzed output waveform provides essential information about the system's condition when frequency components deviate from the nominal value. Since certain frequency variations are permissible, the numerical relay algorithm must assess the waveform, quantify deviations from the nominal frequency, and meet specific requirements to stabilize the power system and operate within predefined limits.

4. WAVELET TRANSFORM VS FOURIER TRANSFORM

In power systems, one of the key elements to maintaining a healthy system provider is maintaining power frequency at a fixed frequency rate. That is, as two major systems worldwide, 50 and 60 Hz, are used with an allowable deviation of ±0.05%, power frequency must be constantly analyzed to detect allowable deviation and cut off the power supply in case of harmful frequency alteration. In classical frequency analysis, the Fourier transform is a powerful means to characterize waveforms based on the transformation of time-based domains into frequency pattern domains [15], [37], as shown in Figure 4.

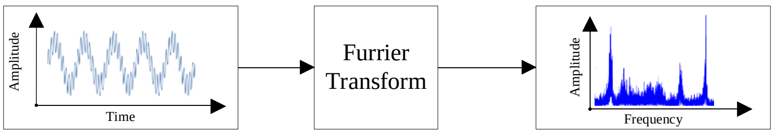

Figure 4. Fourier transform algorithm from time to frequency domain

Yet, a major drawback can be identified as the waveform time characteristic disappearing [28], [29], [31], [32]. As a result, frequency domain analysis prevents distinguishing frequency change time occurrences [33]. For a stationary signal with a constant frequency, the Fourier transform has shown great analysis. However, in transitory frequency changes, the Fourier analysis will lose its ability to spot frequency data changes [33], [38]. Therefore, in this work, a new algorithm of wavelet transform is proposed to analyze power frequency in a numerical relay. With special parameters and mathematical functions based on mother wavelet as in (3):

$$\psi(t) = |a|\psi\left\{\frac{t-\tau}{a}\right\} \quad (3)$$

Wavelets have two distinctive features dilation and translation that allow for adjustable window analysis of waveform frequency components at various scales. This enables the development of data mining models and the extraction of transient information, as illustrated in Figure 5.

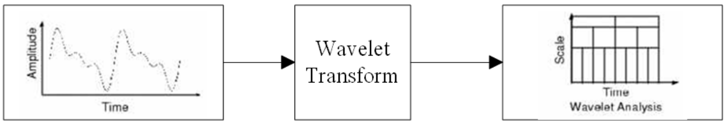

Figure 5. Wavelet transform analysis in time and frequency

With a mean value of zero, a numerous wavelet can be extracted from a specific mother wavelet ψ as a tool for better window analysis fit and characterization in time and frequency domains. In addition, the wavelet transform is compiled as a bank of filters. While low-pass filters extract the approximation coefficients of the waveform, high-pass filters convey the details of the coefficients to present waveform data in numerous frequency components at diverse resolutions [30], [33], as shown in Figure 6.

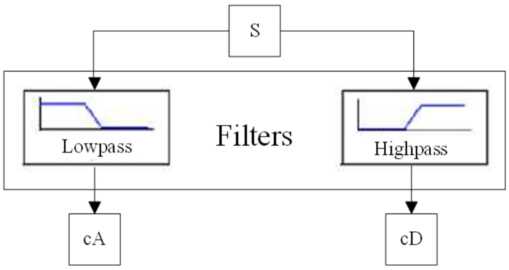

Figure 6. Wavelet high and low pass filtering process

The wavelet transform enables frequency analysis by breaking down the waveform into two meaningful sets of data samples, each representing half of the decomposed waveform. This process can be repeated across multiple levels of decomposition while preserving the waveform's energy [28], [29], [31]–[33], [38], as shown in Figure 7.

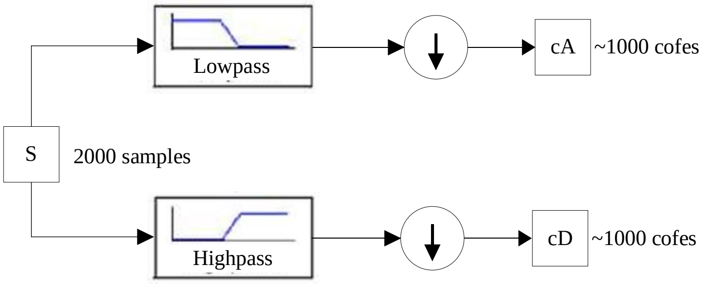

Figure 7. Wavelet decomposition process into half the waveform in each decimation level

As a result, with the wavelet special property of data decomposition, an instantaneous power frequency step was interleaved as in (4), and special banks of filtering for approximation and details coefficients provided scaling and decomposition as in (5).

$$f \cong (\mathrm{I},|w[1]|,\mathrm{I},|w[2]|,\ldots,\mathrm{I},|w[n]|\ldots) \quad (4)$$

$$\begin{bmatrix} \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & & & \\ \frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} & & & \\ & & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \\ & & \frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} & \\ & & & & \ddots \\ & & & & \end{bmatrix} * f = \begin{bmatrix} \frac{\sqrt{2}}{2}(I+|w(1)|) \\ \frac{\sqrt{2}}{2}(I-|w(1)|) \\ \frac{\sqrt{2}}{2}(I+|w(2)|) \\ \frac{\sqrt{2}}{2}(I-|w(2)|) \\ \vdots \end{bmatrix} \Rightarrow \begin{bmatrix} \frac{\sqrt{2}}{2}(I+|w(1)|) \\ \frac{\sqrt{2}}{2}(I+|w(2)|) \\ \vdots \\ \frac{\sqrt{2}}{2}(I-|w(1)|) \\ \frac{\sqrt{2}}{2}(I-|w(2)|) \\ \vdots \end{bmatrix} \quad (5)$$

By obtaining low pass coefficients [$\frac{\sqrt{2}}{2}(A-|w(1)|), \frac{\sqrt{2}}{2}(A-|w(2)|), \cdots, \frac{\sqrt{2}}{2}(A-|w(n)|)$], the decision to trigger the circuit breaker was based on coefficients acceding to a predetermined frequency step threshold for a wavelet. The predetermined threshold values were based on actual waveform maximum and minimum data coefficients at a range of frequency steps for a specific wavelet. Yet, as an orthogonal wavelet with compact support preserves energy, decimated integers are obtained in multiples of the DWT scale [28], [29], [31]–[33], [38]. As a result, in this study, the original waveform was decimated to 1,477 data samples in the first decomposition level and 738 samples in the second level. As shown in Tables 1 to 3, for this case study, wavelet coefficients for a range of frequencies step within the tolerated frequency of 49.5–50.5 Hz and beyond for the Daubechies, Haar, and Coiflets.

Table 1. Daubechie12 wavelet coefficients analysis for a range of frequencies 48.8-51.2 Hz

Phase A												
Over frequency-hertz	50.1	50.2	50.3	50.4	50.5	50.6	50.7	50.8	50.9	51.0	51.1	51.2
Maximum frequency step	364.76	695.22	962.51	1239.70	1288.70	1346.50	1413.50	1416.20	1422.10	1439.70	1425.10	1459.20
Under frequency-hertz	49.9	49.8	49.7	49.6	49.5	49.4	49.3	49.2	49.1	49.0	48.9	48.8
Minimum frequency step	-367.83	-689.68	-936.48	-1223.10	-1321.10	-1406.20	-1439.10	-1440.10	-1438.70	-145.00	-1429.10	-1441.10
Phase B												
Over frequency-hertz	50.1	50.2	50.3	50.4	50.5	50.6	50.7	50.8	50.9	51.0	51.1	51.2
Maximum frequency step	366.93	648.51	952.17	1213.30	1294.70	1325.40	1449.00	1448.80	1469.40	1445.20	1426.50	1435.50
Under frequency-hertz	49.9	49.8	49.7	49.6	49.5	49.4	49.3	49.2	49.1	49.0	48.9	48.8
Minimum frequency step	-337.66	-635.02	-1004.10	-1271.60	-1355.40	-1432.20	-1451.60	-1451.70	-1428.90	-1443.90	-1438.20	-1447.20
Phase C												
Over frequency-hertz	50.1	50.2	50.3	50.4	50.5	50.6	50.7	50.8	50.9	51.0	51.1	51.2
Maximum frequency step	368.06	715.89	980.54	1211.60	1271.90	1321.50	1407.40	1452.80	1462.00	1444.40	1447.70	1445.40
Under frequency-hertz	49.9	49.8	49.7	49.6	49.5	49.4	49.3	49.2	49.1	49.0	48.9	48.8
Minimum frequency step	-372.23	-672.53	-958.27	-1265.80	-1345.90	-1433.60	-1441.00	-1447.80	-1463.80	-1451.40	-1432.90	-1449.20

Table 2. Coif5 wavelet coefficients analysis for a range of frequencies 48.8-51.2 Hz

Phase A												
Over frequency-hertz	50.1	50.2	50.3	50.4	50.5	50.6	50.7	50.8	50.9	51.0	51.1	51.2
Maximum frequency step	319.95	599.84	864.76	1100.90	1233.30	1299.90	1282.50	1256.60	1249.90	1264.40	1256.90	1245.50
Under frequency-hertz	49.9	49.8	49.7	49.6	49.5	49.4	49.3	49.2	49.1	49.0	48.9	48.8
Minimum frequency step	-322.21	-610.02	-869.08	-1102.00	-1228.10	-1237.50	-1236.30	-1245.00	-1245.00	-1245.60	-1239.10	-1235.10
Phase B												
Over frequency-hertz	50.1	50.2	50.3	50.4	50.5	50.6	50.7	50.8	50.9	51.0	51.1	51.2
Maximum frequency step	319.95	599.84	864.76	1100.90	1233.30	1299.90	1282.50	1256.60	1249.90	1254.40	1256.90	1245.50
Under frequency-hertz	49.9	49.8	49.7	49.6	49.5	49.4	49.3	49.2	49.1	49.0	48.9	48.8
Minimum frequency step	-322.21	-610.02	-869.08	-1102.00	-1228.10	-1237.50	-1236.30	-1245.00	-1245.00	-1245.60	-1233.10	-1239.10
Phase C												
Over frequency-hertz	50.1	50.2	50.3	50.4	50.5	50.6	50.7	50.8	50.9	51.0	51.1	51.2
Maximum frequency step	322.25	609.53	865.30	1098.40	1234.80	1274.90	1257.30	1251.50	1253.00	1250.30	1252.30	1274.90
Under frequency-hertz	49.9	49.8	49.7	49.6	49.5	49.4	49.3	49.2	49.1	49.0	48.9	48.8
Minimum frequency step	-320.68	-602.97	-869.12	-1101.00	-1235.30	-1264.10	-1253.60	-1241.00	-1237.10	-1246.30	-1236.40	-1236.90

Table 3. Coeflit wavelet coefficients analysis for a range of frequencies 48.8-51.2 Hz

Phase A												
Over frequency-hertz	50.1	50.2	50.3	50.4	50.5	50.6	50.7	50.8	50.9	51.0	51.1	51.2
Maximum frequency step	326.95	623.74	886.28	1145.00	1287.90	1339.00	1339.90	1325.40	1358.50	1311.60	1302.70	1309.60
Under frequency-hertz	49.9	49.8	49.7	49.6	49.5	49.4	49.3	49.2	49.1	49.0	48.9	48.8
Minimum frequency step	-339.97	-653.06	-896.46	-1130.50	-1268.40	-1326.50	-1306.40	-1324.50	-1319.10	-1298.20	-1274.70	-1306.00
Phase B												
Over frequency-hertz	50.1	50.2	50.3	50.4	50.5	50.6	50.7	50.8	50.9	51.0	51.1	51.2
Maximum frequency step	330.99	619.23	891.26	1130.80	1290.30	1336.40	1301.40	1333.90	1331.30	1308.40	1313.80	1323.80
Under frequency-hertz	49.9	49.8	49.7	49.6	49.5	49.4	49.3	49.2	49.1	49.0	48.9	48.8
Minimum frequency step	-336.40	-615.85	-894.42	-1162.70	-1277.80	-1298.80	-1294.60	-1307.60	-1281.60	-1271.10	-1288.20	-1287.90
Phase C												
Over frequency-hertz	50.1	50.2	50.3	50.4	50.5	50.6	50.7	50.8	50.9	51.0	51.1	51.2
Maximum frequency step	338.72	649.98	904.08	1161.60	1301.10	1325.00	1332.40	1301.70	1308.10	1321.80	1328.70	1315.70
Under frequency-hertz	49.9	49.8	49.7	49.6	49.5	49.4	49.3	49.2	49.1	49.0	48.9	48.8
Minimum frequency step	-334.22	-645.38	-917.63	-1149.70	-1280.40	-1322.20	-1311.30	-1307.30	-1322.30	-1333.20	-1297.20	-1287.40

5. SIMULATIONS AND RESULTS

In this work study, a power system was simulated in MATLAB/Simulink to mimic a real-time numerical frequency (over-frequency or under-frequency) relay. Power frequency scenarios were simulated in real-life circumstances to test the performance of the new measurement algorithm. The scenarios were well considered within the tolerated frequencies and beyond to observe the implications and performance of both the conventional Fourier frequency measurement algorithm and the new proposed DWT measurement algorithm. Consequently, the performance and the control actions of the digital frequency relay were compared under the prospective frequency changes and tolerated margins.

As intended for this relay, the circuit breaker will trip the power system based on frequency relay detection for frequency deviations beyond the tolerated limit. A conventional frequency relay based on the Fourier transform was used to compare performance with the new proposed DWT-based relay. The operation and output for both relays were compared in terms of required data sample analysis, relay compiling duration, accuracy performance, and relay decision time in triggering the power system circuit breaker, as shown in Figure 8.

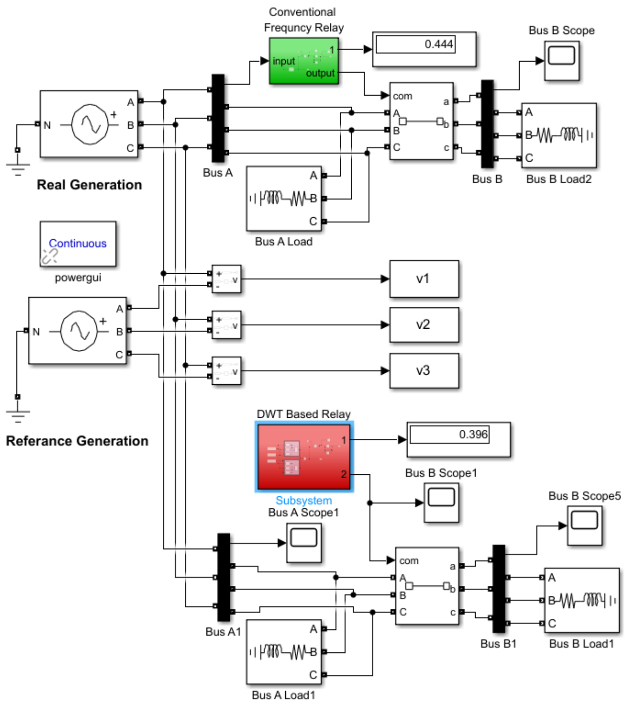

Figure 8. System setup for instantaneous numerical frequency relay testing

As the three phases of the power waveform were examined for frequency alteration, the subject data was filtered and analyzed by the wavelet algorithm. Decomposed waveform and coefficients were extracted and compiled to determine RFD by maximum alteration as in Figure 9.

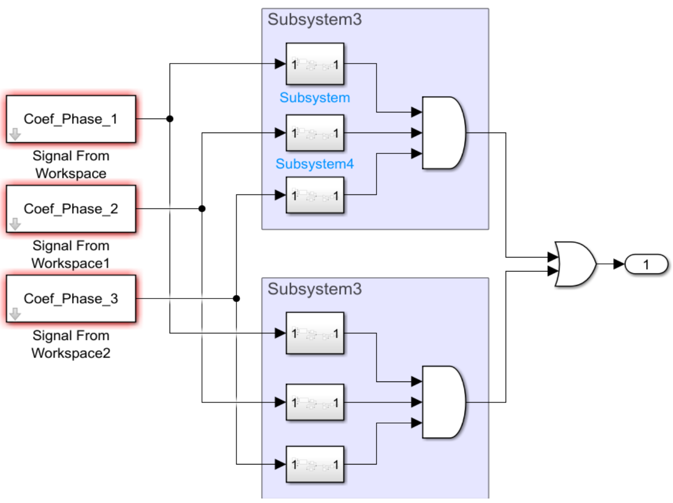

Figure 9. Wavelet coefficients extraction and compiling process

Meanwhile, a pre-determined threshold of maximum and minimum values for numerous frequencies under test was obtained. For instance, in Tables 1 to 3, testing was performed for power frequencies ranging from 48.8 to 51.2 Hz to cover frequency alteration within and outside the tolerated limit using three types of mother wavelet. As the maximum and minimum values for wavelet coefficient were determined for the tolerated frequency alteration, a pre-set threshold was embedded into the new proposed relay setting. As a result, the numerical power relay activates the circuit breaker based on frequency changes beyond the allowable limit, as shown in Figures 10 and 11, for over-frequency and under-frequency system disconnects.

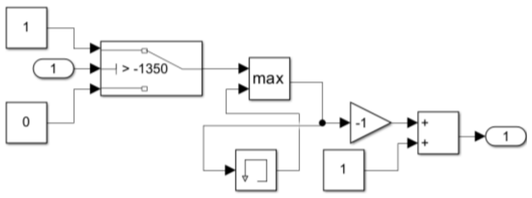

Figure 10. Over-frequency system disconnect algorithm

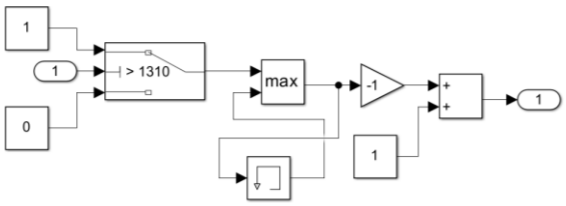

Figure 11. Under-frequency system disconnect algorithm

6. DISCUSSION

In the overall simulation testing, as shown in Figure 8, both algorithms of the Fourier transform and wavelet were examined for power frequency relays in a 50 Hz network. As allowable ±0.05% frequency deviation, both algorithms have allowed power waveforms with frequencies up to 50.5 Hz and down to 49.5 Hz, as in Figure 12. However, waveforms that exceeded the frequency tolerated margins (50.6 Hz and above and 49.6 Hz and below) were disconnected based on both measurement algorithms, as shown in Figure 13.

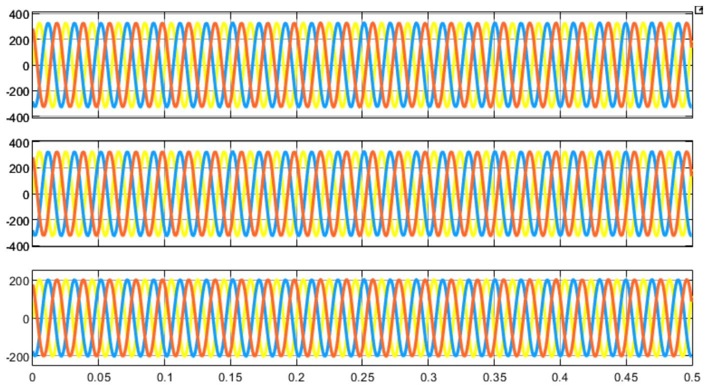

Figure 12. No fault frequency waveform (allowable ±0.05% frequency deviation)

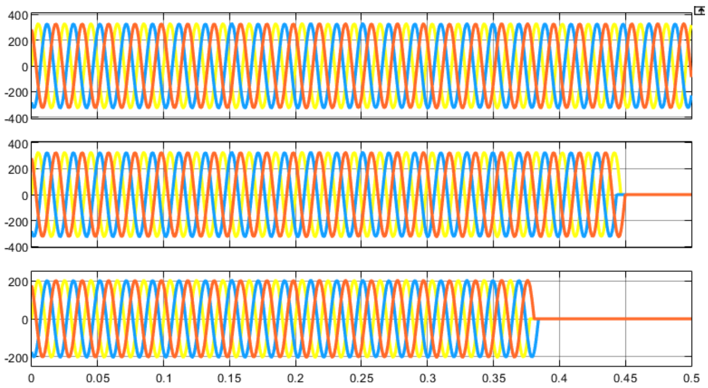

Figure 13. Faulted frequency system disconnect algorithm (exceeding frequency tolerance)

However, as illustrated in Table 4, relay response time was measured based on cut-off frequencies. While an average response time of 0.424 sec for the conventional Fourier measurement algorithm relay, an average of 0.317 sec was defined for the wavelet measurement algorithm relay. That is, a reduction of 25% in relay response was observed to improve the operation of the numerical frequency relay and the reliability of the power network.

Table 4. Power frequency relay response time

Over frequency (Hz)	Fourier method (time in sec.)	Wavelete method (time in sec.)	Under frequency (Hz)	Fourier method (time in sec.)	Wavelete method (time in sec.)
50.6	0.425	0.396	49.4	0.444	0.387
50.7	0.426	0.375	49.3	0.442	0.3538
50.8	0.425	0.35	49.2	0.442	0.3096
50.9	0.424	0.291	49.1	0.4427	0.329
51.0	0.424	0.295	49.0	0.4417	0.307
51.1	0.424	0.2595	48.9	0.442	0.2707
51.2	0.424	0.253	48.8	0.4427	0.2513

In contrast, while the Fourier transform algorithm captured and analyzed 2,866 data samples. Only 733 samples were required for wavelet analysis. As illustrated in Figures 14 and 15 for Fourier and wavelet methods, respectively.

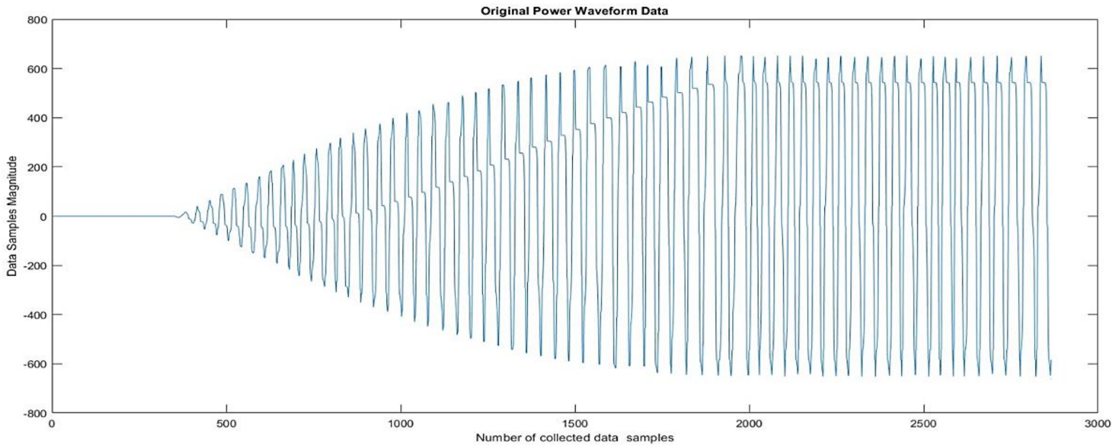

Figure 14 Original power waveform used by Fourier transform

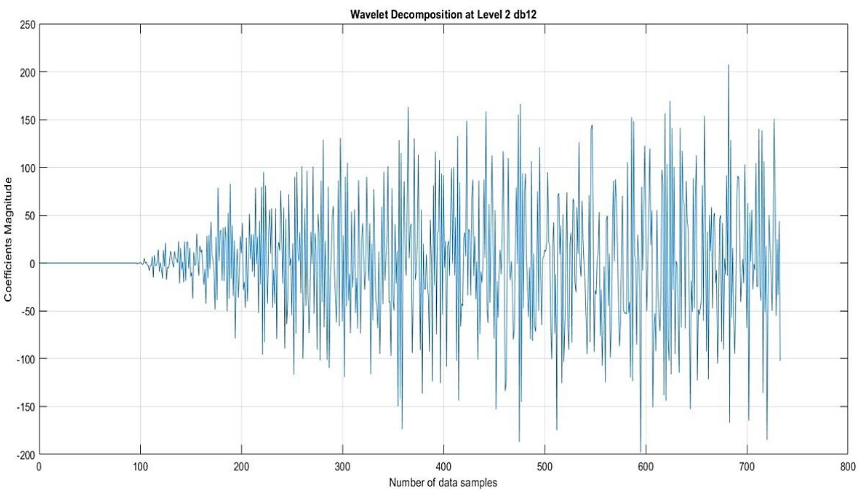

Figure 15. Wavelet decomposed power waveform

7. CONCLUSION

As power generation and load demands suffer an unbalanced phenomenon, the power system will undergo frequency instability, develop unsound operation, and may lead to a blackout. For reliable operation, many researchers have investigated the enhancement of digital power relays, as they have better performance, accuracy, and response time for abnormalities. Therefore, in this work study, a power system was simulated in MATLAB/Simulink with frequency instability to test the digital frequency relay performance with the new proposed algorithm and compare results with classical analysis algorithms. In this test, the proposed algorithm of wavelet transform detection and analysis was tested for the tolerated frequency changes (49.5–50.5 Hz) to ensure the continuity of the power network and conclusive of DWT relaying algorithm decisions. Meanwhile, the testing was performed outside the allowable limits of frequency variation to measure accuracy, response time, and the discontinuity of the power network to bring the system frequency back to normal operation. As a result, the new proposed testing algorithm has shown an advanced frequency relay operation in terms of accuracy detection, less compiling samples, and a 25 % reduction in time response.

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BIOGRAPHIES OF AUTHORS

Emad Awada received the B.S., M.S., and Ph.D. degrees in Electrical Engineering from Prairie View A&M University (PVAMU), USA, in 1998, 2006, and 2011 respectively. His work experiences were in the fields of electrical power, energy, and signal processing. He is currently an Associate Professor at the Department of Electrical Engineering, Al-Balqa Applied University, Jordan. His research interests include power systems, renewable energy, energy conservation, mixed-signal systems, signal processing, and power fault detection. He can be contacted at email: emad.awada@bau.edu.jo.

Akram Al-Mahrouk an Assistant Professor at Philadelphia University. He completed his Ph.D. in Electrical Engineering at Universiti Putra Malaysia in 2020, following his B.Sc. and M.Sc. degrees in Electrical Engineering from Al-Balqa Applied University and Princess Sumaya University for Technology in 2013 and 2016, respectively. His research interests encompass power electronics, optimal control of discrete systems, and renewable energy integration into power systems. He has contributed articles to various peer-reviewed journals and conferences, including IEEE and IREE, and holds patents. His current research focuses on electric vehicles and optimizing operational systems. He can be contacted at email: aalmahrouk@philadelphia.edu.jo.

Eyad Radwan completed his BSc. from JUST in 1996, MSc. and Ph.D. from UPM (Malaysia) in 1999 and 2004 respectively. From 1999 till 2011 he was with UCSI University and served as the Dean of the Faculty of Engineering & Built Environment from 2007 to 2009, and as Chief Operating Officer from 2009 to 2011. He joined the Department of Electrical Engineering at the Applied Science Private University, Jordan in 2012. His specialization is in the area of electrical power, drives, and control. He can be contacted at email: e_redwan@asu.edu.jo.

Tareq A. Alawneh received the B.S. and M.S. degrees in computer engineering from the Jordan University of Science and Technology (JUST), Irbid, in 2006 and 2009, respectively, and the Ph.D. degree in computer engineering from the University of Hertfordshire, U.K., in 2021. He is currently an Assistant Professor at the Electrical Department, at Al-Balqa Applied University. His research interests include cache partitioning algorithms, low-power and high-performance designs, Dynamic random-access memory (DRAM) and cache memories, multi-core systems, IoT, deep and machine learning, Chip multiprocessors (CMPs) systems, image processing, algorithms, network security, computer networks, and embedded systems. He can be contacted at email: tareq.alawneh@bau.edu.jo.

Aws Al-Qaisi received the M.Sc. and Ph.D. degrees in Communication and Signal Processing from Newcastle University, in 2006 and 2010, respectively. He is currently a Professor at the Electrical Engineering Department, College of Engineering and Technology, American University of the Middle East, Kuwait. His research interests include feature extraction, artificial intelligence algorithms and transformations, and digital communication. He is a member of the IEEE Executive Committee in Jordan, responsible for the industrial section. He served as a reviewer for many international journals, where he has published more than 25 scientific articles in the field of communication and signal processing. He can be contacted at email: Aws.Al-Qaisi@aum.edu.kw.