Proceedings of the Sixth IASTED International Conference
EUROPEAN POWER AND ENERGY SYSTEMS
June 26–28, 2006, Rhodes, Greece

TRANSIENT SOURCE LOCATION USING COMPLEX WAVELET-BASED ENERGY

Noraliza Hamzah, Azah Mohamed and Aini Hussain
Universiti Kebangsaan Malaysia,
Bangi 43600, Selangor,
Malaysia
noraliza@vlsi.eng.ukm.my, azah@eng.ukm.my, aini@eng.ukm.my

ABSTRACT

This paper presents a new method for locating the source of capacitor switching transients using the complex wavelet-based energy approach. By using the complex wavelet transform, the transient power at the monitoring point is first calculated and the complex wavelet energy is obtained by integrating the transient power. From the wavelet energy plot against time, a change in wavelet energy from an approximately zero to a negative value indicates that the transient source is in front of the monitoring point. On the other hand, a change in wavelet energy from an approximately zero to a positive value indicates that the transient source is behind the monitoring point. To verify the proposed complex wavelet method, simulations by switching the capacitors using the PSCAD/EMTDC program were simulated for generating oscillatory transients. Comparisons were also made in locating the transient source using disturbance power and disturbance energy technique. Simulation results prove that the complex wavelet-based energy approach is more accurate than the disturbing power and disturbing energy method in locating the source of capacitor switching transients in a power distribution system.

KEY WORDS

Capacitor switching, Power quality, Power system transients, Wavelet transforms

1 INTRODUCTION

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. Utility capacitor switching events can have negative impacts on power quality, such as tripping of drives, halting of production processes, high over-voltage on a transformer, excite circuit resonance, creating transient voltage magnification in the secondary network and problems with sensitive electronic equipment at customer facilities.

In recent years, many efforts have been made to detect, classify and characterize power system transients [1]-[2]. However, not much work has been done to locate these transients as to where the transients originate. It is important to locate transients before any mitigation technique can be done to eliminate the transients since a wrong mitigation solution can aggravate the power system transient problem. The other advantage of locating the source of transient is that it may help in diagnosing power quality problems as to either utility or customer as the transient disturbance contributor.

An analysis for locating the source of transient source disturbance is found in [3] which employed the disturbance power (DP) and disturbance energy (DE) concept 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 and that the directions of the DE as well as the DP flows are used to locate a transient source [3]. The disadvantage of the method is that it relies on the degree of confidence of both the DP and DE. In [4], 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 the ratio rule (R) and the maximum peak of disturbance power rules. 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 disadvantages of these indicators are that they rely on the waveforms of DP and DE and can only be calculated if the three phases of voltages and currents are available.

In this paper, we propose a new method based on the wavelet-based energy to locate the source of capacitor switching transient relative to its monitoring point based the following criteria:

- The proposed method only employs single phase voltage and current waveforms at the monitoring point to be transformed into their complex wavelet counterparts.
- The method only uses wavelet-based energy as an indicator to locate the source of capacitor transient accurately.

2 CAPACITOR SWITCHING TRANSIENTS IN POWER SYSTEM

Power system transients can be classified into oscillatory and impulsive transients. The main causes of oscillatory transients are capacitor energizing, re-strike during capacitor de-energizing, back-to-back capacitor switching and capacitor voltage magnification. Oscillatory transients show damped oscillations with frequencies ranging from a few hundred Hertz up to several megahertz. The basic concept of energization of capacitors is by considering the capacitor switching phenomenon shown in Fig. 1, where resistances are omitted by simplification [5].

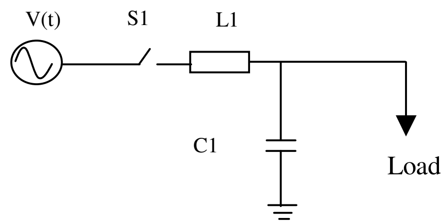

Fig. 1. Simplified circuit with L-C loops

The equations for the current and voltage in the capacitor C1 as shown in Fig. 1, at the instant of closing off switch S1, with switch S2 open are given respectively by [6]:

$$V_{C1}(t) = V - \left[(V - V_{C1}(0).\cos\omega_1 t)\right] \quad (1)$$

$$I_1(t) = \frac{V}{Z_1}\sin\omega_1 t \quad (2)$$

where,

$\omega_1 = \frac{1}{\sqrt{L_1 C_1}}$, natural frequency

$V_{C1}(0)$: initial voltage at C1

V : switched voltage at S1 closing

Z_1= surge impedance given by, $Z_1 = \sqrt{L_1/C_1}$

From (1), it is shown that upon closing of S1, transient overvoltage will occur in the circuit with the voltage higher than the bus voltage. The oscillatory phenomenon of the capacitor switching transient results from the energy exchanged between the inductive and capacitive elements [5]-[6]. Transient oscillations that occur at the capacitor switching instant can be low frequency (300-600Hz) in the case of normal capacitor energizing and can be medium frequency (2-10kHz) at the magnification case. For a normal energizing of capacitor the transient events occur when a capacitor is switched on in which a fast change in the bus voltage occurs because the voltage in the capacitor cannot change instantaneously. The overvoltage in normal energizing is usually between 1.1-1.4 p. u with its oscillation frequency typically between 300-1000Hz. For a back-to-back capacitor energizing, transients involve two capacitors in close vicinity. Back-to-back energizing of capacitors occurs when one of them is fully energized and the other is switched on. The voltage waveforms of the back-to-back energizing events look very much the same as those in normal energizing and almost all features of the normal energizing apply to back-to-back energizing.

3 PRINCIPLE OF TRANSIENT SOURCE LOCATION METHOD

In this section, the principle based on the flow of complex wavelet power and the change in polarity of complex energy to locate the source of transient is explained.

3.1 Locating The Source Of Capacitor Transients

When a power system experiences a transient disturbance, 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 [7]. The sequence of events that will take place when a normal capacitor energizing and back-to-back capacitor energizing occurs can be described by considering a single source system in Fig. 2. From the figure, 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.

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 Fig. 2. 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,

$$P(t) = V(t)I(t)\cos(\alpha(t) - \beta(t)) \quad (3)$$

where V and I is the modulus of voltage and current at the monitoring point, respectively, where α and β is the phase angle of voltage and current respectively. Integrating P, the transient energy is obtained as,

$$E(t) = \int_B^E P(t)dt \quad (4)$$

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

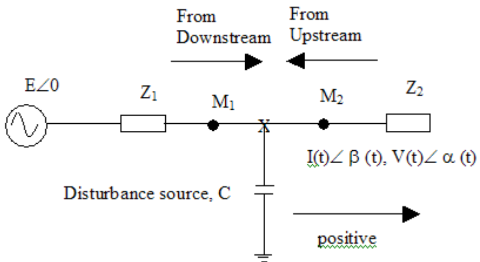

Fig. 2. Illustrating the location of capacitor transient source

Initially, before any transients occur, there is no transient power, thus no energy is delivered to either side of the transient source. However, when a transient occurs, the system falls out of steady-state operation, causing a change in the instantaneous power flow. The instantaneous power is approximately zero before transient occurs. Likewise, the change in energy will also be observed between steady-state condition and during a transient event.

From Fig. 2, at the monitoring point M_2, a positive transient current direction is assumed flowing from the capacitor C towards impedance Z_2. Taking the voltage measurement at M_2 as a reference and assuming that the phase angles of voltage and current can be measured at this point, the active power can be calculated using equation (3). The integral of the real power from the beginning to the end of the transient period as given in equation (4) will provide the transient energy at the monitoring point. The positive direction of real power flow is similar to the real current direction. At M_2, the initial energy at steady state is zero. During transient, more power and energy is delivered at M_2 in which a change in energy from approximately zero to a positive value is expected. Information about changes in the instantaneous transient power and energy allow us to make a decision about the location of the source of transient relative to its monitoring point. Therefore, if a positive energy is obtained, it indicates that the source of transient disturbance is behind the monitoring point or seen as coming from upstream. On the other hand, at M_1, a negative direction of power flow will result in less energy delivered than its steady state value. Hence, from the energy against time plot, a change in energy from approximately zero to a more negative value is expected. If a negative energy is obtained, it indicates that the source of transient disturbance is in front of the monitoring point or seen as coming from downstream. In the proposed method for locating the source of capacitor transients, complex wavelet is employed to obtain the phase angles of voltage and current at the monitoring point during transients, so that the active power and its respective energy can be calculated.

3.2 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. A complex Gaussian wavelet is chosen as the mother wavelet due to its smooth oscillating function and it is given as,

$$\psi_G(x) = C_p e^{-x^2} e^{-jx} \tag{5}$$

where C_P is a scaling parameter and x is the instantaneous voltage or current values. Figure 3 shows the mother wavelet of the complex wavelet used in the analysis.

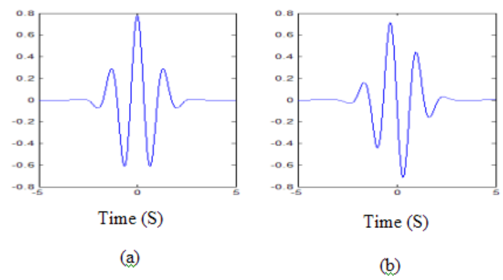

Fig. 3. Mother wavelet of complex Gaussian at scale 8 (a) Real part (b) Imaginary part

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 [8]:

$$\bar{V}_w(t,s) = V_w(t,s)\angle\alpha(t,s) \tag{6}$$

$$\bar{I}_w(t,s) = I_w(t,s)\angle\beta(t,s) \tag{7}$$

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, is given by,

$$p_W(t,s) = V_W(t,s).I_W(t,s).\cos(\theta_W(t,s)) \tag{8}$$

where,

$$\theta_W(t,s) = \alpha_{V,W}(t,s) - \beta_{I,W}(t,s) \tag{9}$$

The power definition in equation (9) is known as the active complex wavelet power. Integrating p_W, the wavelet energy is obtained as,

$$E_W = \int_B^E p_W(t,s)dt \tag{10}$$

where B and E are the starting and ending time 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. For the proposed method, a positive gradient of the wavelet energy indicates that the transient source is behind the monitoring point or upstream. On the other hand, a negative gradient of the wavelet energy indicates that the transient source is in front of the monitoring point or downstream.

4 IMPLEMENTATION OF WAVELET ENERGY TO LOCATE A TRANSIENT SOURCE

The implementation procedure to locate a transient source using the complex wavelet energy is described in this section. The test system used to verify the proposed method is shown in Fig. 4. The test system is fed from a 13.8kV, 15MVA source at 50 Hz frequencies. Two capacitor-switching scenarios are considered in the simulations, namely a correction capacitor switching and back-to-back capacitors switching.

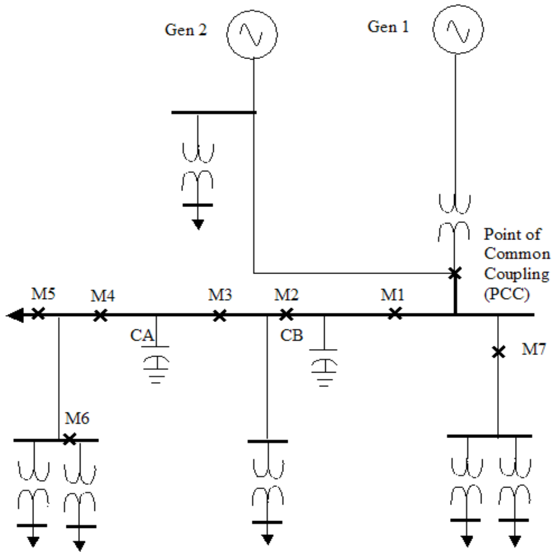

Fig. 4 Test system for transient source location

4.1 Implementation Procedure

The procedures carried out in the proposed method are as follows,

i. Create a transient disturbance condition by simulating a capacitor switching event and obtain the voltage and current data at the monitoring point.
ii. Filter the voltage and current at the fundamental frequency and transform the instantaneous data to its real and imaginary parts using the complex wavelet, 'cgau8'.
iii. Calculate the complex wavelet energy using equations (10).
iv. Graphically plot coordinates of power and energy against time for a period of transient disturbance. If the gradient of complex wavelet energy is positive, the transient source is behind the monitoring point. On the other hand, if the gradient of complex wavelet energy is negative, the transient source is in front of the monitoring point.

5 RESULTS

In this section, simulation results of the proposed wavelet energy method for capacitor switching transient source location are presented for normal energizing capacitor and back-to-back switching capacitor. Results based on the "disturbance power" (DP) and "disturbance energy" (DE) are also presented for the purpose of comparing with the proposed complex wavelet method in locating a transient source due to capacitor switching [3]. The two indicators are defined as [3]:

- If the initial peak of DP and the gradient of DE is positive, the source of transient is in front of the monitoring point (downstream).
- If the initial peak of DP and the gradient of DE is negative, the source of transient is behind the monitoring point (upstream).

Case A: Normal energizing capacitor transient

Now, let us consider switching on CA of the test system in Fig. 5 switched on at 0.725 S while capacitor CB is switched off. Table 1 shows the transient disturbance locations relative to the position of the monitoring points where the monitoring points at M4, M5 and M6 see the disturbance as coming from upstream or behind the monitoring points. The monitoring points at PCC, M1, M2 and M3 see the disturbance as coming from downstream or in front of the monitoring points.

Table 1: Capacitor CA On

Capacitor Transient Locations	Monitoring Locations
Behind monitoring point	M4, M5, M6, M7
In front monitoring point	PCC, M1, M2, M3

Fig. 5a shows the real and imaginary parts of the wavelet based voltage respectively. Fig. 5b shows the change in the wavelet energy is from approximately zero to positive is observed which indicates the source of transient is behind the monitoring point. The result matches the actual origin of the transient, which is behind the monitoring point as in Table 1. Figures 6a)-b) show the disturbance power (DP) and disturbance energy (DE) obtained at a monitoring point, M5. The first peak of the DP is negative which matches the condition that the source of capacitor switching source is behind the monitoring point. However, the DE in Fig. 6b) shows a significant oscillation rather than a downward trend. So, only result from DP indicates an accurate location of the source of transient.

The results shown in Fig. 7 and Fig 8 are from a similar case but the monitoring point is at M1. The real and imaginary parts of the wavelet based voltage shown in Fig. 7a shows an approximately zero voltage before the transient occurs. The wavelet energy in Fig. 8b shows a downward trend, which indicate the source of transient is in front of the monitoring point. The result matches the actual origin of the transient, which is in front of the monitoring point as in Table 1. Figures 8 a)-b) show the disturbance power (DP) and disturbance energy (DE) obtained at a monitoring point, M1. From Fig. 8a), the first peak of the DP is negative before it goes up to a significant positive value. So, this result shows an ambiguity as whether the source of capacitor switching source is behind the monitoring point or in front of the monitoring point. Similarly, the disturbance energy in Fig. 8b) also shows a downward trend before it shows a significant upward trend. Hence, both results cannot conclusively locate the source of transient disturbance for the downstream location.

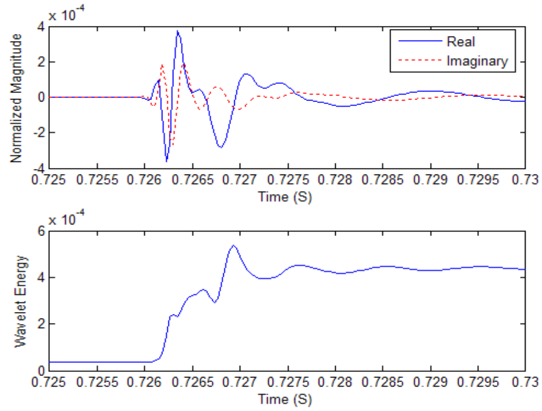

Fig. 5 Transient at M5 a) Complex Wavelet Voltage
b) Wavelet Energy

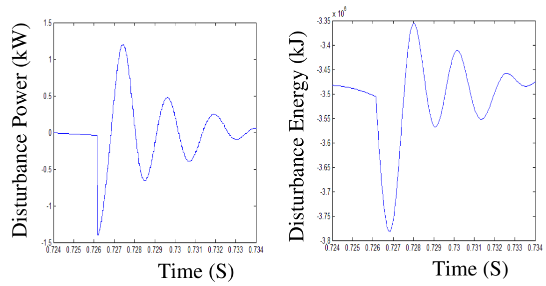

Fig. 6 Monitoring at M5 a) Disturbance Power
b) Disturbance Energy

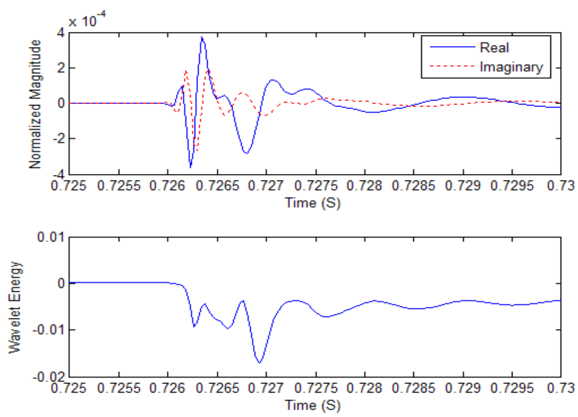

Fig. 7 Transient at M1 a) Complex Wavelet Voltage
b) Wavelet Energy

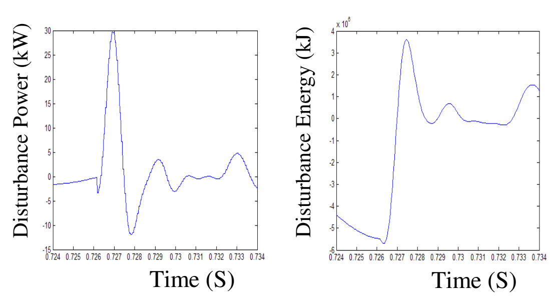

Fig. 8 Monitoring at M1 a) Disturbance Power
b) Disturbance Energy

Case B: Locating The Source Of Transient Due To Back-To-Back Capacitor Switching

An analysis was also carried out for the case of back-to-back (BTB) capacitor switching. To simulate the back-to-back capacitor-switching, capacitor CA is first switched on at 0.725 s and while energizing CA, capacitor CB is switching on at 0.886 s. Table 2 shows the transient disturbance locations relative to the monitoring points. From Table 2, at the monitoring points M5 and M6, the transient disturbance generated by capacitor CB is seen as coming from upstream or behind the monitoring point. For monitoring points at PCC and M1, the transient disturbance due to capacitors CB is seen as coming from downstream or in front of the monitoring point.

Table 2: Back-To-Back Capacitor Switching

Capacitor Transient Locations	Monitoring Locations
Behind monitoring point	M5, M6
In front monitoring point	PCC, M1

Figures 9 present the results obtained for back-to-back switching on capacitor CB at 0.886 s taken at monitoring point M1. The real and imaginary parts of the wavelet based voltage in Fig. 9a show an approximately zero value before transient occurs. Meanwhile, from Fig. 9b the change in the wavelet energy is from approximately zero to negative is observed. From Table 2, the disturbance location with respect to the monitoring point, M1 is noted to be from downstream or in front of the monitoring point.

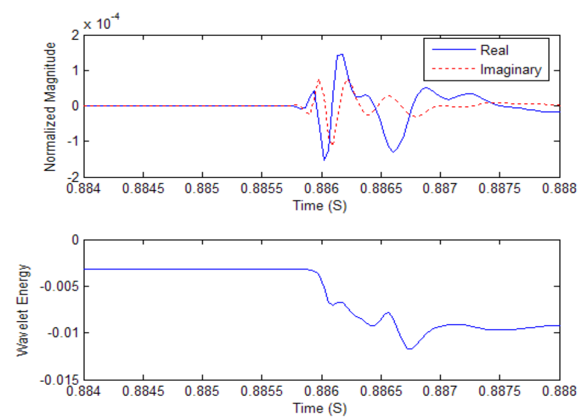

Fig. 9 Monitoring at M1 BTB capacitor switching a) Complex Wavelet Voltage b) Wavelet Energy

Figures 10 a)-b) show the disturbance power (DP) and disturbance energy (DE) obtained at a monitoring point, M1 for a BTB capacitor switching case. From Fig. 10a), the first peak of the DP is negative before it goes up to a significant positive value. Hence a conclusive result cannot be obtained in order to locate the source of capacitor switching transient for this case. Only the disturbance energy in Fig. 10b) shows an upward trend, which indicates the source of transient disturbance for the downstream location.

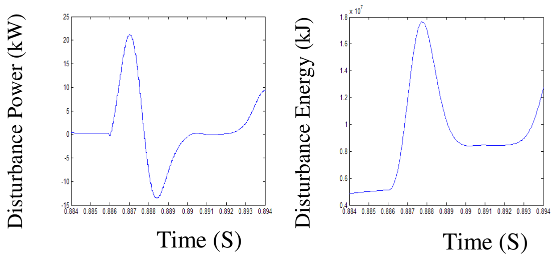

Fig. 10 Monitoring at M1for BTB capacitor switching
a) Disturbance Power b) Disturbance Energy

Figures 11 present the results obtained for back-to-back switching on capacitor CB at 0.886 s taken at monitoring point M5. The real and imaginary parts of the wavelet based voltage in Fig. 11a shows an approximately zero value before transient occurs. The positive gradient of the wavelet energy in Fig. 11b indicates that the location of the transient disturbance is behind the monitoring point, M5 which agrees with actual transient location with respect to the monitoring point, M5 as stated in Table 2. Figures 12a)-b) show the disturbance power (DP) and disturbance energy (DE) obtained at a monitoring point, M5. The first peak of the DP is negative which matches the condition that the source of capacitor switching source is behind the monitoring point. However, the DE in Fig. 12b) shows a significant oscillation rather than a downward trend. So, only result from DP indicates an accurate location of the source of transient.

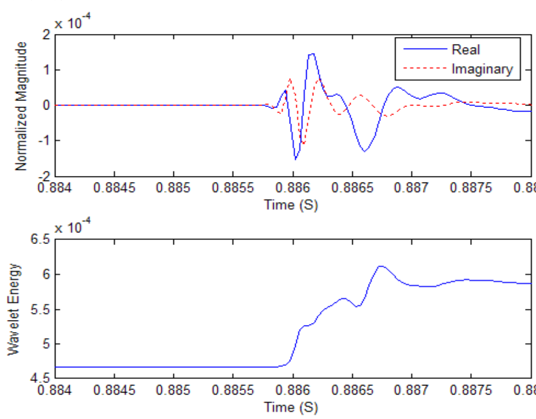

Fig. 11 Monitoring at M5 BTB capacitor switching
a) Complex Wavelet Voltage b) Wavelet Energy

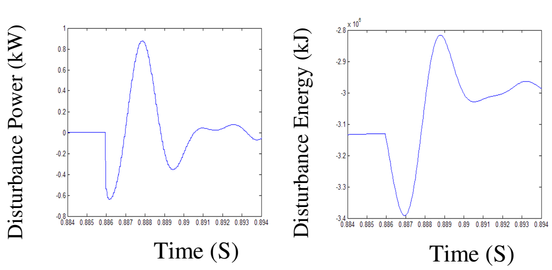

Fig. 12 Monitoring at M5for back-to-back capacitor switching a) Disturbance Power b) Disturbance Energy

6 CONCLUSION

This paper has proven that the source of capacitor transient disturbance can be located by examining a change in the polarity of the complex wavelet-based energy in power distribution systems. A comprehensive analysis was carried out in which the gradient of complex wavelet energy has been proven to be accurate in locating the source of transient caused by normal capacitor switching and back-to-back capacitor switching. A comparison with a disturbance power and disturbance energy technique has proven that the wavelet technique is more accurate than the DP and DE method in locating the source of capacitor switching transient. The advantage of the proposed method is that it requires only single-phase voltage and current measurements at the monitoring point, thus overcome the shortcoming of three-phase measurement required as in the disturbance power and energy method [3].

REFERENCES

[1] S. Santoso, E. J. Powers, W. M. Grady, & A. C. Parson, Power Quality Disturbance Waveform Recognition Using Wavelet-Based Neural Classifier-Part 1: Theoretical Foundation, *IEEE Trans. Power Delivery*, *15*. 2000. 222-228.

[2] S. Santoso, E. J. Powers, W. M. Grady, & A. C. Parson, Power Quality Disturbance Waveform Recognition Using Wavelet-Based Neural Classifier-Part 2: Application, *IEEE Trans. Power Delivery*, *15*, 2000, 229-235.

[3] Y A. C. Parson, W. M. Grady, E. J. Powers, & J. C. Soward, A direction finder for power quality disturbances based upon disturbance power and energy, *IEEE Trans. Power Delivery*, *15*, 2000, 1081-1086.

[4] A. C. Parsons, W. M. Grady, E. J. Powers & J. C. Soward, Rules for Locating the Sources of Capacitor Switching Disturbances, *Proc. Power Engineering Soceity Summer Meeting*, 1999, 794-799.

[5] W. D. Stevenson, Jr, *Elements Of Power System Analysis,*(McGraw-Hill, Singapore,1982)

[6] S. Santoso, W. M. Grady, E. J. Powers, J. Lamoree & S. C. Bhatt, Characterization of Distribution Power Quality Events with Fourier and Wavelet Transforms, *IEEE Trans. Power Delivery*, *15*, 2000, 247-254.

[7] D. J. Zhang, Q. H. Wu, Z. Q. Bo & B. Caunce, Transient Positional Protection of Transmission Lines Using Complex Wavelets Analysis, *IEEE Trans. Power Delivery*, *18*, 2003, 705-710.

[8] J. Driesen & R. Belmans, Wavelet-based power quantification approaches, *IEEE Trans. Instrum. Measurement.52*, 2003,1232-1238.