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Continuous wavelet transform for ferroresonance phenomena in electric power systems

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A B S T R A C T

The common characteristics of a nonlinear system are multiple equilibrium points, limit cycles, jump resonance and sub-harmonic generation. Ferroresonance is also a nonlinear electrical phenomenon, which occurs frequently in power systems including no-load saturable transformers, transmission lines and single/three phase switching. In this work, we modeled the 380 kV West Anatolian Electric Power Network of Turkey, by performing numerical simulations using MATLAB-Simulink Power System Block-set. We generated the signals that are characteristics to the ferroresonance in order to exhibit the emergence of the nonlinear phenomenon. In addition, using the continuous wavelet transform (CWT), we observed the behavior of the ferroresonance both in time and frequency domains. Using the results of the CWT and Power Spectral Density (PSD) applications, the ferroresonance is determined from the emergence of the over voltage changes and the inter-harmonics of between $100 \pm \Delta f$ and $200 \pm \Delta f$ depending on frequency resolution $\pm\Delta f$.

1. Introduction

One of the most serious problems in electrical power systems is related to the existence of over-voltages resulting under a ferroresonant condition. It generally occurs when the system is unbalanced, like switching or the series connections of the capacitors with transformer magnetizing impedance. This situation can result in over-voltages that can cause failures in transformers, cables, and arresters [1–9]. The ferroresonance phenomenon composes to the high voltage levels because – 1 – of the relative ratios of losses, magnetizing impedance and cable capacitance fall into its more favorable range [5,6,8]. Also, the abnormal rates of harmonics and transient or steady-state over-voltages can often be dangerous for most electrical equipments in the power systems [10,11]. Therefore, in the related literature, the ferroresonance is defined as a general term applied to a wide variety of interactions between capacitors and iron-core inductors that result in unusual voltages and/or currents [1–18].

In this sense, the ferroresonance phenomenon is known as a nonlinear phenomenon that causes over-voltages in power systems [19,20]. The effect of the ferroresonance is not only be described as the jump to a higher fundamental frequency state, but also is given with bifurcations to the sub-harmonic, quasi-periodic, and chaotic oscillations in any circuit containing a nonlinear inductor [5,18,20]. This term was first used by P. Boucherot in 1920 to appellation of oscillations in circuits with nonlinear inductance and capacitance [18,19].

In this paper, West Anatolian Electric Power Network (WAEPN) of 380 kV is modeled and the characteristics due to the ferroresonance behavior are extracted. In this manner, spectral analysis techniques are applied to one of the phase (Phase R) voltages of the sample power network and obtained results are sufficient to denote the frequency properties.

2. Continuous wavelet transform

The use of wavelet transform is particularly appropriate since it gives information about the signal both in frequency and time domains. Let $f(x)$ be the signal, the continuous wavelet transform of $f(x)$ is then defined as

$$Wf(a,b) = \int_{+\infty}^{-\infty} f(x)\psi^{*}_{a,b}(x)dx \quad (1)$$

where $(*)$ indicates the complex conjugate, and

$$\psi_{a,b}(x) = \frac{1}{\sqrt{|a|}}\psi\left(\frac{x-b}{a}\right), \quad a,b \in R, \quad a \neq 0 \quad (2)$$

Here, ψ is called as a wave or the mother wavelet and it have two characteristic parameters, namely, dilation (a) and translation (b), which vary continuously. The translation parameter, "b",

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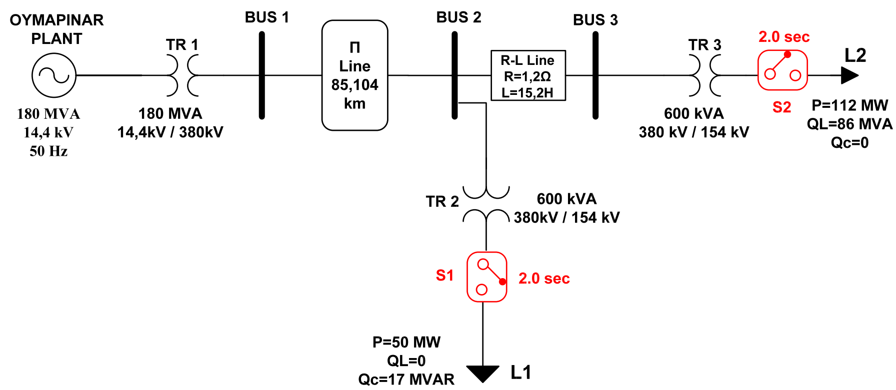

Fig. 1. Simplified Model of Oymapinar–Seydisehir line for WAPN in Turkey.

Table 1
Parameters of electrical components used for Oymapinar–Seydisehir line.

Electrical components	Parameters
Generator	180 MVA, 14.4 kV, 50 Hz
Transformers	TR_1:180 MVA, 14.4 kV/380 kV TR_2: 600 kVA, 380 kV/154 kV TR_3: 600 kVA, 380 kV/154 kV
Lines	π Line(B_1-B_2): 85.104 km R: 0.2568 Ω/km L: 2e−3 H/km C: 8.6e−9 F/km Line(B_2-B_3): R:1Ω L: 1e−3 H
Loads	L_1: P = 50 MW, Qc = 17 MVAR L_2: P = 112 MW, Q_L = 86 MVA
Switches	S_1: 2–4 s-On 0–2 s-Off S_2: 2–4 s-On 0–2 s-Off

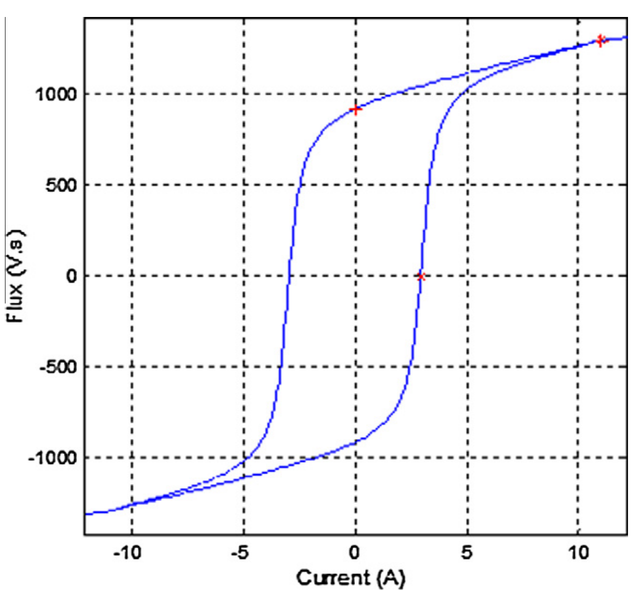

Fig. 2. Magnetization characteristic curve.

controls the position of the wavelet in time. A "narrow" wavelet can access high-frequency information, while a more dilated wavelet can access low-frequency information. This means that the parameter "a" varies with different frequency. Here, the mother wavelet function provides the following condition which is given by the following equation:

Table 2
Numerical values of some magnetization characteristics.

Characteristics	Numerical values
Saturation flux	1299.5 V s
Saturation current	11.023 A
Coercive current	2.9394 A
Remnant flux	920.48 V s

$$\int_{-\infty}^{+\infty} \psi(x)dx = 0 \quad (3)$$

And it provides the admissibility condition as follows:

$$C_\Psi = \int_0^{+\infty} \frac{|\psi(\omega)|^2}{\omega} d\omega \quad (4)$$

Here, $\psi(\omega)$ stands for the Fourier transform of $\psi(x)$. The admissibility condition implies that the Fourier transform of $\psi(x)$ vanishes at the zero frequency [21,22].

Continuous wavelet transform shows the result in time-scale plane. In this sense it works at different scales of the analyzing the function as a different approach from other methods like Gabor and Short-Time Fourier Transform in non-stationary signal analysis. This is an advantage of the CWT approach over the other methods as mentioned above. Because, the scale concept change the length of the analyzing function and in this manner analyzing function is not a constant function. Hence this type transformation determines very small effects or anomalies in the signal.

3. Ferroresonance phenomena and its modeling

In this section, the ferroresonance phenomena is introduced for electric power systems and its modeling is shown using the real power system parameters for west Anatolian Electric Power System network of 380 kV in Turkey.

3.1. Ferroresonance phenomena

Ferroresonance is a jump resonance, which can suddenly jump from one normal steady-state response (sinusoidal line frequency) to another ferroresonance steady-state response. It is characterized by an over-voltage and random time duration, which can cause dielectric and thermal problems in transmission and distribution systems. Due to the nonlinearity of the saturable inductance, many properties of the ferroresonance possesses associated with a nonlinear system is listed as follows.

Table 3
Different combinations of the switches.

	Before Ferroresonance	Ferroresonance Region	Time Delay
CASE 1	S1 S2	S1 S2	—
CASE 2	S1 S2	S1 S2 t=2.0sec	—
CASE 3	S1 S2	S1 S2	—
CASE 4	S1 S2	t=2.0sec S1 S2 t=2.0sec	Δτ=0 Sec
CASE 5	S1 S2	t=2.0sec S1 S2 t=2.2sec	Δτ=0.2 Sec

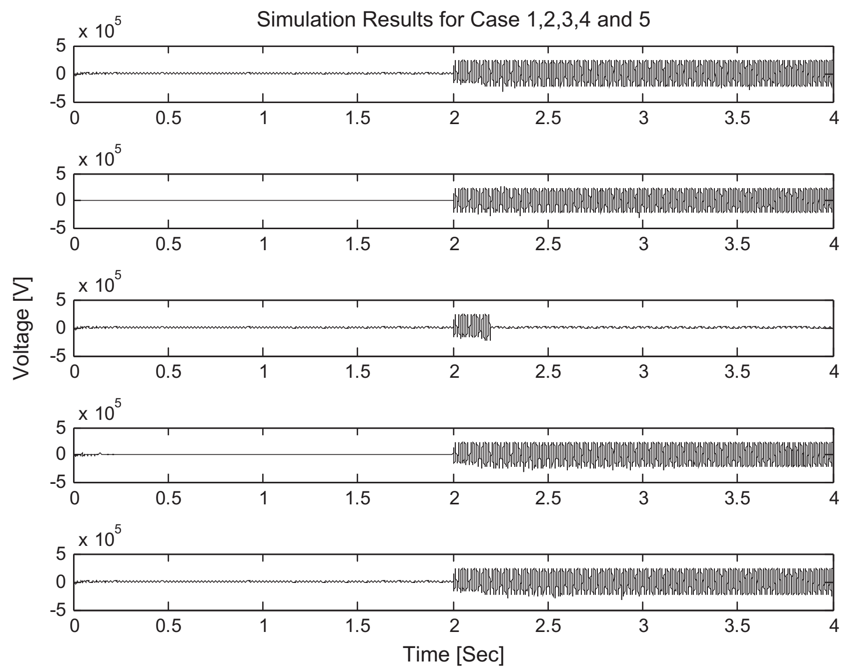

Fig. 3. Voltage variations for the ferroresonance phenomena under different scenarios.

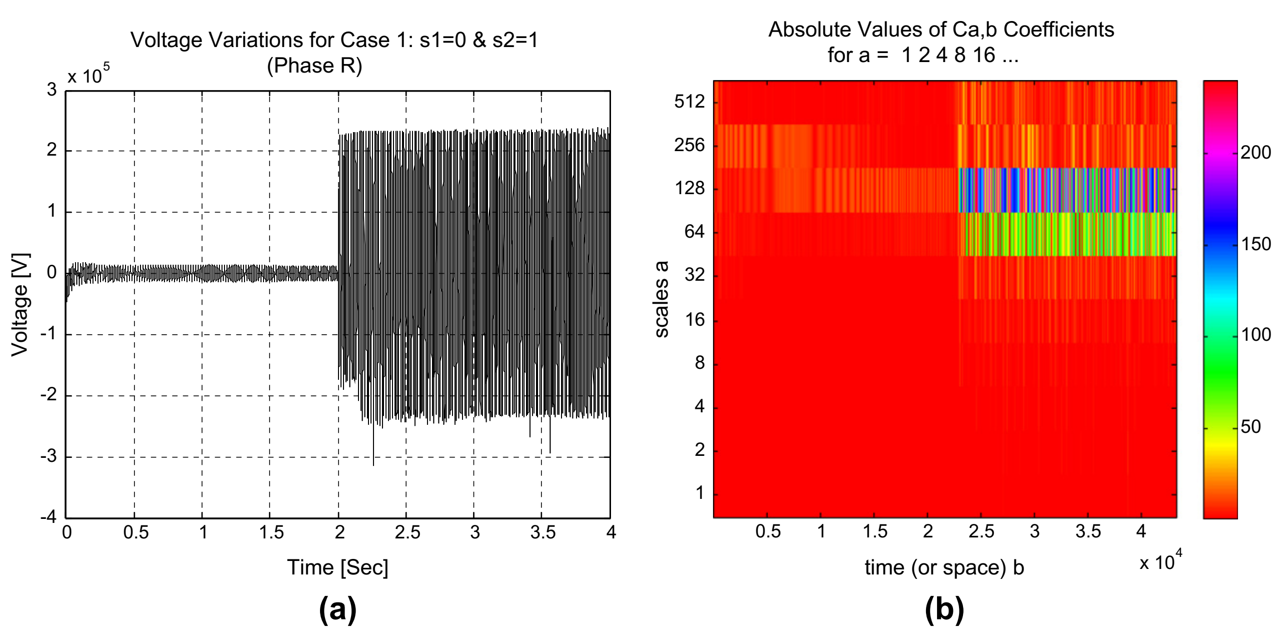

Fig. 4. Simulation result and continuous wavelet analysis for case 1. (a) Voltage variation for Phase R and (b) time-scale analysis plot.

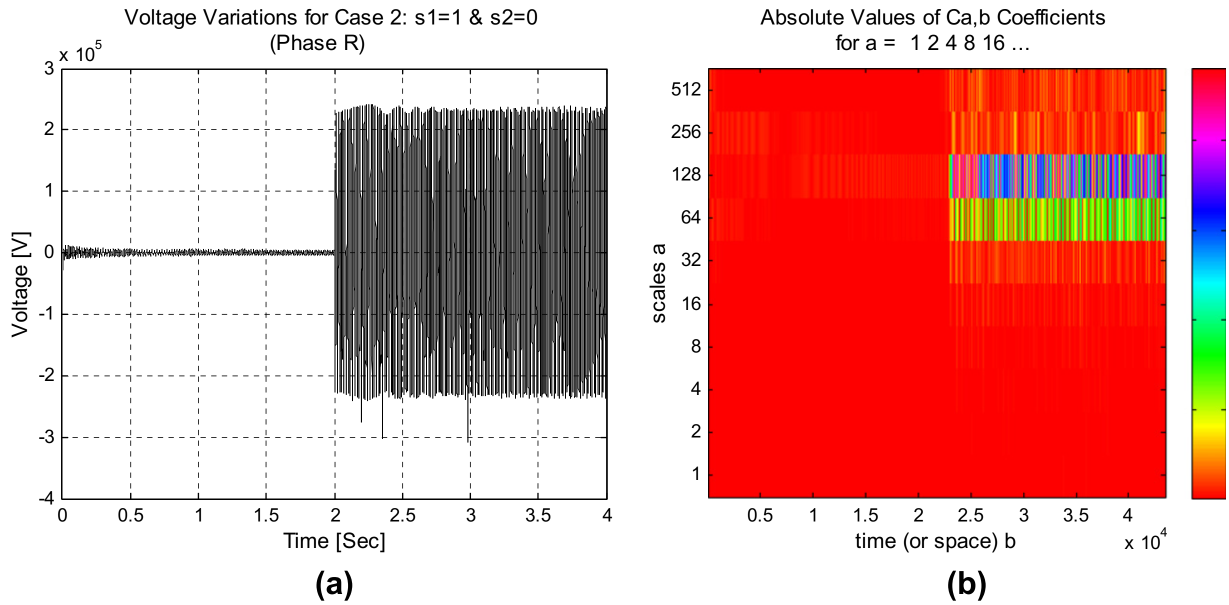

Fig. 5. Simulation result and continuous wavelet analysis for case 2. (a) Voltage variation and (b) time-scale analysis plot.

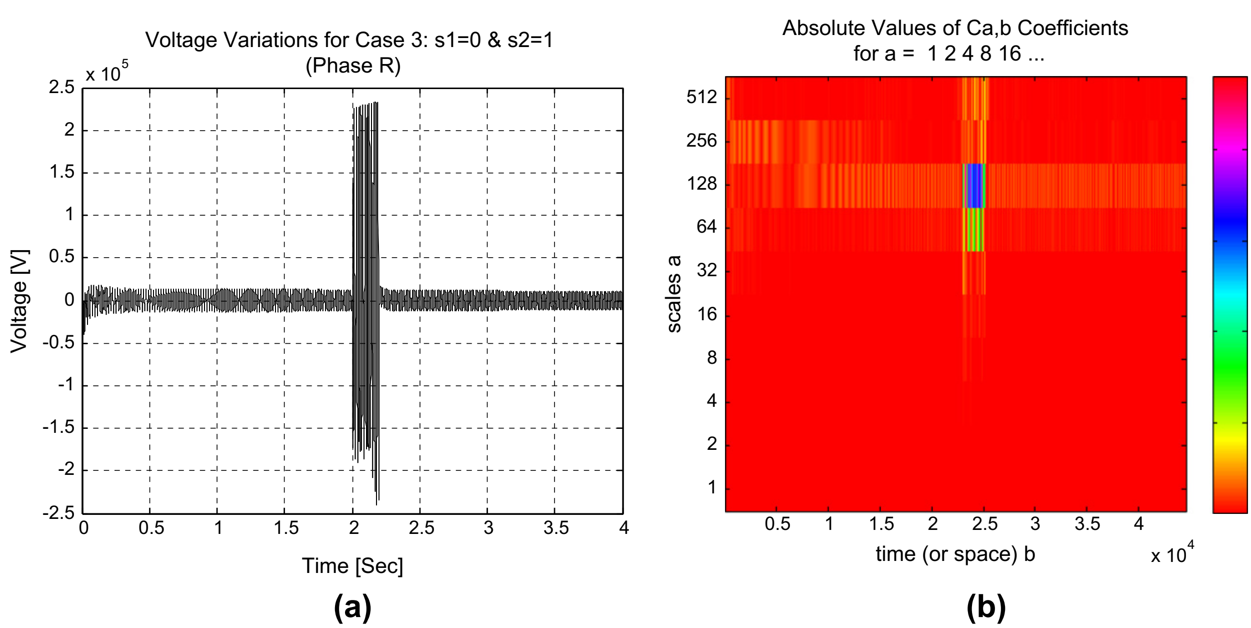

Fig. 6. Simulation result and continuous wavelet analysis for case 3. (a) Voltage variation and (b) time-scale analysis plot.

Several steady-state responses can exist for a given configuration and given set of parameters. The different solutions can occur, depending on the time of switching performed in the circuit (initial conditions). Ferroresonance is highly sensitive to the change of initial conditions and operating conditions.

Ferroresonance may exhibit different modes of operation which are not experienced in linear system.

The frequency of the voltage and current waveforms may be different from the sinusoidal voltage source.

Ferroresonance possesses a jump resonance, whereas the voltage may jump to an abnormally high level [9].

3.2. Modeling and simulations

As an application, WAEPN-West Anatolian Electric Power Network model of 380 kV in Turkey is represented in Fig. 1. The modeling and simulation studies are realized in MATLAB Power System Block-set.

Some electrical specifications of the components used in the Oymapinar–Seydisehir line can be given in Table 1.

Magnetization characteristic curve is shown in Fig. 2 and its parameters are given in Table 2.

3.3. Simulations on the model under the different scenarios

Using the simplified model as shown in Fig. 2, ferroresonance phenomena are created under the different scenarios which are given by Table 3. In Table 3, switches (S_1) and (S_2) are used to remove the loads L_1 and L_2. Considering the various combinations of the switch states, voltage measurements are taken from Bus-2 and Bus-3 of the power system [17].

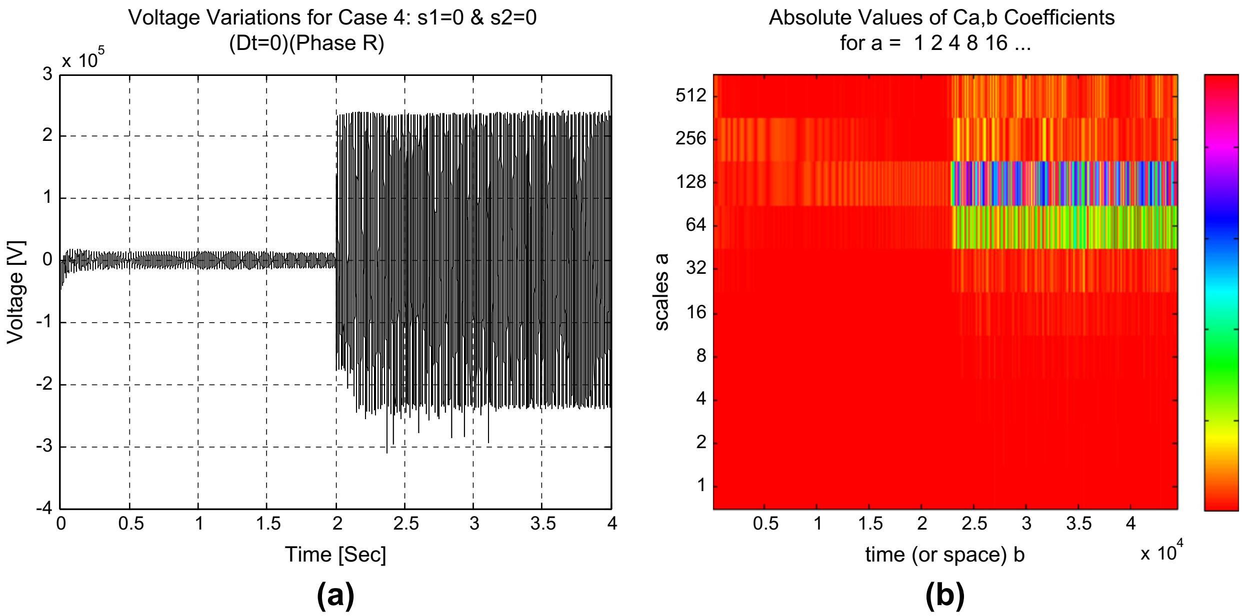

Fig. 7. Simulation result and continuous wavelet analysis for case 4. (a) Voltage variation and (b) time-scale analysis plot.

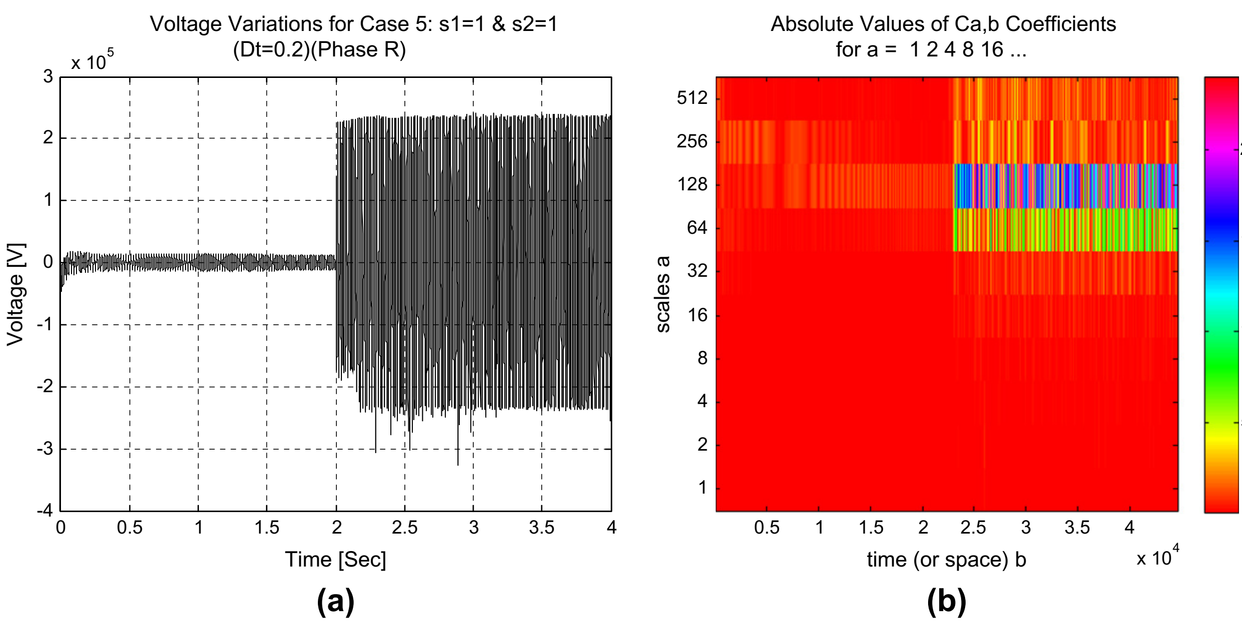

Fig. 8. Simulation result and continuous wavelet analysis for case 5. (a) Voltage variation and (b) time-scale analysis plot.

Before the ferroresonance, all switches are on positions while the ferroresonance phenomena are occurred in different on–off positions of the switches. These different situations are indicated by cases 1–5 as given in Table 3.

To indicate the ferroresonance effect, voltage variation for single phase (Phase R) in the model can be given by Fig. 3. Here, Fig. 3 shows the voltage variations to be occurred in the case of removing the load through the switch S_1 (at 2nd s), which takes place at the end of the TR_3.

According to Fig. 3, over-voltage variations are observed as a result of the ferroresonance effect by the switching.

3.4. Feature extraction by the wavelet analysis

Using the different combinations of the switches as indicated in Table 1, five different case studies can be shown by the following figures and then, time-scale properties of each different case is presented for the ferroresonance phenomena.

3.4.1. Case 1

For a given power system model as shown in Fig. 1, switches S_1 and S_2 are related to each load group at the ON and OFF positions respectively. And also, the voltage measurements are taken for the three phases from the bus 2. However, voltage variations of the Phase R are only shown.

As observed from the results of Fig. 4, ferroresonance state localizes at around the scale 128 between the 2 and 4 s. Here the equality of the scale 128, in terms of the frequency scale, is approximately 120 Hz [17].

3.4.2. Case 2

Here, switch S_1 is OFF-position while the switch S_2 is ON-position. For this case, the related voltage measurements are taken

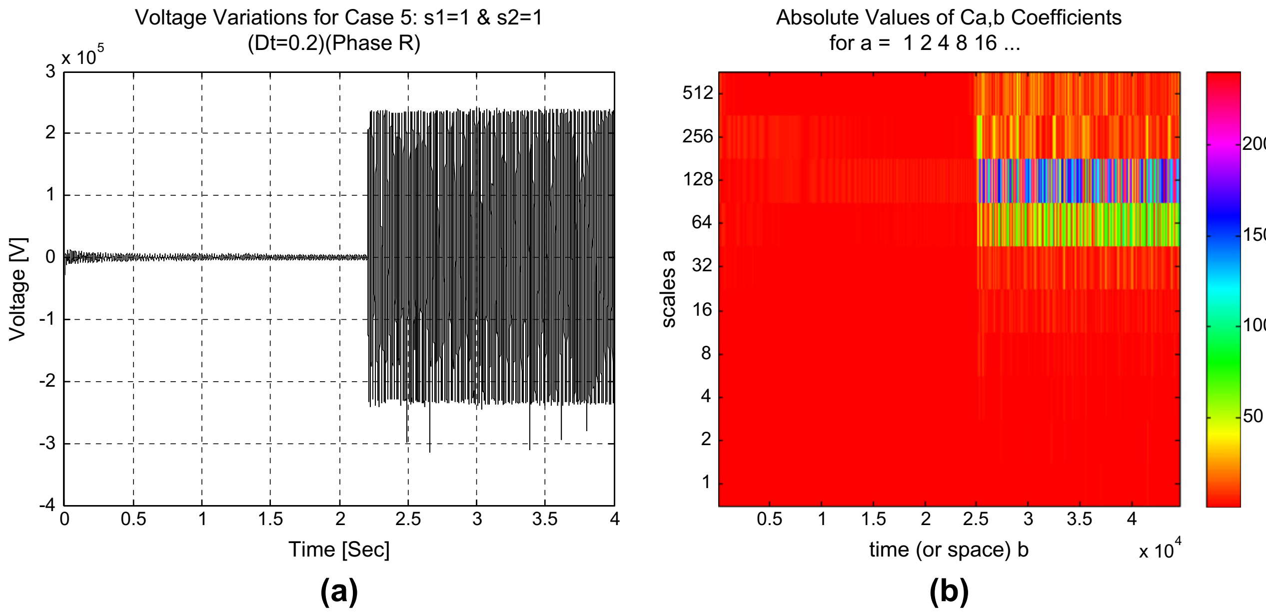

Fig. 9. Simulation result and continuous wavelet analysis for case 5 (bus 3). (a) Voltage variation and (b) time-scale analysis plot.

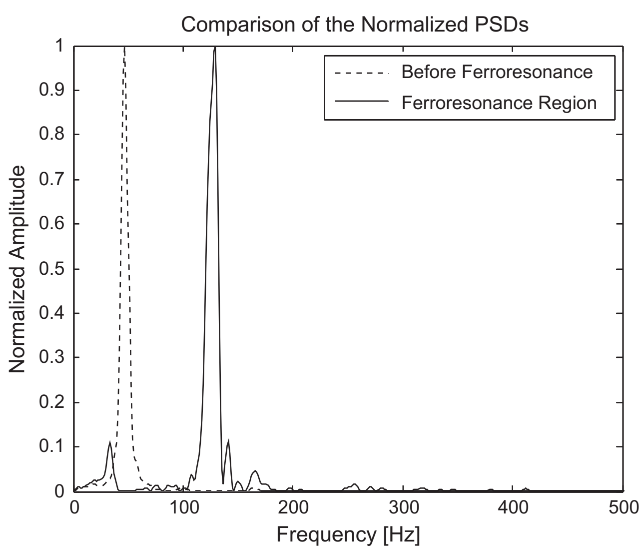

Fig. 10. Comparisons of the PSDs for ferroresonance and non-ferroresonance parts of the voltage variation in the case study 1.

from the bus 3 as seen in Fig. 1. Hence similar results are obtained like the case 1. The characteristic frequency region for the ferroresonance phenomena is localized at around the 120 Hz again.

3.4.3. Case 3

The case 3 is different from the previous examples. Here, only switch 1 has OFF position between the 2nd and 2.2 s, causing ferroresonance for a very short duration like $\Delta t = 0.2$ s. However, the frequency properties are almost the same like the previous cases.

3.4.4. Case 4

In this case the switches 1 and 2 are instantaneously opened, namely they have OFF position with time difference with each others $\Delta t = 0$ s, and the measurements are taken from bus 2 again. But, there is no any importance of the switching because the same frequency properties are obtained.

3.4.5. Case 5

Here the switching positions are considered sequentially, namely the time difference between the off positions for both of the switches 1 and 2 is $\Delta t = 0.2$. The voltage measurements are taken from the bus 2 again. For this reason the effect of the second switch is unimportant and the frequency properties of the ferroresonance phenomenon is similar with the former examples.

In the case 5, similar to observe the effect of the measurement point and switching it is repeated for the measurements taken from the bus 3 as follows.

3.4.6. Case 5 (bus 3)

As seen in Fig. 9, these results are similar, consequently, the ferroresonance phenomena is presented at around the 120 Hz.

As a result, according to these simulation samples, there are no any important effects of the switching position. Here the necessary condition is only switching itself [17].

During this continuous wavelet analysis, all Figs. 4b–9b present the localization of the ferroresonance phenomena and this localization directly determines the relation between time and scale which depends on the frequency in terms of the practical interpretation of the analysis.

4. Concluding remarks

As indicated in the case studies above, the ferroresonance phenomena can be observed by removing the loads at the end of the transmission line. In this manner, it is independent various switching positions. As a result of the unique switching, over-voltage variations occur on the system and these variations are described in the form of the non-stationary data considering the ferroresonance and non-ferroresonance parts of the overall data.

In this sense, taking the case 1, which is indicated in Table 1, the related voltage variation for this case is separated two stationary data like ferroresonance and non-ferroresonance parts. Hence, considering the power spectral density functions for each part, their comparisons are given on the magnitude-frequency plane. This situation is shown by Fig. 10.

According to results of Fig. 10, the properties of the ferroresonance phenomena can be defined by the frequency components occurred between 100 and 200 Hz.

Generally, this research is focused on the continuous wavelet transform (CWT) application based upon the non-stationary data which was resulted in the ferroresonance phenomenon and, the results of the CWT analysis perfectly reflect the time-scale properties of the entire data. As a result, the CWT shows the effect of the ferroresonance event at around the 120 Hz. This localization property of the CWT analysis is very suitable with the frequency interval defined between the 100 and 200 Hz through the PSD approach.

Consequently, the ferroresonance phenomena occur as a result of the switching in the manner of the removing of the loads and the frequency properties are defined by the inter harmonics between 2nd and 4th harmonics of the fundamental frequency appeared of around 120 Hz (namely between the 100 and 200 Hz) for this research.

This value can be comparably observed from the related figure, Fig. 10. As a second stage, this is related to the quasi-periodic mode. In this manner, the spectrum is a discontinuous and its frequency components can be defined as: $nf_1 + mf_2$, here n and m are integers. As seen in Fig. 10, dominant frequency component occurs at $120 \pm \Delta f$ Hz after the ferroresonance event as a result of the switching effect. Here the term of Δf is frequency resolution in the spectral plane. And also, other frequency components in this spectrum are at $f_1 = 30 \pm \Delta f$ and $f_2 = 150 \pm \Delta f$ Hz respectively. Hence this dominant frequency can be defined as a quasi-periodic component by $nf_1 + mf_2 = 9(30 \pm \Delta f) - 1(150 \pm \Delta f) = 120 \pm 8\Delta f$ Hz and the ratio between the frequencies $30 \pm \Delta f$ and $150 \pm \Delta f$ Hz must be given as an irrational number. Quasi-periodic mode (see Fig. 5c) is given as a non-periodic one. The spectrum is a discontinuous spectrum whose frequencies are expressed in the form: $nf_1 + mf_2$ (where n and m are integers and f_1/f_2 is an irrational number). The stroboscopic image shows a closed curve.

In the future, for the long-transmission lines, the switching effects will be studied with all details of the ferroresonance phenomena.

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