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LOCATING TRANSIENT DISTURBANCE SOURCE USING COMPLEX WAVELETS

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Abstract. This paper presents the application of complex wavelet energy for locating the source of a transient disturbance. By using the complex wavelet transform, the current and voltage at the monitoring point are decomposed into its real and imaginary parts. The transient power based on complex wavelets at the monitoring point is then calculated and the complex wavelet energy is obtained by integrating the transient power. The wavelet energy of a transient disturbance is plotted against time in which, the transient source location is determined by examining the gradient of the wavelet energy. From the wavelet energy plots, it can be concluded that a negative gradient of wavelet energy indicates that the transient source is downstream or in front of the monitoring point. On the other hand, a positive gradient of wavelet energy of the transient source indicates that the transient source is upstream or behind the monitoring point. To verify the wavelet energy method, simulations using the PSCAD/EMTDC software have been performed. Switching of capacitors has been simulated for generating the oscillatory transient of a power distribution system. Simulation results prove that the complex wavelet energy is capable of correctly locating the transient source in a power distribution system.

Keywords: Power quality, transient, complex wavelet transform

Abstrak. Kertas kerja ini membentangkan penggunaan tenaga berasaskan anak gelombang kompleks untuk menentukan lokasi punca gangguan fana. Dengan menggunakan anak gelombang kompleks, arus dan voltan di titik pengawasan dapat diuraikan ke bahagian nyata dan khayalannya. Kuasa fana berasaskan anak gelombang kompleks di titik pengawasan dikira dan hasil dari kamiran, tenaga anak gelombang kompleks diperolehi. Tenaga anak gelombang kompleks diplot melawan masa dan lokasi punca gangguan fana diperoleh berasaskan kecerunan graf tenaga anak gelombang tersebut. Melalui graf tenaga anak gelombang melawan masa, kecerunan negatif menunjukkan bahawa lokasi punca gangguan fana adalah berada sebelum titik pengawasan. Simulasi gangguan fana telah dilakukan dengan menggunakan perisian PSCAD/EMTDC. Hasil dari simulasi ini, data-data voltan dan arus diperoleh di titik pengawasan. Kejadian fana berayun diperlakukan melalui pensuisan pemuat di dalam sistem agihan kuasa ujian. Keputusan simulasi telah membuktikan bahawa kaedah tenaga anak gelombang kompleks berkeupayaan menentukan lokasi punca gangguan fana dalam sistem agihan kuasa dengan betul.

Kata kunci: Kualiti kuasa, fana, anak gelombang kompleks

1.0 INTRODUCTION

In recent years, many efforts have been made to detect, classify, and characterize power quality disturbances such as harmonic, voltage sag, and transients [1, 2].

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However, not much work has been done to locate these disturbances as to where the disturbances originate. The requirement to locate power quality disturbances becomes more important today before any disturbance mitigation technique is done to eliminate the disturbance. The other advantage of locating the source of power quality disturbance is that any disputes among the major responsibility party can be resolved fairly. This paper is focused on transient voltage disturbance, as it may be considered as the second major power quality disturbances after voltage sag because it frequently occurs in power system networks.

Transient voltage is a common disturbance that is caused by capacitor switching, lightning and generated by some power electronic device when they are switched on. Capacitor switching events can have negative impacts on power quality, such as tripping of drives, halting of production processes, a high over-voltage on a transformer, excite circuit resonance, creating transient voltage magnification in the secondary network and causing problems with sensitive electronic equipment at customer facilities.

Signal processing techniques which employ time-frequency and wavelet analyses have been applied widely for transient disturbance analysis. Time frequency analysis has been popular in the analysis of transient disturbance signal analysis as it can provide localized time scale information. Thus, time-frequency technique has been employed to detect transient disturbances due to capacitor switching [3].

An analysis for locating transient source disturbance is found in [4] which employed the disturbance power (DP) and disturbance energy (DE) to determine which side of a recording device the transient originates. The principle of the DP and DE indicators is based on the concept that active power tends to flow away from a nonlinear load [4] and that the directions of the DE as well as the DP flows are used to locate a transient source. The disadvantage of the method is that it relies on the degree of confidence of both the DP and DE. In [5], two other indicators have been introduced for transient source location which is also based on the waveforms of the DP and DE and are known as a ratio rule (R) and a maximum peak of disturbance power rules. The ratio rule is based on the ratio of a maximum negative excursion of the DE to the change in the DE in which, the ratio is given as $R = |DE/\Delta DE|$. The rule sets a threshold value such that if $R < 25\%$ and $R \geq 25\%$, the disturbance is in front and behind the monitoring point, respectively. Meanwhile, the maximum peak of disturbance power is based on empirical observations of the disturbance power characteristics using the field-test data. A positive maximum peak of the disturbance power indicates the disturbance is in front of the monitoring point whilst a negative maximum peak of the disturbance power indicates the disturbance is behind the monitoring point. The method also considers a majority-voting scheme to decide on the location of a transient disturbance. The disadvantages of these indicators are that they only rely on the waveforms of DP and DE and it can only be calculated if the three phases steady-state voltages and currents are available to process the data.

From the literature, complex wavelet transform has been used to provide the instantaneous phase-related information such as that of a transient signal [6, 7]. One of the early application of a complex wavelet is found in [7], in which a mother wavelet known as the "Chaari wavelet" is used to analyze waveforms in terms of their argument and modulus. Another application of complex wavelet in power system analysis is for detecting a fault position according to their relative traveling times and polarities [8]. The algorithm adopted in [8] analyzes the arrivals of the successive fault-generated high-frequency transients to determine which line in a network is faulted and to locate the fault source. Complex wavelet is also used to determine phase information of the sending and receiving signals in low-voltage distribution network [9].

This paper proposes a method which is based on a phase angle difference between voltage and current at the monitoring point, to locate the source of transient disturbance. In this paper, instantaneous voltage and current waveforms at the monitoring points are transformed into their complex components by using the complex Gaussian wavelet. The proposed method exploits a complex wavelet transform to determine the instantaneous voltage and current angle at a measuring point. The complex wavelet transform is used since it has been proven to be able to provide a difference in phase information of the transient signals in [8, 9]. From these complex component values, the information based on the change in energy flow will be used to locate a transient disturbance as to whether it is behind or in front of the monitoring point.

2.0 PRINCIPLE OF TRANSIENT SOURCE LOCATION METHOD

According to [8 - 10], when a power system experiences a transient disturbance which may be caused by a fault or capacitor switching, the total voltage and current signals at any point in the system can be considered as consisting of three parts which are sinusoidal steady-state component, superimposed quantities due to the occurrence of transient which is considered in traveling wave, and the remainder is the transient-generated high-frequencies component. Since the transients have frequencies much higher than the power system frequency, a system behaves much differently when subjected to these high frequencies than it does with the normal power system frequency [10]. These factors make an analysis of transient disturbance becomes more complicated [11].

The sequence of events that will take place when a capacitor switching occurs can be described by considering a single source system in Figure 1. From Figure 1, immediately after a capacitor is switched on, the energization of a capacitor will result in an immediate drop in system voltage towards zero, followed by a fast recovery voltage (overshoot) and finally, an oscillatory transient voltage superimposed on the fundamental waveform. These voltage transients act just like a voltage source whereby they will push current to propagate in the form of traveling waves bi-directionally from the point of origin. The transient or surge current will travel towards either the utility or the facility side. Therefore, any equipment in front of or behind a transient source will be subjected to voltage stress that can result in an insulation failure.

If the fundamental voltage or current component is separated from the total transient voltage and current respectively, the remainder voltage and current component should include superimposed quantities and transient-generated high-frequencies component. By considering these two components of voltage and current as in the propagation of waves in a transmission line behavior, these wave components will travel to Z_1 and Z_2 of Figure 1. If the transient voltage phase at the monitoring point is used as a reference, a relative difference between voltage and current angle can be calculated. Assuming the magnitude and angle of voltage and current at the monitoring point can be obtained, the transient active power can be calculated as follows,

$$P(t) = V(t)\, I(t) \cos \theta(t) \tag{1}$$

where V and I are the modulus of voltage and current at the monitoring point, respectively, and θ is the difference between the voltage and current phase angles. Integrating P, the transient energy is obtained as,

$$E(t) = \int_B^E P(t)\, dt \tag{2}$$

where B and E are the initial and end period of a transient disturbance, respectively.

From Figure 1, at the monitoring point M_B, a positive transient current direction is assumed flowing from the capacitor C towards impedance Z_2. Taking the voltage measurement at M_B as a reference and assuming that the phase angles of voltage and current can be measured at this point, the real power can be calculated using Equation (1). The integral of the real power from the beginning to the end of the transient period as given in Equation (2) will provide the flow of the transient energy at the monitoring point. The use of Fourier analysis is not possible to provide instantaneous phase angles of voltage and current and therefore in this paper, a complex wavelet is employed to obtain the phase angles of voltage and current so that the active power at the monitoring point can be calculated. From Figure 1, when transient disturbance occurs behind the monitoring point or seen as coming from upstream, at the monitoring point M_B, transient current flows in a positive direction. A positive wavelet-based transient active power will be produced and by plotting the transient energy against time, the transient energy will increase which is observed as a positive gradient on the plot. Therefore, if the wavelet-based energy gradient is positive, it indicates that the source of transient disturbance is behind the monitoring point or seen as coming from upstream. On the contrary, when transient disturbance occurs in front of the monitoring point or seen as coming from downstream, at the monitoring point M_A, transient current flows in a negative direction. A negative wavelet-based transient active power will be produced and by plotting the transient energy against time, the transient energy will decrease, which is observed as a negative gradient on the plot. Therefore, if the wavelet-based energy gradient is negative, it indicates that the source of transient disturbance is in front of the monitoring point or seen as coming from downstream.

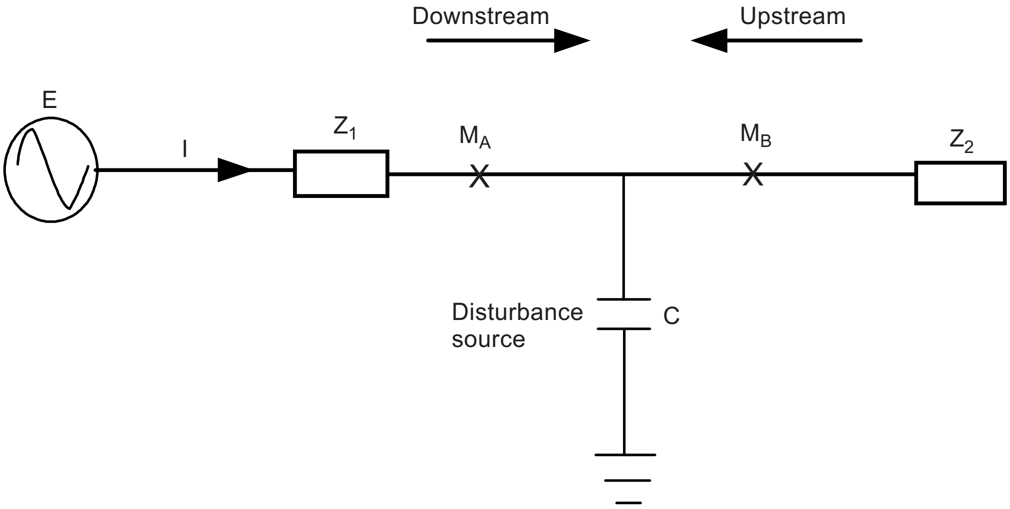


Figure 1 Illustrating the transient source location analysis

Thus, this paper investigates the application of complex wavelet to obtain the effective phase angles of voltage and current for evaluating the complex wavelet-based power and energy at the monitoring point. This wavelet-based power and energy will be used to locate the source of transient as whether it is from upstream or downstream relative to the monitoring point.

3.0 COMPLEX WAVELET-BASED POWER AND ENERGY MEASUREMENT

A new approach to analyze the location of a transient disturbance is proposed by using the complex wavelet transform. The original wavelet function, known as mother wavelet, which is generally designed based on some desired characteristics associated to that function, is used to generate all the wavelet basis functions. A wavelet transform is a two-parameter expansion of a signal in terms of a particular wavelet basis functions or wavelets. All other wavelets are obtained by simple scaling and translation of $\psi(t)$ as,

$$\psi_{j,k}(t) = 2^{j/2}\psi(2^{j}t - kT) \tag{3}$$

where,

c, a wavelet coefficient	j, indicates wavelet frequency scale
k, indicates wavelet time scale	ψ, a mother wavelet

In this paper, a complex Gaussian wavelet is chosen as the mother wavelet due to its smooth oscillating function and it is given as,

$$\psi_G(x) = C_p e^{-x^2} e^{-jx} \tag{4}$$

where C_P is the scaling parameter and x is the instantaneous voltage or current values.

A transient disturbance is obtained by filtering the raw waveform to separate the transient from the fundamental system frequency waveform. This process is analogous to subtracting the steady-state voltage and current from their respective instantaneous values [4].

In a single-phase system, the instantaneous amplitude and phase values of a filtered voltage and current, $\bar{V}_W$ and $\bar{I}_W$ for each sub band or scale s at time t, are given by [6]:

$$\bar{V}_W(t,s) = V_W(t,s) \angle \alpha(t,s) \tag{5}$$

$$\bar{I}_W(t,s) = I_W(t,s) \angle \beta(t,s) \tag{6}$$

Using the transient voltage and current amplitudes and the transient phase difference between voltage and current, a complex-wavelet based momentary active power quantity, p_W which is analogous to the Fourier-based active power definition, is given by,

$$p_W(t,s) = V_W(t,s).I_W(t,s).\cos(\theta_W(t,s)) \tag{7}$$

where,

$$\theta_W(t,s) = \alpha_{V,W}(t,s) - \beta_{I,W}(t,s) \tag{8}$$

The power definition in Equation (7) is known as the active wavelet power. It is also noted that the active wavelet differs from the time-domain physical power of $p(t) = v(t).i(t)$, due to the fact that a transient is a frequency domain oscillating quantity. Integrating p_W, the wavelet energy is obtained as,

$$E_W = \int_B^E p_W(t,s)\, dt \tag{9}$$

where B and E are the initial and end period of a transient disturbance, respectively. The complex wavelet energy, E_W is considered as an indicator for locating a transient source. It is plotted against time and its gradient is used to locate a transient source.

From the complex wavelet transform, the real part of the wavelet analysis (WTR) and the imaginary part of the wavelet analysis (WTI) can be obtained for the analyzed signals. The amplitude (WTM) and phase ($WTPH$) of the wavelet transform can be obtained using,

$$WTM = \sqrt{WTR^2 + WTI^2} \tag{10}$$

$$WTPH = \arctan\left(WTI / WTR\right) \tag{11}$$

Magnitude and phase for voltage and current at the monitoring points can be calculated using the following equations:

$$WTM_V = \sqrt{WTI_V{}^2 + WTR_V{}^2} \tag{12a}$$

$$WTPH_V = \arctan\left(WTI_V / WTR_V\right) \tag{12b}$$

$$WTM_1 = \sqrt{WTI_I{}^2 + WTR_I{}^2} \tag{13a}$$

$$WTPH_I = \arctan\left(WTI_I / WTR_I\right) \tag{13b}$$

$$\cos\theta = \cos\left(WTPH_V - WTPH_I\right) \tag{14}$$

where subscripts $_V$ and $_I$ represent voltage and current respectively.

4.0 IMPLEMENTATION OF WAVELET ENERGY TO LOCATE A TRANSIENT SOURCE

The implementation procedure to locate a transient source using the wavelet energy is described in this section. Simulation is carried out by using the PSCAD/EMTDC program. Voltage and current waveforms are used to compute the power and energy quantities and all data processing codes are done via Matlab script files.

4.1 Test System

The test system used to verify the proposed method is shown in Figure 2. The test system is fed from a 13.8 kV, 15 MVA source at 50 Hz frequency. In this paper, the waveforms of two different sampling rates have been used, namely 512 samples per cycles and 256 samples per cycles for voltage and current waveforms. Three capacitor switching scenarios are considered in the simulations, namely a correction capacitor switching, back-to-back capacitors switching and a re-strike of capacitor switching case. For each case, the wavelet-based transient power and energy are computed. In each case, capacitors, CA and CB are switched on at the peak point of the supply system voltage and several monitoring points considered are PCC, M1, M2, M3, M4, M5, and M6.

The switching at the peak of system voltage is done since this is a common occurrence of transient for many types of switches because the insulation across the switch contact tends to break down when the voltage across the switch is at a maximum value [6].

4.2 Implementation Procedure

The instantaneous voltage and current contain both the fundamental and the transient frequencies. Therefore, the fundamental frequency is filtered before applying the complex wavelet transform. The following steps describe the procedure carried out in the proposed method.

(i) Create a transient disturbance condition by simulating capacitor switching at a specified location.
(ii) Obtain the voltage and current data at the monitoring point.
(iii) Filter the voltage and current at the fundamental frequency.
(iv) Transform the instantaneous of voltage and current data to its real and imaginary parts of the complex wavelet, "cgau8" using the complex Gaussian function written in Matlab. The value of the scaling parameter used is 2 and x is the instantaneous voltage and current values.
(v) Calculate the transient active power and its transient energy using Equations (7) and (9), respectively.
(vi) Graphically plot coordinates of power and energy against time for a period of transient disturbance.
(vii) Check the polarity of the gradient for the transient energy. If it is positive, the transient source is upstream or behind the monitoring point. On the other hand, if it is negative, the transient source is downstream or in front of the monitoring point.

5.0 ANALYSIS OF TRANSIENT SOURCE LOCATION

In this section, simulation results of the proposed transient energy method for transient source location method are presented for single capacitor switching, back-to-back capacitor switching and re-strike cases. Results are presented using the complex wavelet energy to locate the source of transient.

5.1 Complex Gaussian Wavelet Transform

The families of the complex Gaussian wavelet, "cgau" are used to analyze a transient waveform in order to choose the most suitable mother wavelet to represent the transient disturbance. From the calculation carried out on the coefficients values, the highest value of coefficient is obtained at scale 2. Scale 2 is the value of the scaling parameter of the complex Gaussian wavelet as shown in Equation (4). A mother wavelet of "cgau8" is chosen as the mother wavelet because it gives the highest coefficient at scale 2, which means that it is the best mother wavelet to simulate the transient. Figure 3 shows a mother wavelet of "cgau8".

The capacitor is set to switch on when phase A voltage is at its peak value. Figure 4(a) shows the voltage signal where the transient starts to occur at 0.885 S and reach its steady-state at 0.9 S. The voltage drops first before it begins to oscillate. This phenomenon matches the description of transient in Section 2, where after the voltage drop it is followed by a fast recovery (overshoot) and finally, an oscillatory transient

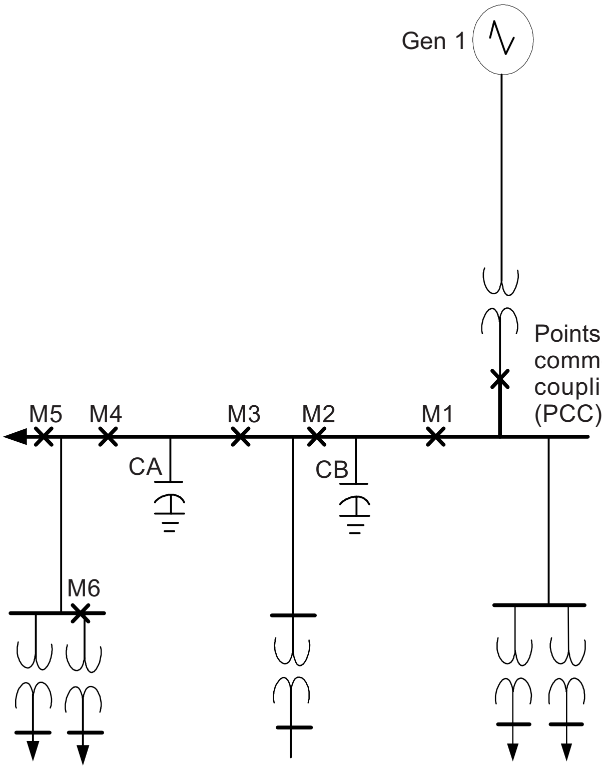
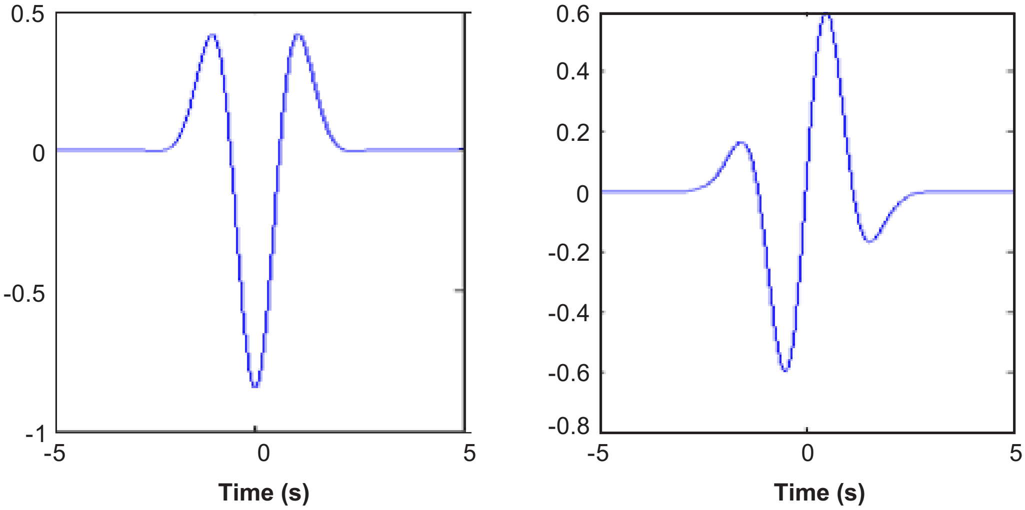


Figure 2 Test 1 system for transient source location



(a) Real part

(b) Imaginary part

Figure 3 Mother wavelet of complex Gaussian at scale 2

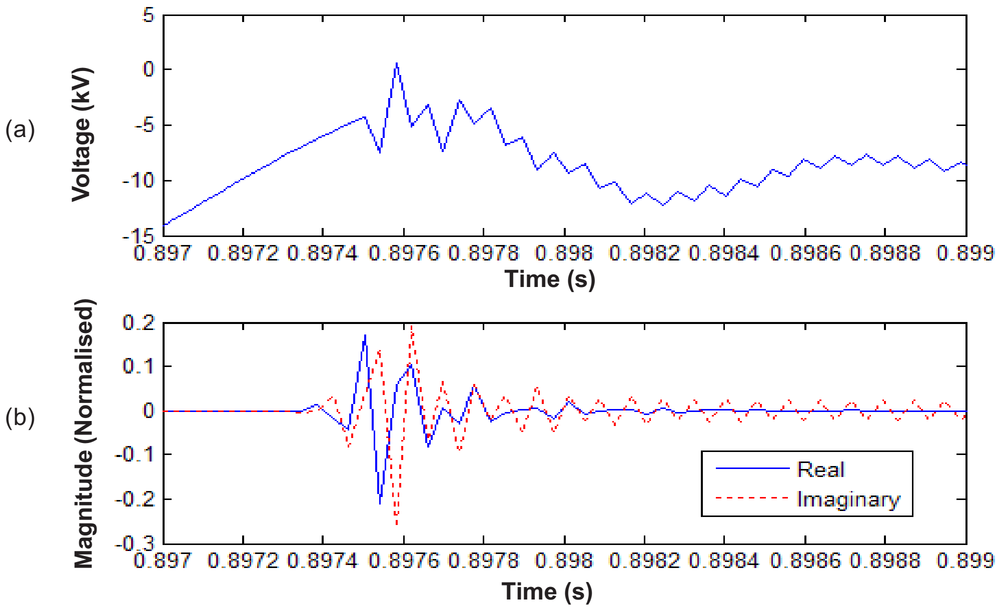


Figure 4 (a) Original transient voltage and (b) Complex Gaussian wavelet at scale 2 of "cgau8"

voltage superimposed on the fundamental waveform. These oscillatory transient frequencies resulted from the capacitor switching event. The respective voltage and current signal of phase A is filtered to separate the fundamental frequency before it is processed by the Gaussian complex transform.

Figure 4(a) shows the actual voltage signal and Figure 4(b) illustrates its respective real and imaginary part using "cgau8" at scale 2.

5.2 Results from Capacitor Switching Transient

In this section, discussions and results of the proposed wavelet-based transient power and energy method for transient disturbance source location are presented. Three switching capacitor cases, namely a correction capacitor switching, back-to-back capacitor switching and re-strikes of capacitor switching are discussed for voltage and current waveforms with a sampling rate of 512 per cycle.

5.2.1 Correction Capacitor Switching

For a correction capacitor switching, simulation of Test system 1 in Figure 2 is carried out where capacitor CA is switched on while capacitor CB is switched off. Table 1 shows the transient disturbance locations relative to the position of the monitoring points.

When capacitor CA is switched on while capacitor CB is switched off, the monitoring points at M4, M5, and M6 see the disturbance as coming from upstream or behind the

Table 1 Capacitor CA on

Disturbance location	**Monitoring point**
Behind monitoring point (Upstream)	M4, M5, M6
In front of monitoring point (Downstream)	PCC, M1, M2, M3

monitoring points. On the other hand, the monitoring points at PCC, M1, M2, and M3 see the disturbance as coming from downstream or in front of the monitoring points.

Figures 5 and 6 show the transient voltage and the respective wavelet power and wavelet energy when a transient source is said to be coming from downstream or in front of the monitoring points at PCC and M1. In all these figures, the transient voltage starts to occur at 0.886 until 0.897 S. From Figure 5(b), the wavelet power starts to drop at the beginning of the transient until it will rise up and drop again at the end of the transient duration. The wavelet power in Figure 6(b) also shows the same characteristics as the wavelet power in Figure 5(b) in which, it drops at the beginning of the transient until it will rise up and drop again at the end of the transient period. This wavelet power does not show a significant pattern, and therefore, it cannot be used as an indicator for locating transient source. By observing the wavelet energy shown in Figure 5(c), it is observed that the wavelet energy starts to decrease significantly at

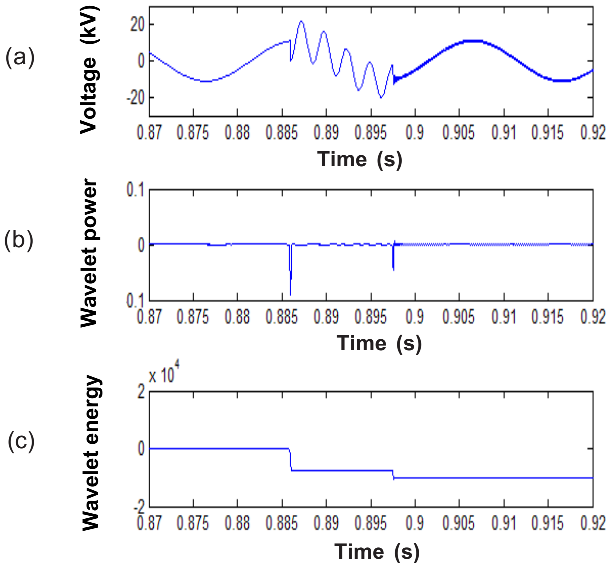


Figure 5 Downstream, CA on (a) transient voltage observed at PCC, (b) wavelet power, p_W, and (c) wavelet energy, E_W

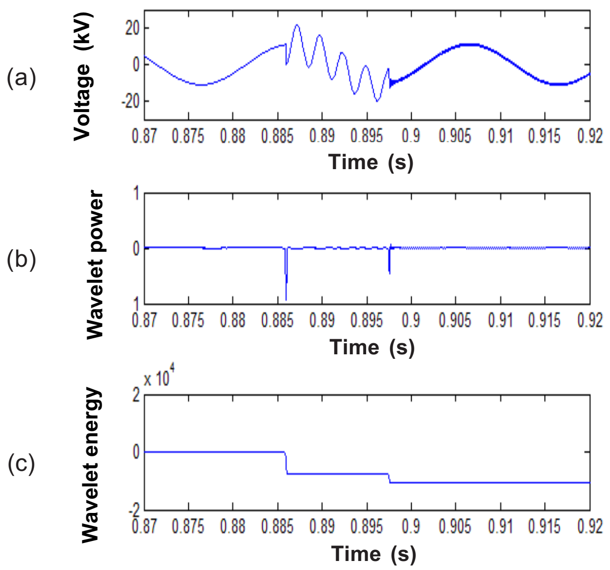


Figure 6 Downstream, CA on (a) transient voltage observed at M1, (b) wavelet power, p_W, and (c) wavelet energy, E_W

0.886 S and remains constant until the end of the transient period, 0.897 S. This decrease in wavelet energy is considered as a negative gradient of the wavelet energy. Similarly, Figure 6(c) shows a decrease in wavelet energy which is considered as a negative gradient of the wavelet energy. This wavelet energy shows a significant pattern, and therefore, is used as an indicator for locating a transient source. From Figures 5(c) and 6(c), the negative gradient of wavelet energy indicates a correct location of the source of transient disturbance which is in front of the monitoring point or seen as coming from downstream.

Figures 7 and 8 show the transient voltages and the respective wavelet energy for the transient disturbances that are from upstream. In all these figures, the transient voltage starts to occur at 0.886 until 0.897 S. Figures 7(b) and 8(b) show a plot of wavelet energy where it is observed that the wavelet energy starts to increase at the beginning of the transient until the end of the transient period, 0.897 S. The increase in wavelet energy is considered as having a positive gradient of the wavelet energy. The positive gradient of wavelet energy indicates a correct location of the source of transient disturbance which is behind the monitoring point or seen as coming from upstream.

The final value of the wavelet energy at M5 in Figure 7(b) is higher than the value at M6 in Figure 8(b) which suggests that as the resistance from the disturbance source (which is the correction capacitor) increases, the value of wavelet energy decreases.

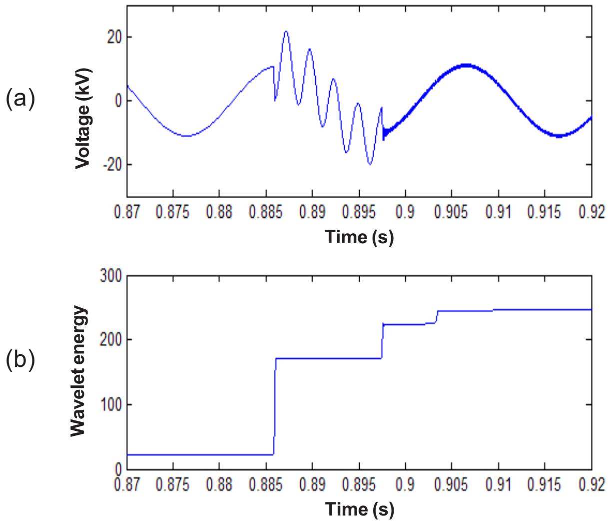


Figure 7 Upstream (a) transient voltage observed at M5 and (b) wavelet energy, E_W

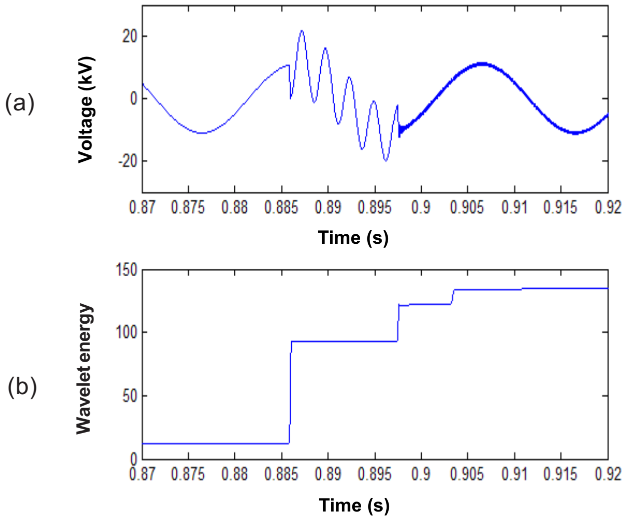


Figure 8 Upstream (a) transient voltage observed at M6 and (b) wavelet energy, E_W

5.2.2 Back-to-back Capacitor Switching

An analysis was also carried out for back-to-back capacitor switching. To illustrate the back-to-back capacitor switching scenario, a test system of Figure 2 is employed where the capacitor CB is switched on from 0.725 until 0.882 S. Upon the switching off capacitor CB, then the capacitor CA is switched on at 0.882 until 0.9 S.

Table 2 shows the position of the transient disturbance locations relative to the monitoring points. From Table 2, at the monitoring points M5 and M6, the transient

Table 2 Back-to-back capacitor switching

Disturbance location	Monitoring point
Upstream from CA and CB	M5, M6
Downstream from CA and CB	PCC, M1
Upstream from CA but downstream from CB	M2, M3

disturbance is seen as coming from upstream or behind the monitoring point for capacitors CA and CB. On the other hand, at the monitoring points PCC and M1, the transient disturbance is seen as coming from downstream or in front of the monitoring point for capacitors CA and CB. At the monitoring points M2 and M3, the transient disturbance is seen as coming from downstream or in front of capacitor CB but as coming from upstream or behind the monitoring point of capacitor CA.

Figure 9 shows the transient voltage and the respective wavelet energy when recorded at the monitoring points PCC. From Figure 9(a), it is depicted that transient occurs at 0.725 S and re-occurs at 0.882 S. These transients occur as capacitor CA and CB was switched on at 0.725 S and 0.82 S consecutively. Figure 9(b) shows a significant decrease in the wavelet energy at 0.725 S and also at 0.882 S consecutively. A negative gradient of the wavelet energy in Figure 9(b) indicates a correct location of the source of transient disturbance which is in front of the monitoring point or seen as coming from downstream. These results concur with the actual location of a transient source in Table 2.

Figure 10 illustrates the transient voltage and the respective wavelet energy when recorded at the monitoring point M6. Figure 10(a) shows transient occurs at 0.725 S

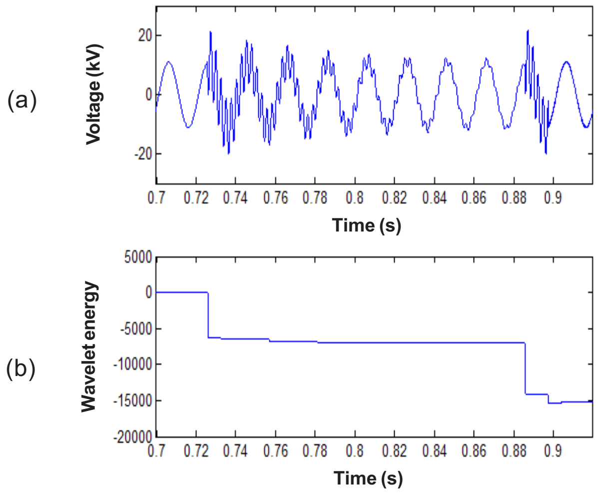


Figure 9 Downstream for back-to-back capacitor switching (a) transient voltage at PCC and (b) wavelet energy, E_W

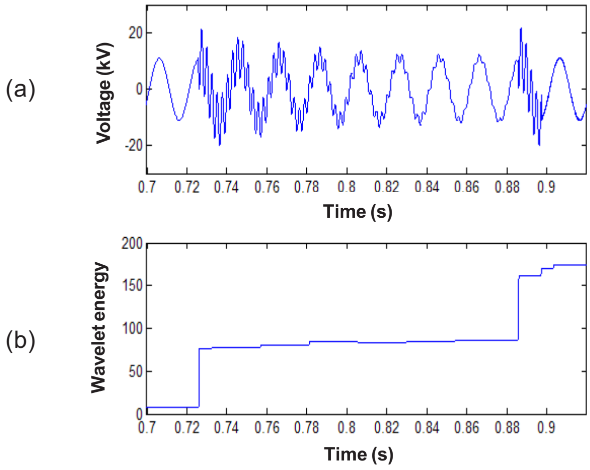


Figure 10 Downstream for back-to-back capacitor switching (a) transient voltage at M6 and (b) wavelet energy, E_W

and re-occurs at 0.882 S. A significant increase in the wavelet power is seen at 0.725 S and also at 0.882 S consecutively is observed in Figure 10(b). These transient happens as capacitor CA and CB were switched on at 0.725 S and 0.82 S consecutively. A positive gradient of the wavelet energy in Figure 10(b) indicates a correct location of the source of transient disturbance which is in front of the monitoring point or seen as coming from upstream. This result concurs with the actual location of a transient source in Table 2.

Figure 11 shows the transient voltage and the respective wavelet energy when recorded at the monitoring points M2. From Figure 11(a), it can be seen that transient

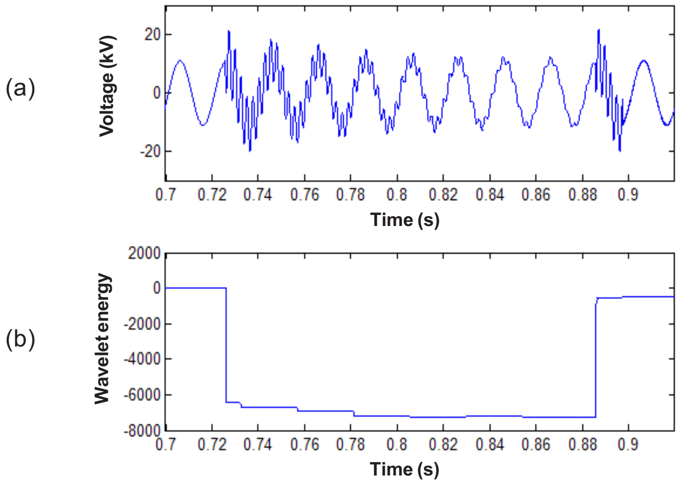


Figure 11 Back-to-back capacitor switching (a) transient voltage at M2 and (b) wavelet energy, E_W

occurs at 0.725 S and re-occurs at 0.882 S. A significant decrease and increase in the wavelet energy gradient is observed at 0.725 S and 0.882 S respectively in Figure 11(b). A negative gradient of the wavelet energy from 0.725 until 0.882 S in Figure 11(b) is obtained when capacitor CB is switched on. The negative gradient indicates a correct location of the source of transient disturbance which is in front of the monitoring point or seen as coming from upstream. On the contrary, a positive gradient of the wavelet energy from 0.882 until 0.92 S in Figure 11(b) is obtained when capacitor CA is switched on. The positive gradient indicates a correct location of the source of transient disturbance which is behind the monitoring point or seen as coming from upstream. These results are in agreement with the actual location of a transient source in Table 2 where capacitor CA and CB are switched on at 0.725 S and 0.882 S consecutively.

5.2.3 Capacitor CA Re-strike Case

The third simulation scenario is a capacitor switching re-strike case. In this case, capacitor CA is switched on at 0.72 S and during the de-energizing it re-strikes at 0.882 S. Table 3 shows the position of the transient disturbance locations relative to the monitoring points.

Table 3 Capacitor CA re-strike case

Disturbance location	**Monitoring point**
Behind monitoring point (Upstream)	M4, M5, M6
In front of monitoring point (Downstream)	PCC, M1, M2, M3

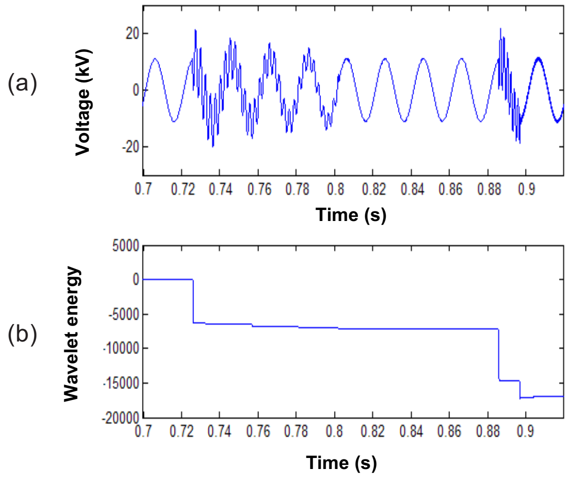


Figure 12 Capacitor CA re-strike case for downstream (a) transient voltage observed at PCC and (b) wavelet energy, E_W

Figure 12(a) and (b) depicts the results of wavelet energy at PCC with its respective wavelet energy at PCC. Figure 12(a) shows transients occur at 0.725 S and re-occur during the deenergizing at 0.882 S. From Figure 12(b), it is observed that the wavelet energy decreases significantly at the beginning of the transient which is at 0.725 S. Another significant decrease in the wavelet energy is observed when the capacitor re-strikes at 0.882 S. A negative gradient of the wavelet energy from the figure indicates that the disturbance is in front of capacitor CA or from downstream. Thus, the results concur with the actual location of a transient source in Table 3 where the disturbance is seen coming from downstream at monitoring point PCC.

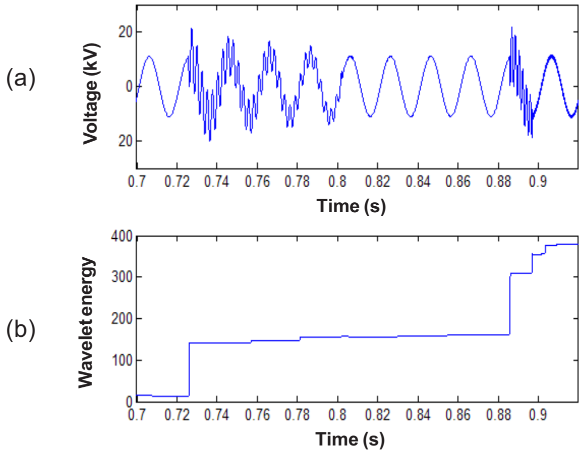


Figure 13 Capacitor CA re-strike case for upstream (a) transient voltage observed at M5 and (b) wavelet energy, E_W

Figure 13(b) depicts the result of wavelet energy at M5. From Figure 13(b), it is observed that the wavelet energy increases significantly at the beginning of the transient which is at 0.725 S. A significant increase in the wavelet energy is also observed when the capacitor re-strikes at 0.882 S. A positive gradient of the wavelet energy from the figure indicates that the disturbance is in behind capacitor CA or from upstream.

6.0 CONCLUSIONS

This paper has shown that the source of transient disturbance can be located by examining the direction of wavelet energy flow in power distribution systems. The complex wavelet has been proven to be able to generate effective phase angles of voltage and current at the monitoring points. These phase angles are used for evaluating the wavelet energy flow within the transient short period in which it is capable to distinguish as to whether the transient source is in front of or behind the monitoring point. From the simulations, a positive gradient of wavelet energy indicates that the transient source is behind the monitoring point or upstream. On the other hand, a negative gradient of wavelet energy indicates that the transient source is in front of the monitoring point or downstream. If several recording devices are available in a power distribution system, the source of the disturbance can be located.

As disturbance caused by transient will only be attended when many complaints are received from customers, then the most significant contribution in localizing a transient source is at the PCC in which it may help in diagnosing power quality problems as to either utility or customers as the transient disturbance contributor. Most of the time, monitoring will only be carried out at a specific power quality problem area, hence the proposed method is very practical and economic since it can locate the direction of the transient relative to the monitoring point. Simulation results have shown that satisfactory performance has been achieved at different monitoring points. The advantages of the proposed method can be listed as follows:

(i) It requires only single-phase voltage and current measurement at the monitoring points, thus overcome the shortcoming of three-phase measurement requirement in the disturbance power and energy method in [5].
(ii) The method does not require a steady-state voltage and current waveform to calculate the wavelet-based power and energy. Thus, it is better than the method of using the disturbance power and energy as the indicator in [5] where extra waveforms of voltage and current are required in evaluating a transient source location.
(iii) Since the method is able to locate the source of a transient disturbance at the PCC which is the point between a utility and a customer, it can be used to penalize responsible parties that cause the disturbance if regulation is to be enforced in the future.

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