Applications of Complex Wavelets to Locate Source Of Transient In Power System

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Abstract— This paper provides solutions in locating the source of the transient based on complex wavelet energy. 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. Initially, there is no wavelet energy during steady-state condition, but during a transient condition, a wavelet energy is produced by the transient disturbance in power distribution systems. By examining the change in the wavelet energy between the steady state condition and during transient event, it is possible to locate the source of a transient disturbance. 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 from downstream or 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 from upstream or behind the monitoring point. To verify the proposed complex wavelet method, simulations using the PSCAD/EMTDC software have been performed. Simulation results prove that complex wavelet energy is capable of locating accurately the source of transients in a power distribution system.

Index Termss— Power quality, transient analysis, wavelet transform

I. 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. A wrong mitigation solution can aggravate the power system transient problem because only after information about a disturbance source location is available, can power-quality trouble shooting, diagnosis and mitigation be carried out. 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. This means that the degree of confidence will be reduced if the results of DE and DP do not match. 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 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 $R = \left| DE^{-} / \Delta DE \right|$. The rule sets a threshold value such that if R < 25% and R ≥ 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 rely on the waveforms of DP and DE and can only be calculated if the three phases of voltages and currents are available.

From the literature, neither time frequency nor wavelet transform has been employed to locate the source of transient disturbances. However, complex wavelet transform has been used to provide the instantaneous phase-related information such as that of a transient signal [5, 6]. One of the early application of a complex wavelet is found in [6] in which a mother wavelet known as the "Chaari wavelet" is used to analyze waveforms in terms of their argument and modulus.

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Another application of complex wavelet in power system analysis is for detecting a fault position according to their relative traveling times and polarities [7]. The algorithm adopted in [7] 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 has also been used to determine phase information of the sending and receiving signals in low-voltage distribution networks [8]. By considering the phase differences between the receiving and the sending signals, the Mallat and Mayer's based complex wavelet is employed to obtain the phase information of these signals.

This paper proposed a new method based on the complex wavelet analysis to locate the source of a transient relative to its monitoring point. The method exploits the complex wavelet transform to calculate the difference between transients voltage and current angle at a measuring point. The complex wavelet transform is used because it has been proven to be able to provide a difference in phase information of the transient signals in [7,8]. In this paper, instantaneous voltage and current waveforms at the monitoring points are transformed into their complex components by using the complex Gaussian wavelet. From these complex component values, the characteristics oscillation of the wavelet power is used to classify the cause of a transient and the change in energy flow is be used to locate a transient disturbance as to whether it is behind or in front of the monitoring point.

II. Capacitor Switching Transient

Power system transients can be classified into oscillatory and impulsive transients [9]. The main cause of oscillatory transients are capacitor energizing, re-strike during capacitor de-energizing, back-to-back capacitor switching and capacitor voltage magnification. For an impulsive transient, lightning is the main cause. 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 [10].

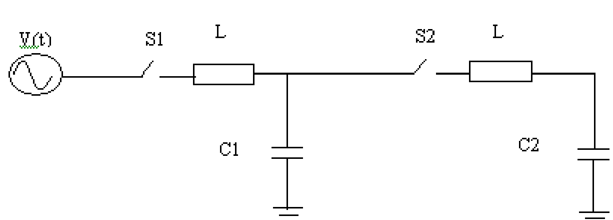

Fig. 1. Simplified circuit with L-C loops

In electrical power systems where the natural frequency of the LC loop are higher than the fundamental frequency (50 Hz), the over voltage should continuously increase as the ratio of the natural frequencies approach unity since the natural frequency is constant [11]. 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 [12]:

$$V_{C1}(t) = V - \left[(V - V_{C1}(0).\cos \omega_1 t)\right] \quad (3)$$

$$I_1(t) = \frac{V}{Z_1} \sin \omega_1 t \quad (4)$$

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 (3), it is shown that upon closing of S1, transient over voltage will occur in the circuit with the voltage higher than the bus voltage. Considering Fig. 1 with S2 already being switched off and upon switching off S1, the voltage on the remote capacitor C2 (p.u) is represented by the following equation [13],

$$\frac{V_{C2}}{V} = 1 + A\cos \phi_1 t + B\cos \phi_2 t \quad (5)$$

The amplified voltage at the remote capacitor, C2 is composed of three components i.e. the source voltage and two oscillatory components Φ_1 and Φ_2. This phenomenon is known as amplification or magnification of the voltage. The oscillatory phenomenon of the capacitor switching transient results from the energy exchanged between the inductive and capacitive elements [10,11]. The energy stored in the capacitor elements ($\frac{1}{2}CV^2$) flows into the inductive elements ($\frac{1}{2}LI^2$). 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. There are several types of capacitor energizing events namely normal energizing capacitor, back-to-back capacitor switching, utility capacitor magnification and restrike on capacitor opening events.

A Normal Energizing of Capacitor

Capacitors energizing transient events are one of the most common transient events present in power systems. The transient events occur when a capacitor is switched on. At the instant of switching, a fast change in the bus voltage occurs because the voltage in the capacitor cannot change instantaneously. The over voltage in normal energizing is usually between 1.1-1.4 p. u with its oscillation frequency typically between 300-1000Hz and last for less than half a cycle of the power frequency [16]. The oscillatory phenomena of capacitor switching transient are the result of energy exchange between the capacitive elements into the inductive elements [10,14].

B Back-to-back Capacitor Energizing

Back-to-back 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 [14].

C Capacitor Voltage Magnification

Closing off the utility capacitor causes magnification at the remote capacitor voltage. One that appears to be most commonly associated with this phenomena occurs when capacitors are being switched on from a bus which supplies a step-down transformer that has shunt capacitors installed on the secondary side [13]. Energizing a primary loop will excite the natural modes of oscillation in both primary and secondary loops [11]. Energizing the secondary loop's capacitor will take place when the primary loop's capacitor is switched off and at the same time transient overvoltage is observed at the secondary loop which is the remote capacitor voltage. This phenomenon is subjected to a severe over voltage of more than 3 p.u even when the tuning of both primary and secondary loops is not exact [11].

III. Principle Of Transient Source Location Method

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

According to [7-8], 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. The sequence of events that will take place when a normal capacitor energizing, capacitor switch restrike, capacitor voltage magnification 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,

$$P_t = V_t I_t \cos(\alpha_t - \beta_t) \quad (6)$$

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,

$$E_t = \int_B^E P_t dt \quad (7)$$

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

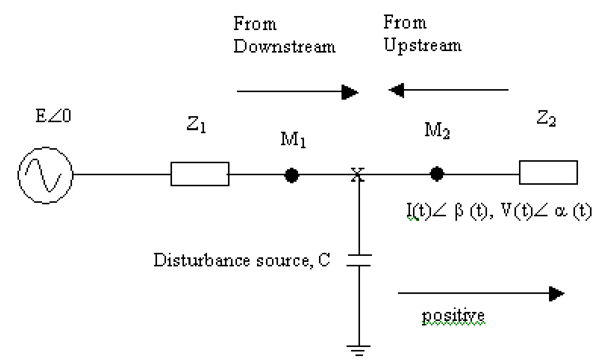

Fig. 2. Illustrating the transient source location analysis

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. Likewise, the change in energy will also be observed between steady-state condition and during a transient event. Information about changes in the instantaneous transient power is so small compared to the changes in the instantaneous transient energy.

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 (6). The integral of the real power from the beginning to the end of the transient period as given in equation (7) 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 more positive values 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 is delivered than its steady state value which is zero. 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 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.

IV. Implementation Of Wavelet Power and Wavelet Energy To Locate A Transient Source

The implementation procedure to locate a transient source using the complex wavelet power and energy is described in this section. Switching of capacitors are carried out to produce oscillatory transients. The sampling rates of the signal is 512 samples per cycle. The test systems used in this paper are shown in Fig. 3. The implementation procedure to locate a transient source using the complex wavelet energy is described in this section

A Test Systems

The test system used to verify the proposed method is shown in Fig. 5. The test system is fed from a 13.8kV, 15MVA source at 50 Hz frequencies. For oscillatory transients, three capacitor-switching scenarios are considered in the simulations, namely a correction capacitor switching, back-to-back capacitors switching and voltage magnification.

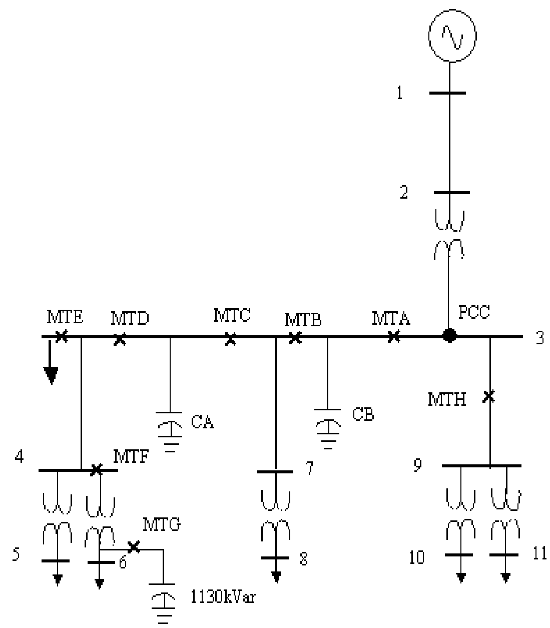

Fig. 3 Test System IEEE 11

B Implementation Procedure

The following steps describe the procedures carried out in the proposed method.

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 active complex wavelet power and its complex wavelet energy using equations (6) and (7), respectively.

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 upstream or behind the monitoring point. On the other hand, if the gradient of complex wavelet energy is negative, the transient source is downstream or in front of the monitoring point.

V. Results

In Fig. 3, capacitor CA is used for normal capacitor switching. The location of the source of transient with its respective monitoring points are tabulated in Table 1 in which capacitor CA is switched on at t = 0.725 s. From Table 1 and Fig. 3, if the monitoring is performed at PCC, MTA, MTB and MTC, the location of transient sources are seen from downstream. On the other hand if the monitoring is performed at MTD, MTE, MTF, MTG and MTH, the transient sources are seen from upstream.

TABLE 1
DETAILS OF NORMAL SWITCHING OF CA AND ITS RESPECTIVE MONITERING POINTS OF IEEE 11 BUS

Capacitor Switching	Monitoring Point	Transient Source Location
CA	PCC, MTA, MTB, MTC	Downstream
CA	MTD, MTE, MTF, MTG, MTH	Upstream

Details analysis on the complex wavelet technique is shown in Fig. 4. The voltage waveform in Fig. 4 is taken at PCC which is downstream as seen from capacitor CA. From Fig. 4a, the over voltage is resulted when capacitor CA is switched on at t = 0.725 s is 1.4 p.u and the oscillation period is 0.003 s with frequency of 333 Hz. The voltage is filtered using high pass Butterworth and the result is shown in Fig. 4b. The filtered waveform is transformed into the complex Gaussian wavelet as shown in Fig. 4c. The same procedure is carried out for current and the product of voltage and current is called the complex wavelet power in Fig. 4d. Fig. 4d shows the complex energy of the same waveform at PCC. From Fig. 4e, no transient is observed before capacitor CA is switched on at t=0.725 s. In Fig. 4, T1 is the duration of the transient starting from the switching of capacitor CA at t=0.726 s until t=0.727 s. From Fig. 4b, the oscillation decreases during T2 and subsequently, the complex voltage also shows the same phenomenon in which it disappears at t = 0.0729 s. From Fig. 4e, no transient is observed before capacitor CA is switched on, hence the complex energy is zero. In Fig. 4e, during T1, a change in energy from zero towards a negative value is observed. During T2, the energy increases until it reach a stable state at t = 0.729 s. This characteristic can be explained because during T2, transient magnitude is decreased and voltage returns to its original state. From Fig. 4b, the oscillation decrease during T2 and the complex voltage also shows the same phenomenon in which it reaches zero value at t=0.0729 s. From Fig. 4e, the negative gradient indicates that the source of the transient source is from downstream.

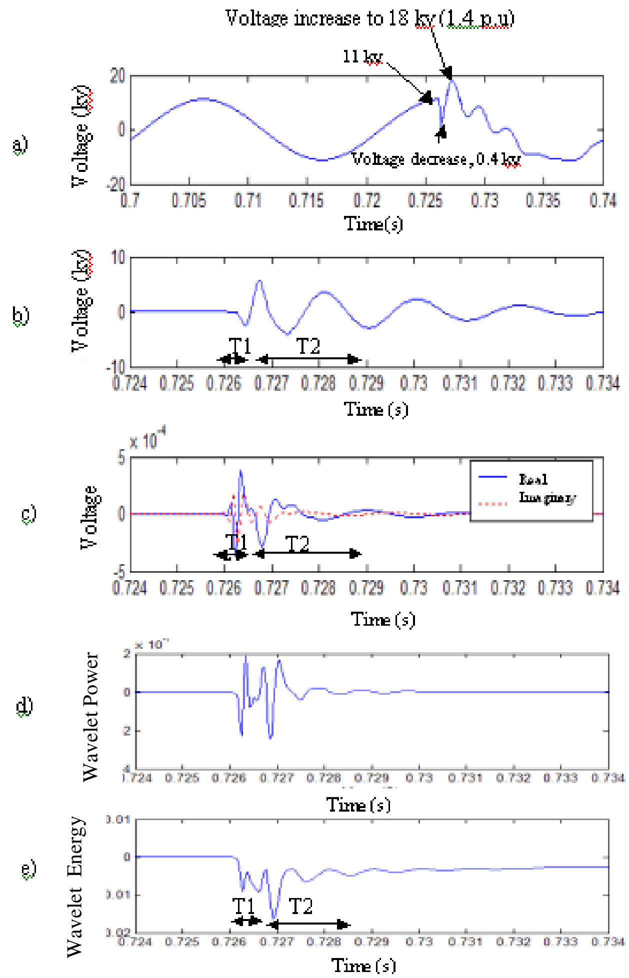

Fig. 4 Results from normal capacitor switching at PCC a) Original Voltage b) Filtered Voltage c) Complex Wavelet Voltage d) Complex Wavelet Power e) Complex Wavelet Energy

Two more results of the wavelet nergy are shown in Fig. 5. Fig. 5a shows the decrease in complex wavelet energy when the transient source is at MTC which indicate that the source of transient is from downstream. On the other hand, in Fig. 5b, the complex wavelet energy increase when the transient source is at MTG which explains that the transient source is from upstream. These results are in a good agreement with the details in Table 1. The details for back-to-back capacitor switching of capacitor CB are tabulated in Table 2.

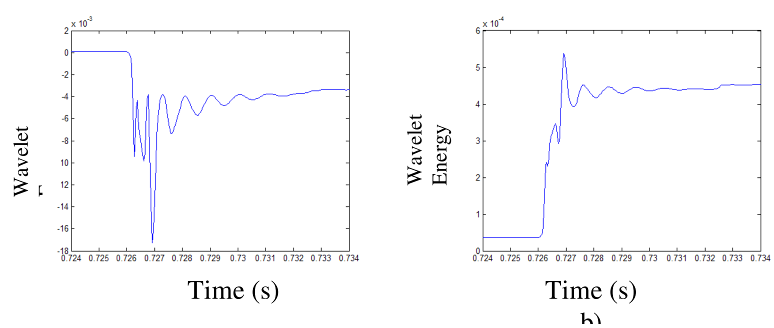

Fig. 5 Complex Wavelet Energy at a) MTC b) MTG

TABLE 2

DETAILS OF BACK-TO-BACK CAPACITOR SWITCHING OF CB AND ITS RESPECTIVE MONITORING POINTS OF IEEE 11 BUS

Monitoring point	Gradient of Complex wavelet energy	Transient Source Location	Actual transient source location
MTA	negative	downstream	downstream
MTE	positive	upstream	upstream
MTH	positive	upstream	upstream

Two samples of results for back-to-back capacitor switching are presented in Fig. 6. Figure 6a shows the complex wavelet energy decreases when the transient source is at MTA in which for downstream case. On the other hand, in Fig. 6b, the complex wavelet energy decreases when the transient source is at MTE for upstream case. Hence the wavelet energy is accurate in locating the source of transient for back-to-back capacitor switching.

Simulation for voltage magnification as a result from capacitor switching is also presented in Fig. 7. The transient over voltage at capacitor CA and its respective magnification voltage at MTG is shown in Fig. 7a and Fig. 7b respectively. In Fig. 7b, a magnification of voltage at MTG is resulted from the switching of capacitor CA. In Fig. 7c, it is shown that the wavelet energy at MTG increases in which indicates that the transient source is from upstream in which the source of transient is capacitor CA which is from upstream as seen from the 1130kvar capacitor in Fig. 3

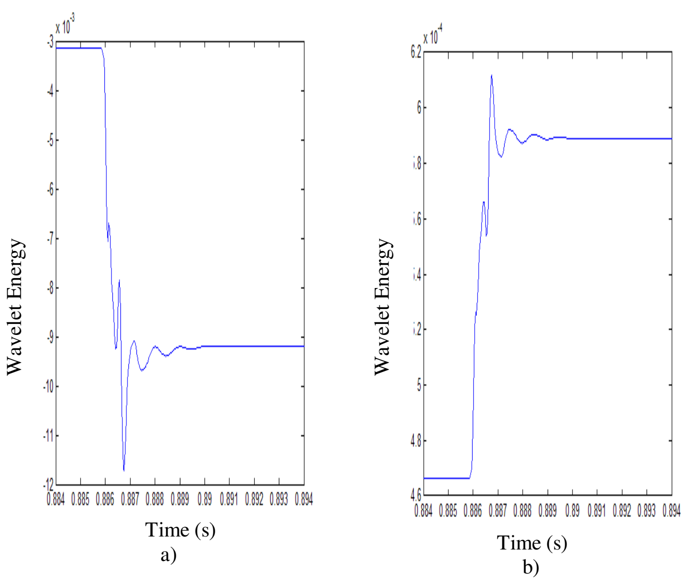

Fig. 6 Back to back capacitor switching at:
a) MTA b) MTE

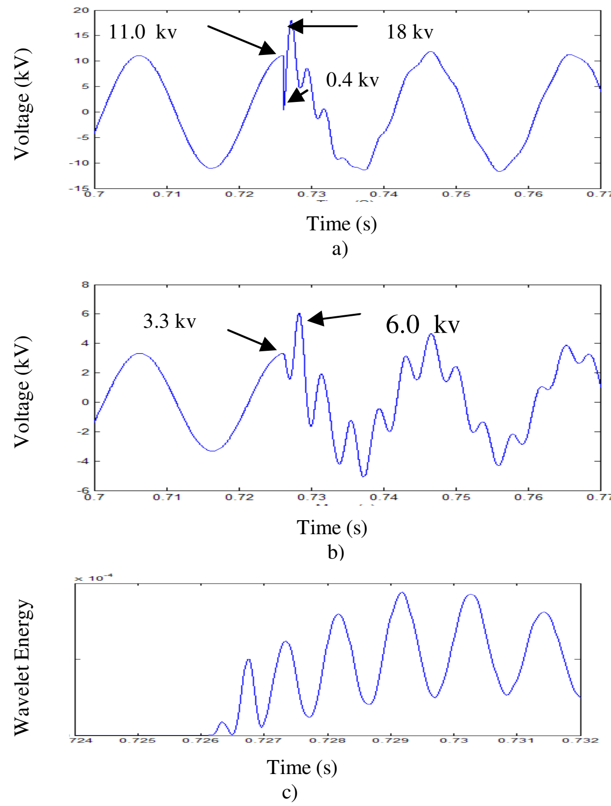

Fig. 7 Magnification of capacitor voltage at MTG
a) Transient Voltage b) Magnifying Voltage
c) Wavelet Energy

VI. VI CONCLUSION

This paper has presented that the source of transient disturbance in power distribution systems can be located by examining the gradient of a wavelet energy. 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 power and 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, the increase in wavelet energy indicates that the transient source is from upstream. On the other hand the decrease in wavelet energy indicates that the transient source is from downstream. If several recording devices are available in a power distribution system, the source of the disturbance can be located. The method has been proven on normal capacitor switching, back-to-back capacitor switching and also the magnification voltage.

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 customer as the transient disturbance contributor. 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:

- 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].
- 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.
- 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.

VII. 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, vol. 15, pp. 222-228, July 2000.

[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, vol.15, pp. 229-235, July 2000.

[3] Y. J. Shin, A. C. Parson, E. J. Powers, W. M Grady, "Time-Frequency Analysis of Power System Disturbance Signals for Power Quality," in Proc. 1999 IEEE Power Engineering Society Summer Meeting, vol. 1, pp. 402-407.

[4] L. Angrisini, P. Daponte, M. D'Apuzzo, A. Testa, "A Measurement Method Based on the wavelet transform for power quality analysis," IEEE Trans. Power Delivery, vol. 13, pp. 990-998, Oct. 1998.

[5] 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, vol. 15, pp. 1081-1086, July 2000.

[6] A. C. Parsons, W. M. Grady, E. J. Powers and J. C. Soward, "Rules for Locating the Sources of Capacitor Switching Disturbances," Proc. Power Engineering Soceity Summer Meeting, July. 18-22, pp. 794-799, 1999.

[7] J. Driesen and R. Belmans, "Time frequency analysis in power measurement using complex wavelets," in Proc. IEEE Int. Symposium Circuits and Systems, May 26-29, 2002.

[8] J. Driesen and R. Belmans, "Wavelet-based power quantification approaches," IEEE Trans. Instrum. Meas., vol. 52, pp. 1232-1238, pp. 2003.

[9] M. Meunier and F. Brouaye, " Fourier transform, wavelets, prony analysis: Tools for harmonics and quality of power," in Proc. 8th Int. Conf. Harmonics and Quality of power, Athens, Oct. 14-16, 1998, pp. 71-76.

[10] R. Fehr, "The Trouble With Capacitors – Part 2," Electrical Construction & Maintenance Magazine, Jan1, 2004.

[11] W. D. Stevenson, Jr, Elements Of Power System Analysis, McGraw-Hill, 1982, pp. 113-122.

[12] S. Sanotoso, 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, vol. 15, pp. 247-254, January 2000.

[13] A. Greenwood, "Electrical Transients in Power System", John Wiley & Sons inc., New York 1991.

[14] IEEE, FEET Appear Protective Devices Committee, WG 3.4.17, "Impact of Shunt Capacitor Banks on Substation Surge Environment and Surge Arrester Applications", IEEE Trans. Power Delivery, vol. 15, no. 4, pp. 1798-1807, October 1996.

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