The Effects of the Fault Inception Angle in Fault-Induced Transients on Series Compensated and Non-Compensated Transmission Lines

A. H. P. Sobrinho+, F. B. Costa*, B. A. Souza+

***Abstract*—The fault-induced transient analysis is an important tool for high-speed fault detection, classification, and location. Therefore, the assessment of the effects of fault parameters such as fault location, resistance, and inception angle in fault-induced transients is quite remarkable for fault diagnosis. In addition, series compensation usually causes fails in conventional protective methods and the investigation of the effects of a series capacitor in fault-induced transients is also important. This paper aims to study the effects of the fault inception angle in the energy of the fault-induced transients in voltages and currents for both non-compensated and series compensated transmission lines. The features of fault-induced transients are evaluated by means of the wavelet coefficient energy analysis. The faults were simulated in real-time by using the Real Time Digital Simulator (RTDS™) and the wavelet analysis was performed offline by using the software Matlab®.**

***Index Terms*—Fault-induced transients, series compensation, transmission lines, wavelet coefficient energy.**

I. Introduction

It is well-known that series compensation on transmission lines may be responsible for fails in fundamental frequency-based methods for fault location [1]. Series compensation may include both subharmonic-frequency oscillations on the system and voltage and current inversions, that affect the operation of distance and directional protective elements.

When a fault occurs upon a transmission line, the abrupt change in voltage at the point of the fault generates a high frequency electromagnetic impulse called traveling wave which propagates along the line in both directions away from the fault point at speeds close to light velocity. As a consequence, fault-induced transients with low and high frequency components can be observed at each line terminal [2].

The fault-induced transient analysis may be an important tool to implement transmission line protective methods, such as real-time fault detection, classification, and location algorithms, because such transients contain extensive information about the fault type, location, direction, and sustained time [3]. However, it is important to verify the effects of the fault parameters, such as fault inception angle, resistance, and location in the features of fault-induced transients for both non-compensated and compensated transmission lines.

Voltages and currents during faults are non-stationary signals due to the transients. Therefore, the wavelet coefficient energy analisys may be an efficient tool to evaluate the behavior of the energy of the fault-induced transients. This task can be performed by using the Maximal Overlap Discrete Wavelet Transform (MODWT) [4].

The effects of the fault inception angle in the energy of the fault-induced transients are evaluated by means of the wavelet coefficient energy. However, this paper extends the analysis of [4] by evaluating the effects of both non-compensated and series compensated lines in the energy of fault-induced transients. Advantages and disadvantages of the wavelet coefficient energy (energy regarding fault-induced transients) analysis for high-speed fault detection, classification, and location are also dealt in this paper. The fault-induced transient simulation is performed by using the Real Time Digital Simulator (RTDS™).

This paper is organized as follows: Section 1: Introduction; Section 2: Series Compensation on Transmission Lines; Section 3: Wavelet Coefficient Energy; Section 4: Power System Model Simulation; Sections 5: Features of Fault-Induced Transients on Non-Compensated and Series Compensated Lines in single line-to-ground (SLG), line-to-line (LL), double line-to-ground (DLG), and three line faults; Section 6: Conclusions.

II. Series Compensation on Transmission Lines

Series compensation by using a capacitor is useful to reduce the effects of the transmission line series reactance. The main advantages of series compensated transmission lines are:

- Increasing of power transfer capability;
- Increasing of both steady-state and transient stability limits;
- Reducing of loss and voltage drops;
- Influence on load flow in parallel transmission lines.

As disadvantage, the series compensation includes subharmonic-frequency oscillations on the system due to the changing of the line reactance. Therefore, series compensation may affect fundamental frequency-based protective methods, whereas travelling wave-based methods may not be affected by these compensations. In addition, series compensation on transmission lines may include voltage and current inversions, that may affect the operation of distance and directional protective elements [5].

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High-frequency transients can be also generated by series compensation, but these transients are attenuated by analog and digital filters in microprocessor-based relays [6]. Once conventional protection methods are influenced by the series compensation, it is a great motivation to verify its influence in high-frequency transient-based algorithms.

III. Wavelet Coefficient Energy

The wavelet transform is a mathematical tool for signal analysis which decomposes a signal into different frequency bands by a process of scaling and displacement on a base function named mother wavelet. Discrete Wavelet Transform (DWT) and Maximal Overlap Discrete Wavelet Transform (MODWT) are used in most power system disturbance analysis. Both of them are commonly implemented as a bank of filters scaled in octaves. The down-sampling process is only presented in DWT. Therefore, fault-induced transients are fastest detected by means of MODWT [3].

The idea behind the MODWT is that a signal may be an input for two filters (scale and wavelet filters), i.e., low- and high-pass filters, respectively. The low-pass filter outputs (s) are the scaling coefficients (low frequency information of the input signal), while the high-pass filter outputs (w) are the wavelet coefficients (high frequency information). This process comprises the step in the first scale. The scaling coefficients may be input for other bank of filters, resulting in scaling and wavelet coefficients in various scales.

According to the theorem of Parceval, the energy of a signal can be decomposed in terms of the energy of the wavelet coefficients at scales $j = \{1, 2, ..., J\}$ and the energy of the scaling coefficients at the scale J of MODWT [7], as follow:

$$\sum_{k=1}^{k_t} |x(k)|^2 = \sum_{k=1}^{k_t} |s_J(k)|^2 + \sum_{j=1}^{J}\sum_{k=1}^{k_t} |w_j(k)|^2, \tag{1}$$

wherein s_J are the scaling coefficients at scale J; w_j are the wavelet coefficients at scale j $\leq J$;$\sum_{k=1}^{k_t} |s_J(k)|^2$ is the scaling coefficient energy at scale J; $\sum_{k=1}^{k_t} |w_j(k)|^2$ is the wavelet coefficient energy at scale j; $\sum_{k=1}^{k_t} |x(k)|^2$ is the energy of the original signal; k_t is the total number of samples of the signal.

By using an one-cycle sliding window, the wavelet coefficient energy ($\dot{\mathcal{E}}$) of the MODWT, computed at sample k_i and at the first scale, is defined as [4]:

$$\dot{\mathcal{E}} = \sum_{k=k_i-\Delta k}^{k_i} |w(k)|^2, \tag{2}$$

wherein $\Delta k = f_s/f$ is the coefficient amount equivalent to one cycle of the fundamental power frequency (f); f_s is the sampling frequency.

The mother wavelet Daubechies with four filter coefficients (db4) was used in this paper due to its good performance in transient analysis in power system signals [8].

IV. Power System Model Simulation

The effects of the fault inception angle in fault-induced transients for non-compensated and series compensated lines were evaluated using the simplified power system transmission depicted in Fig. 1, which was modeled and simulated by using the RTDS$^{\text{TM}}$. That power system is composed of a 500 kV transmission line lenght of 400 km, two circuit breakers (CB_1 and CB_2) and two voltage sources (S_1 and S_2) with the respective equivalent impedances (Z_1 and Z_2). A fixed series capacitor (SC) at the middle of the line is switched in/off for compensated/no-compensated line. In this paper, the compensation degree is equal to 40%.

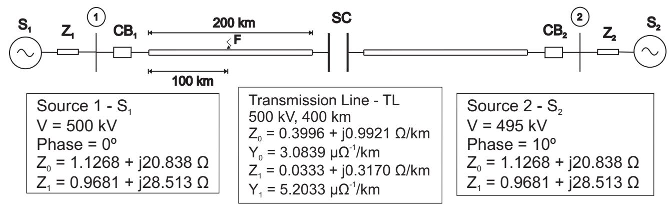

Fig. 1. Simplified power system model.

All kinds of faults with fault resistance $r_f = 1\ \Omega$, fault distance $d_f = 100$ km from the bus 1, and fault inception angle from 0 to 180 electrical degrees (1 by 1) as well as faults for non-compensated and compensated lines were simulated, totaling 1810 faults. In this paper, the fault inception angle is the angle of the phase A voltage in the fault point (v_{Af}).

At the fault location, the sample related to fault inception time is k_f, that corresponds to the phase angle θ_f of the voltage v_{Af}. However, due to the transit time of the traveling waves from the fault location to bus 1, fault-induced transients at bus 1 start at sample k_1, wherein $k_1 > k_f$. At sample k_1, the phase angle of the phase A voltage (v_a) is $\theta_f + \Delta\theta$, wherein $\Delta\theta = ((k_1 - k_f)/nA).180^\circ$ (function of the fault location) and nA is the number of samples per cycle of v_a.

The behavior of the energy of the transients is proportional to the wavelet coefficient energy [4]. Therefore, in order to obtain the behavior of fault-induced transient energy with respect to the fault inception angle in both non-compensated and series compensated lines, the wavelet coefficient energy of voltages and currents at bus 1 were evaluated for each type of fault. The wavelet coeffient energy for all voltage and current signals are $\dot{\mathcal{E}}_{v_a}^{type}$, $\dot{\mathcal{E}}_{v_b}^{type}$, $\dot{\mathcal{E}}_{v_c}^{type}$, $\dot{\mathcal{E}}_{v_n}^{type}$, $\dot{\mathcal{E}}_{i_a}^{type}$, $\dot{\mathcal{E}}_{i_b}^{type}$, $\dot{\mathcal{E}}_{i_c}^{type}$, and $\dot{\mathcal{E}}_{i_n}^{type}$, wherein $type$ may be any kind of fault (AG, BG, CG, AB, BC, CA, ABG, BCG, CAG, or ABC fault).

V. Features of Fault-Induced Transients on Non-Compensated and Series Compensated Lines

In this section, it is shown the effects of the fault inception angle in the energy of the fault-induced transients, evaluated by means of the wavelet coefficient energy for both non-compensated and series compensated lines and for all types of faults.

A. Single Line-to-Ground Faults

Fig. 2 depicts the wavelet coefficient energy of the voltage signals versus the fault inception angle for AG, BG, and CG faults on non-compensated and series compensated lines. Fig. 3 depicts the same analysis obtained for currents signals.

By using regression analysis, it was verified that [4]

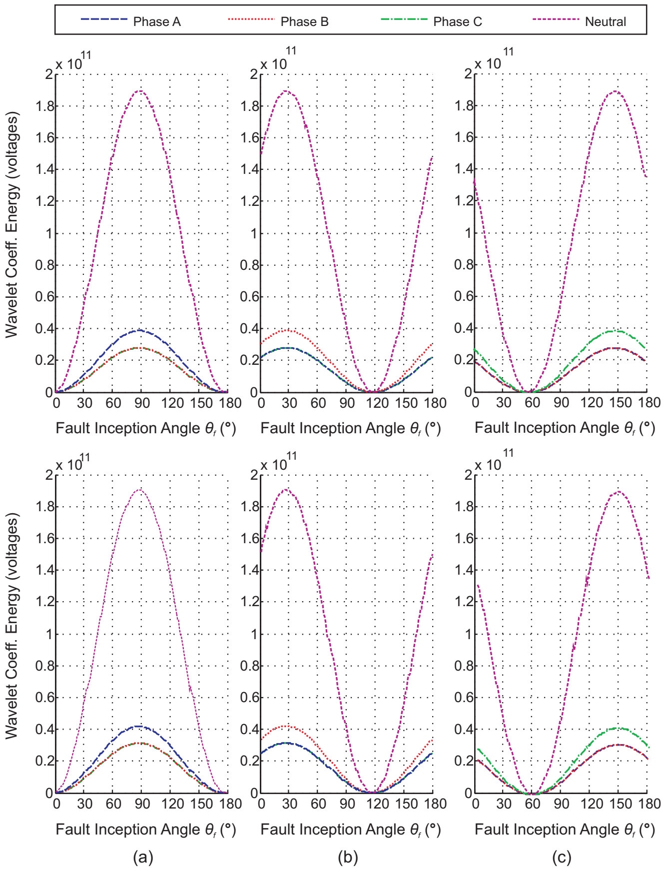

Fig. 2. Wavelet coefficient energy obtained in bus 1 to voltages for non-compensated and series compensated lines: (a) AG faults; (b) BG fauts; (c) CG faults.

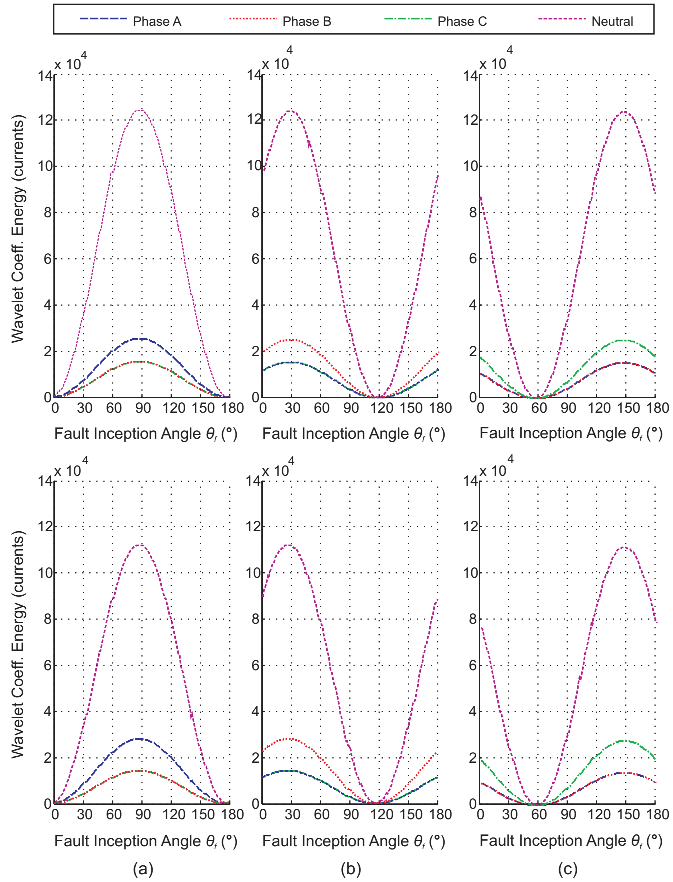

Fig. 3. Wavelet coefficient energy obtained in bus 1 to currents for non-compensated and series compensated lines: (a) AG faults; (b) BG fauts; (c) CG faults.

$$\dot{\mathcal{E}}(\theta_f) = E_1 \sin^2(\theta_f + \beta), \tag{3}$$

for all voltages and currents, wherein E_1 is the amplitude of the energy and $\beta = \{0, -120°, \text{and } 120°\}$ for AG, BG, and CG faults, respectively.

According to Figs. 2 and 3, wavelet coefficient energy for both voltage and current signals as well as the energy of the fault-induced transients present the following features:

- The wavelet coefficient energy are square sinusoidal functions of the fault inception angle;
- The energy of fault-induced transients are larger than the steady-state energy, ideal for fault detection purpose;
- The energy peak (related to the most severe transients) corresponds to the maximum voltage in faulted phase. Therefore, with regard to AG, BG, and CG faults, fault-induced transients are more intensive when $\theta_f = 90°, 30°, \text{and } 150°$, respectively;
- There are fault inception angles for which the wavelet coefficient energy values are almost zero (there are no transients): 0°, 120°, and 60° for AG, BG, and CG faults, respectively. Therefore, algorithms based on travelling waves or transient analysis probably will fail to detect faults in such fault inception angle;
- Due to mutual coupling effects between phases, both voltage and current signals in sound phases are also affected by fault-induced transients. However, as expected, the energy related to the transients in faulted phases is clearly distinguished from sound phases. Thus, transient-based analysis can be used for fault classification purpose;
- The fault-induced transients are detected at sample corresponding to $\theta_f + \Delta\theta$. However, the energy regarding to transients are function of $\theta_f + \beta$, wherein β depends on the type of fault. Therefore, $\Delta\theta$ can be identified and the fault can be located by using information of only one bus;
- For series compensation cases, the behavior of the wavelet coefficient energy does not changed. However, transients were a little more intensive. Therefore, the compensation will not affect travelling wave or transient-based fault detection methods.

B. Line-to-Line Faults

Fig. 4 depicts the wavelet coefficient energy of the voltage signals versus the fault inception angle for non-compensated and series compensated transmission lines, in a case of line-to-line faults. Fig. 5 depicts the wavelet coefficient energy regarding to current signals, respectively.

According to Figs. 4 and 5, wavelet coefficient energy for both voltage and current signals as well as the energy of the fault-induced transients present the following features:

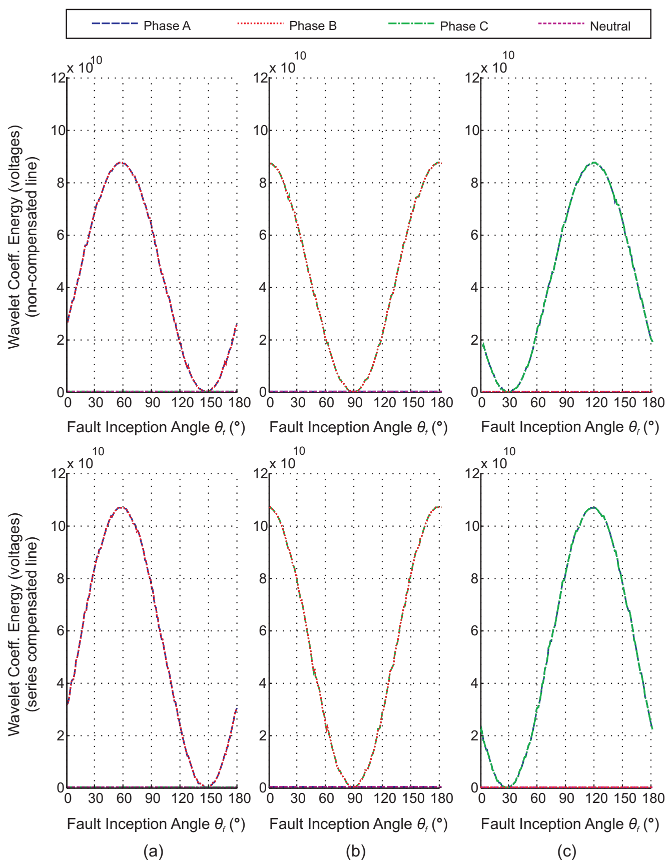

Fig. 4. Wavelet coefficient energy obtained in bus 1 to voltages for non-compensated and series compensated lines: (a) AB faults; (b) BC fauts; (c) CA faults.

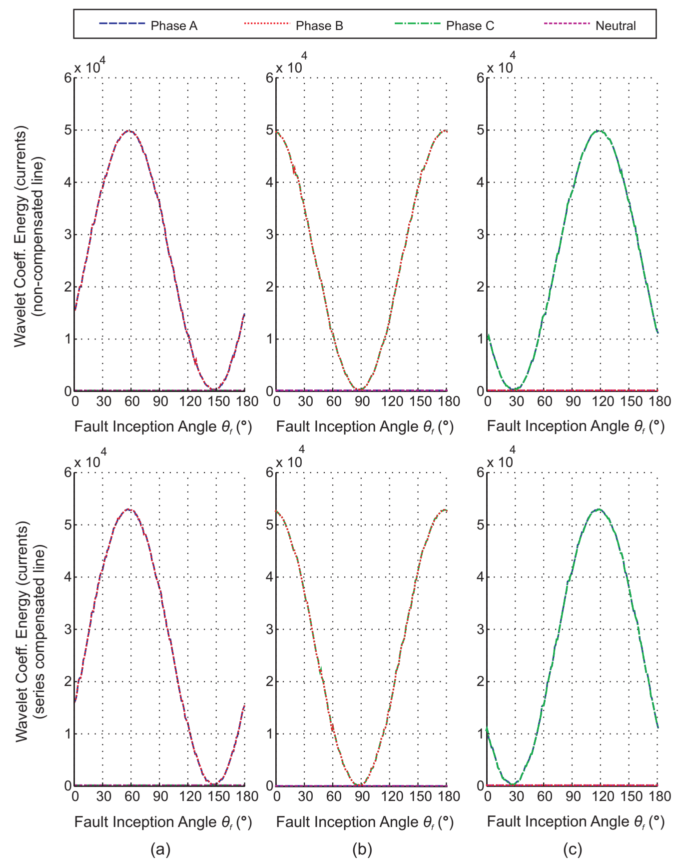

Fig. 5. Wavelet coefficient energy obtained in bus 1 to currents for non-compensated and series compensated lines: (a) AB faults; (b) BC fauts; (c) CA faults.

- The wavelet coefficient energy are square sinusoidal function of the fault inception angle (Eq. 3);
- Once the maximum line voltage is higher than the maximum phase voltage, LL faults generate wavelet coefficient energy (fault-induced transients) more severe than SLG faults;
- The most severe fault-induced transient conditions for LL faults are $\theta_f = 60°, 0°$, and $120°$ for AB, BC, and CA faults, respectively;
- The wavelet coefficient energy are almost zero for fault inception angles of $150°, 90°$ and $30°$ for AB, BC, and CA faults, respectively. Therefore, algorithms based on transients or travelling waves analysis may fail to detect LL faults with such angles;
- Due to the mutual coupling between the phases, both the faulted phases produce fault-induced transients in the sound phase. However, transients produced by the two faulted phases have the same magnitude but with different polarities. It means that the wavelet coefficient energy for the sound phase is almost zero [4]. Therefore, these energy can be useful for the fault classification purpose;
- For series compensation cases, the behavior of the wavelet coefficient energy does not changed. Transients were just a little more intensive. Therefore, the compensation will not affect the travelling wave or transient-based fault detection methods.

C. Double Line-to-Ground Faults

Fig. 6 depicts the energy waveforms of the voltage signals for double line-to-ground faults on non-compensated and series compensated lines. Fig. 7 depicts these waveforms for current signals.

For DLG faults, wavelet coefficient energy for voltage and current signals as well as the energy of fault-induced transients present the following features:

- Wavelet coefficient energy are square sinusoidal function of the fault inception angle (Eq. 3);
- DLG faults produce fault-induced transients for all possible fault inception angles and the fault can be always detected by means of the travelling wave or transient analysis;
- Taking into account the same fault resistance, fault location and system load, the maximum value of the wavelet coefficient energy is greater in DLG faults than SLG and LL faults (Figs. 2, 4, and 6). Therefore, the fault-induced transients in DLG faults are more severe than transients in SLG and LL faults.
- There are fault inception angles where fault-induced transients in DLG faults present the same features of fault-induced transients in LL faults. For instance, when $\theta_f = 60°$, $\dot{\mathcal{E}}^{DLG}_{v_a} \approx \dot{\mathcal{E}}^{DLG}_{v_b} \neq 0$ and $\dot{\mathcal{E}}^{DLG}_{v_c} \approx \dot{\mathcal{E}}^{DLG}_{v_n} \approx 0$ (Figs. 4 and 6). Therefore, transient-based methods may probably fail in fault classification in these specific

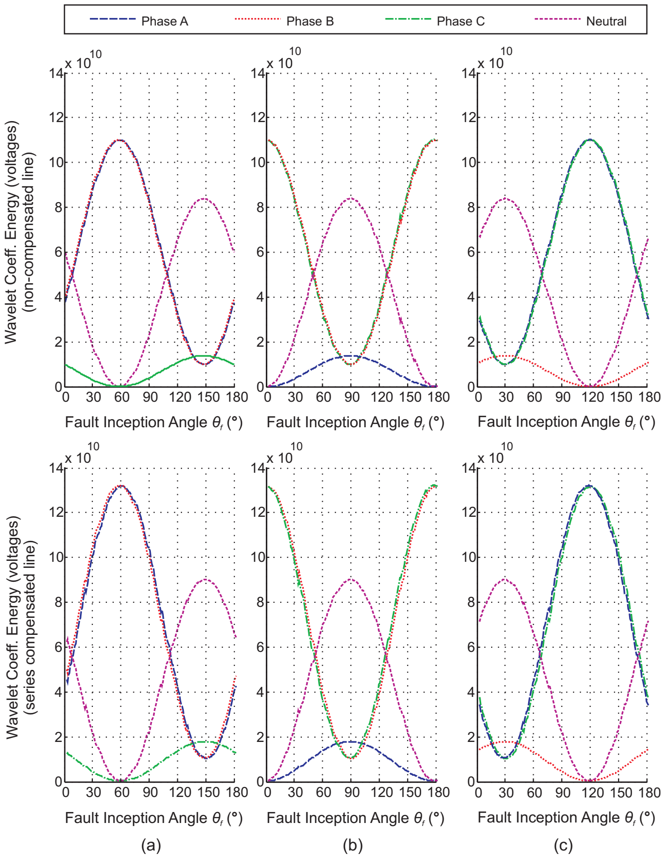

Fig. 6. Wavelet coefficient energy obtained in bus 1 to voltages for non-compensated and series compensated lines: (a) ABG faults; (b) BCG fauts; (c) CAG faults.

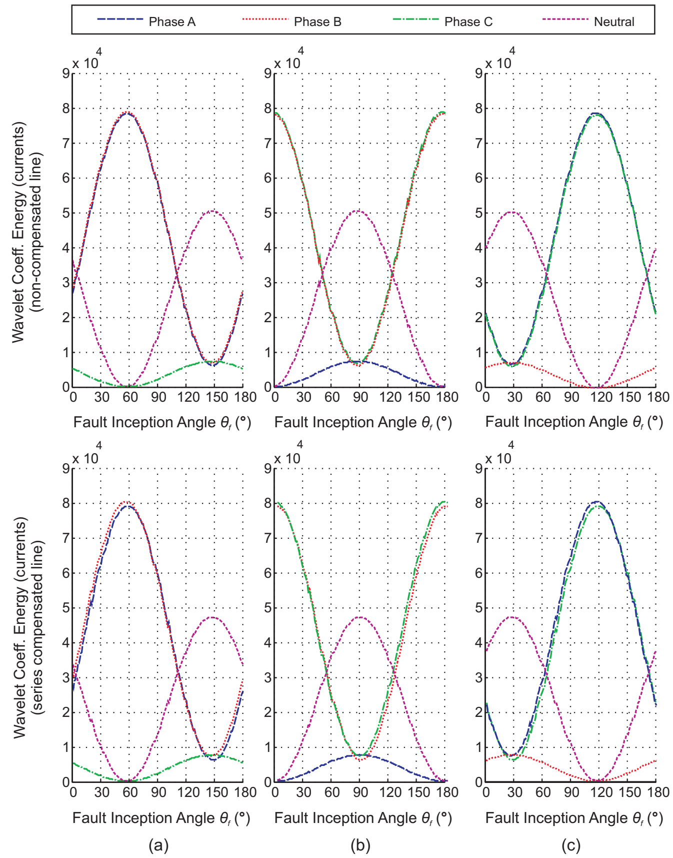

Fig. 7. Wavelet coefficient energy obtained in bus 1 to currents for non-compensated and series compensated lines: (a) ABG faults; (b) BCG fauts; (c) CAG faults.

angles;

- The compensation of the line will not affect the travelling wave and transient-based fault detection methods, because the features of the energy are the same with/without compensation.

D. Three Line Faults

Fig. 8 depicts the wavelet coefficient energy as a funtion of the fault inception angle for three line faults on both non-compensated and series compensated lines. The following features were observed:

- The wavelet coefficient energy are square sinusoidal function of the fault inception angle (Eq. 3);
- The wavelet coefficient energy of voltage and current signals are phase-shifted by 60 electrical degrees;
- For the fault inception angles $\theta_f = \{0^\circ, 60^\circ, \text{and } 120^\circ\}$, fault-induced transients of ABC faults present similar features of fault-induced transients of BC, AB, or AC faults, respectively. In these cases, a three-phase fault may be classified as LL faults by using transient-based methods for fault classification;

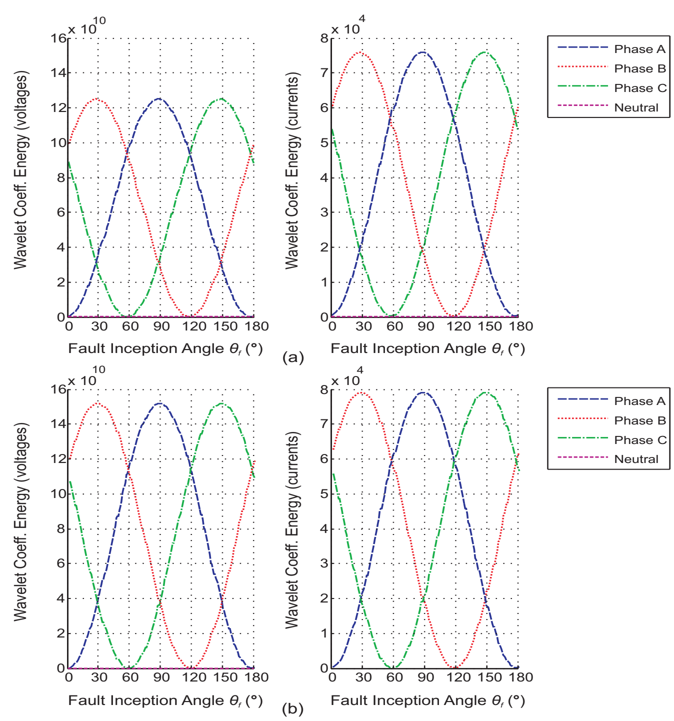

Fig. 8. Wavelet coefficient energy obtained in bus 1 to ABC faults: (a) voltages and currents in the non-compensated line; (b) voltages and currents in the series compensated line.

- For the fault inception angles $\theta_f = \{30°, 90°, \text{and } 150°\}$, fault-induced transients of ABC faults present similar features of fault-induced transients of BG, AG, or CG faults, respectively. In these cases, a three-phase fault may be classified as SLG faults by using transient-based methods for fault classification;
- The series compensation will not affect the travelling wave and transient-based fault detection methods, because the features of the energy are the same with/without compensation.

VI. Considerations on Practical Applications

The high-frequency components of the traveling waves generated by the faults are not within conventional transducer frequency ranges. In addition, the traveling wave-based fault diagnosis requires a high sampling frequency, limiting its application. However, the fault-induced transients with a typical frequency spectrum from a few hundred Hz to various kHz can provide extensive information about the fault type, detection, location, direction, and sustained time in satisfactory agreement with real application in high-speed protective relays. The traveling wave-based protection can provide very fast relay operation in transmission lines and the MODWT may be an interesting tool for real-time processing in fault diagnosis.

In this paper, the effects of instrument transformers, capacitive voltage transform (CVT) and current transform (CT), were not taken into account . These instruments are essential in practical applications. Therefore, an analysis regarding its effects in the wavelet coefficient energy for both voltage and current signals is required.

The effects of the fault resistance, fault location, transmission line compensation degree as well as the system loading in the fault-induced transients for each type of fault are also essential in practical applications such as fault detection and location in digital relays.

VII. Conclusions

The effects of both the fault inception angle and series compensation in the energy of fault-induced transients in both voltages and currents were evaluated by using the wavelet coefficient energy analysis taking into account all kinds of short-circuits.

It was verified that the energy of fault-induced transients in all voltages and currents, for all kinds of faults, are square sinusoidal functions of the fault inception angle.

With regarding to the series compensation, it was observed that this line compensation does not affect the main feature of fault-induced transients. Therefore, travelling wave and transient-based algorithms for fault detection are not influenced by series compensated transmission lines.

It was observed that travelling wave and transient-based methods by using the wavelet transform may be useful for high-speed fault detection, classification, and location.

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