Detection of ferroresonance phenomenon for the west anatolian electric power network in Turkey

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ABSTRACT. Ferroresonance is an electrical phenomenon in nonlinear character, which frequently occurs in power systems containing saturable transformers and single or more-phase switching on the lines for the disjunction of the loads. In this study, the ferroresonance phenomena are considered under the modeling of the West Anatolian Electric Power Network of 380 kV in Turkey. The ferroresonance event is carried out using the switching to remove the loads at the end of the lines. In this sense, two different cases are considered. Firstly, the switching is applied at the 2nd second and the ferroresonance effects are observed between the 2nd and the 4th second of the voltage variations. As a result, the ferroresonance and non-ferroresonance cases observed before the ferroresonance, are compared with each other using the Fourier transform techniques. Hence, the properties of the ferroresonance event, which are defined between the 100 and 200 Hz, are presented in the frequency domain.

Keywords: ferroresonance, west anatolian electric power system, power system modeling, spectral analysis, feature extraction.

RESUMO. Detecção de fenômeno ferroresonância para rede de energia elétrica anatólia do oeste na Turquia. Ferroresonancia é um fenômeno elétrico em caráter não-linear, o que freqüentemente ocorre em sistemas de potência contendo transformadores saturável, e mudar uma ou mais fases nas linhas de separação das cargas. Neste estudo, os fenômenos de ferroresonancia são considerados sob a modelagem da Anatólia do Oeste Rede de Energia Elétrica de 380 kV, na Turquia. O ferroresonancia ocorre utilizando a mudança para remover as cargas, no final das linhas. Nesse sentido, dois casos são considerados diferentes. Em primeiro lugar, a mudança é aplicada em 2 segundos e os efeitos de ferroresonancia são observados entre segundos 2 e 4. Como resultado, o ferroresonance e casos ferroresonancia não observado antes da ferroresonancia são comparados uns com os outros usando a transformada de Fourier técnicas. Assim, as propriedades da ferroresonancia, que são definidas entre os 100 e 200 Hz, são apresentadas no domínio da freqüência.

Palavras-chave: ferroresonancia, sistema de energia elétrica da Anatólia do Oeste, modelagem de sistemas de energia, análise espectral, extração de característica.

Introduction

In the studies, 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 (ABDALLAH; EL-KADY, 2005; BUIGUES et al., 2007; CHARALAMBOUS et al., 2007; IRAVANI, 2000; JACOBSON et al., 1999; JACOBSON; MENZIES, 2001; KUMAR et al., 2006; SAIED et al., 1984; SAKARUNG, 2005; STOJKOVSA et al., 2001; TANGGAWELU et al., 2003). P. Boucherot used this term for the first time in 1920 in the appellation of oscillations in circuits with nonlinear inductance and capacitance (SUTHERLAND; MANNING, 2006). Nowadays, more suitable mathematical tools used to investigate the ferroresonance are provided through the nonlinear dynamic methods (SAKARUNG, 2005). In this sense, the ferroresonance phenomenon is known as a nonlinear phenomenon that causes overvoltage in power systems. Here, magnitudes of the over voltage variations are several times higher than those of the steady case amplitudes in time domain as well as some harmonics and other frequency components which are defined in the frequency domain. As a result, these high over-voltages cause failures in transformers, cables, and arresters of the power system (ABDALLAH; EL-KADY, 2005;

BUIGUES et al., 2007; CHARALAMBOUS et al., 2007; IRAVANI, 2000; JACOBSON et al., 1999; JACOBSON; MENZIES, 2001; KUMAR et al., 2006; SAIED et al., 1984; SAKARUNG, 2005; STOJKOVSA et al., 2001; SUTHERLAND, MANNING, 2006; TANGGAWELU et al., 2003). Also, in terms of the frequency components, the abnormal rates of harmonics can often be dangerous for most electrical equipment in the power systems. In this manner, it is important to define the characteristic properties of the frequency domain analysis of the ferroresonance phenomenon.

The effect of the ferroresonance not only described as the jump to a higher frequency state, but also it is given with bifurcations to the sub-harmonic, quasi-periodic, and chaotic oscillations in any circuit containing a nonlinear inductor (STOJKOVSA et al., 2001; SAKARUNG, 2005; TOKIC et al., 2005). A more suitable mathematical tool for studying ferroresonance and other nonlinear systems is provided by nonlinear dynamic methods (SAKARUNG, 2005).

In this research, the West Anatolian Electric Power Network of 380 kV in Turkey is considered for modeling and simulation of the ferroresonance event. The modeling and simulation studies are performed in the MATLAB-SIMULINK™ environments. Consequently, the ferroresonance event is carried out using the switching to remove the loads at the end of the lines. Ferroresonance and non-ferroresonance parts of the voltage variations for single phase are compared with each other. Hence some frequency components, which are represented as features of the ferroresonance phenomenon, are determined between 100 and 200 Hz using the spectral analysis methods. Also, the role of time delay due to the switching operation is emphasized with highly correlated results appearing at around 3rd, 5th, and 7th harmonics of the fundamental frequency.

Material and methods

Spectral analysis methods

Short time Fourier transform (STFT) is an alternative method to classical Fourier transform in terms of the non-stationary data analysis. In this manner, the spectrogram approach, based on the STFT, is used to track the non-stationary data on the time-frequency plane. Under this section, the Power Spectral Density variation, which is determined for stationary case, is introduced as well as the short Fourier transform technique. Besides, the coherence analysis approach is defined to show the correlation between the signals in frequency

domain. These spectral analysis methods are affectedly used in the various fields of power engineering (TASKIN et al., 2009).

Power Spectral Density and Coherence Approach

A common approach for extracting the information about the frequency features of a random signal is to transform the signal to the frequency domain by computing the discrete Fourier transform. For a block of data of length N samples the transform at frequency $m\Delta f$ is given by:

$$X(m\Delta f) = \sum_{k=0}^{N-1} x(k\Delta t) \exp\left[- j2\pi km / N\right] \qquad (1)$$

Where Δf is the frequency resolution and Δt is the data-sampling interval. The auto-power spectral density (APSD) of $x(t)$ is estimated as:

$$S_{xx}(f) = \frac{1}{N}\left|X(m\Delta f)\right|^2, f = m\Delta f. \qquad (2)$$

The cross power spectral density (CPSD) between $x(t)$ and $y(t)$ is similarly estimated. The statistical accuracy of the estimate in Equation (2) increases as the number of data points or the number of blocks of data increases.

The cause and effect relationship between two signals or the commonality between them is generally estimated using the coherence function. The coherence function is given by:

$$C_{xy}(f) = \frac{\left|S_{xy}(f)\right|}{\sqrt{S_{xx}(f)S_{yy}(f)}}, 0 < C_{xy} < 1 \qquad (3)$$

Where S_{xx} and S_{yy} are the APSDs of $x(t)$ and $y(t)$, respectively, and S_{xy} is the CPSD between $x(t)$ and $y(t)$. A value of coherence close to unity indicates a highly linear and close relationship between the two signals (VASEGHI, 1996).

Short Time Fourier Transform and Spectrogram

The short time Fourier transform (STFT) introduced by Gabor in 1946 is useful in presenting the time localization of frequency components of signals. The STFT spectrum is obtained by windowing the signal through a fixed dimension window. The signal may be considered approximately stationary in this window. The window dimension fixed both time and frequency resolutions. To define the STFT, let us consider a signal x(t) with assumption that it is stationary when it is windowed through a fixed dimension window g(t), centered at time location τ. The Fourier transform of the windowed signal yields the STFT (VASEGHI, 1996).

$$STFT\{x(t)\} \equiv X(\tau, f) = \int_{-\infty}^{+\infty} x(t)g(t - \tau)\exp[-j2\pi ft]dt \quad (4)$$

The equation maps the signal into a two-dimensional function in the time-frequency (t, f) plane. The analysis depends on the chosen window $g(t)$. Once the window $g(t)$ is chosen, the STFT resolution is fixed over the entire time-frequency plane. In a discrete case, it becomes:

$$STFT\{x(n)\} \equiv X(m, f) = \sum_{n=-\infty}^{+\infty} x(n)g(n - m)\,e^{-jwn} \quad (5)$$

The magnitude squared of the STFT yields the "spectrogram" of the function.

$$Spectrogram\{x(t)\} \equiv \left|X(\tau, f)\right|^2 \quad (6)$$

Using the spectrogram, non-stationary properties of the signal can be easily determined on the time-frequency plane.

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 overvoltage, which can cause dielectric and thermal problems in transmission and distribution systems. Due to the nonlinearity of the saturable inductance, ferroresonance possesses many properties associated with a nonlinear system, such as:

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 a 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.

Modeling of the west anatolian electric power system

There are two aspects to be considered in this section. The first one is the modeling of the power system with MATLAB-SIMULINK™ and the second one is related to the various simulations to be realized in this model to observe the behavior of the ferroresonance phenomena.

Modeling of the power system

Modeling of the West Anatolian Electric Power Network model of 380 kV in Turkey is represented in Figure1. The modeling and simulation studies are realized by using the MATLAB Power System Blockset.

The parameters of all electrical equipments used in the simplified model of the sample power system can be shown in the following Table 1.
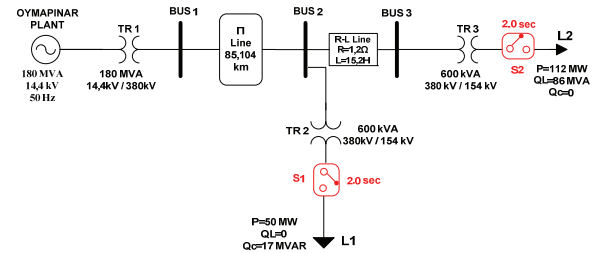

Figure 1. Simplified model of Oymapinar-Seydisehir line for West Anatolian power network in Turkey.

Table 1. Parameters of electrical components used in Oymapinar-Seydisehir line.

Electrical Components	Parameters
Generator	180 MVA, 14.4 kV, 50 Hz
Transformers	TR_1:180 MVA, 14.4kV 380kV^{-1} TR_2: 600kVA, 380kV 154kV^{-1} TR_3: 600kVA, 380kV 154kV^{-1}
Lines	π Line(B_1-B_2): 85.104 km R:0.2568 Ω km^{-1} L: 2 mH km^{-1} C: 8.6 nF km^{-1} Line(B_2-B_3): R:1Ω L:1mH
Loads	L_1:P=50 MW, Qc=17 MVAR L_2:P=112MW, Q_l=86 MVA
Switches	S_1: 2 – 4 sec. on 0 - 2 sec. off S_2: 2 – 4 sec. on 0 - 2 sec. off

Simulations on the model

Using the simplified model, as shown in Figure 1, ferroresonance phenomena is created under the scenarios which are given in Table 2. In Table 2, 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. Before the ferroresonance, all switches are on while the ferroresonance phenomena have occurred in different on-off positions of the switches. These different situations are indicated by cases 1-4 as shown in Table 2.

Table 2. Different combinations of the switches.

	Before Ferroresonance		Ferroresonance Region		Time Delay
Case 1	S_1	S_2	S_1	S_2	-
Case 2	S_1	S_2	S_1	S_2 t=2.0sec	-
Case 3	S_1	S_2	t=2.0sec S_1	S_2 t=2.0sec	Δt = 0 sec.
Case 4	S_1	S_2	t=2.0sec S_1	S_2 t=2.2sec	Δt = 0.2 sec.

Looking at case 1 which is denoted in Table 2, the voltage variations can be shown in the following figures for three phase measurements. As seen in Figure 2, the ferroresonance phenomenon begins at 2nd and it then causes it to over- voltage as a result of the load removing.
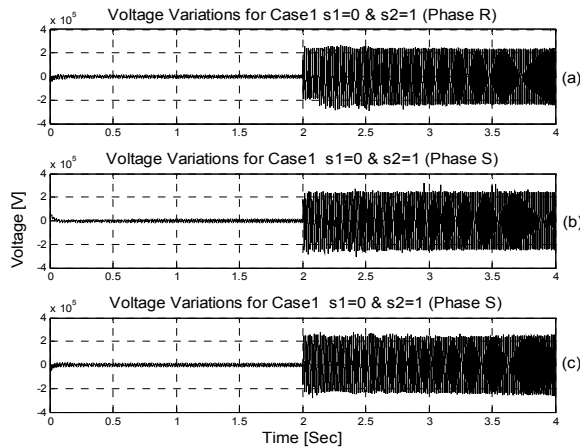

Figure 2. Overall data for three phase measurements in Case 1. a) Phase-R, b) Phase-S and c) Phase-T.

In this study, phase R is used for the data analysis because the others are similar. The data, including both parts of the ferroresonance and non-ferroresonance in case 1, is called as overall data. Time - frequency variation of the overall data for case 1 can be shown in Figure 3.
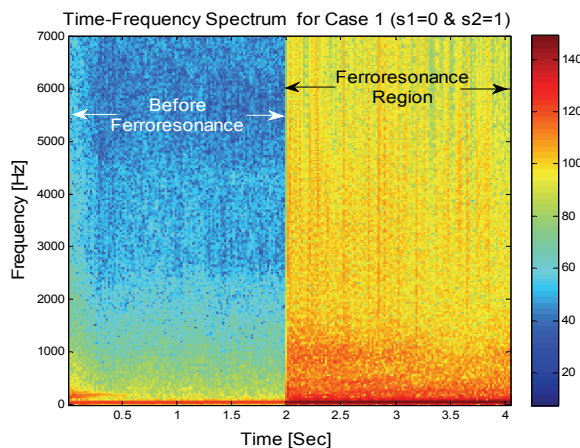
Figure 3. Characteristics of the voltage variation for the phase R in Time-Frequency plan.

Results and discussion

Time-frequency analysis results and feature extraction

The time-frequency analysis of the voltage measurement for phase R, in case 1, is shown in Figure 3. Here the limits of the ferroresonance phenomenon are easily determined. According to these limitations,

the most important features can be extracted from the frequency range, which is defined between 0 and 500 Hz, shown in Figure 3.

Namely, the huge amplitudes can be observed between 0 and 500 Hz as seen in Figure 3. For this reason the power spectral density (PSD) variation of this signal is presented between 0 and500 Hz. Hence, considering the PSD shown in Figure 4, the fundamental frequency at 50 Hz and a small peak appearing at 100 Hz are used to determine the overall data as well as the small bifurcation effect seen in the fundamental frequency.
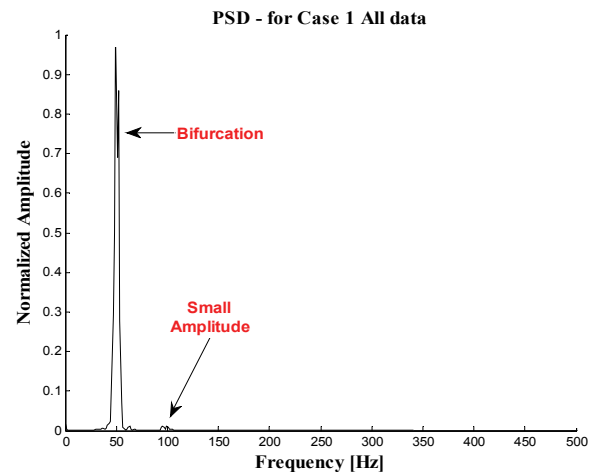

Figure 4. PSD for overall data in Case 1.

However, for more specific determination, instead of using the overall data, its non-ferroresonance and ferroresonance parts are considered respectively. Thus, PSD of the non-ferroresonance part is shown in Figure 5. As seen in Figure 5, there is a small peak at 150 Hz as well as a fundamental frequency at 50 Hz. However, it was observed that there was an increase in the number of the bifurcation states occurring at 50 Hz.
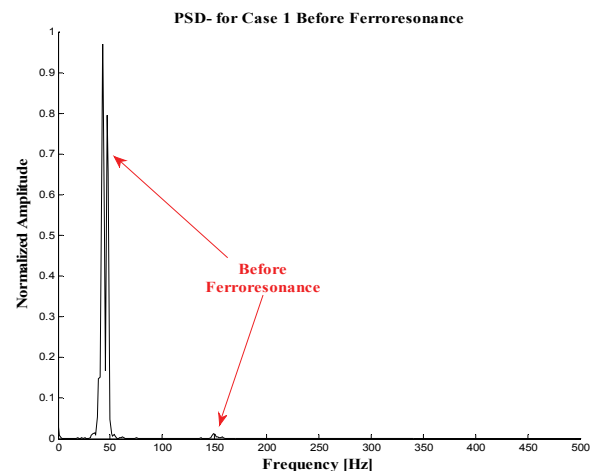

Figure 5. PSD for non-ferroresonance part of the overall data.

In this sense, this situation can be interpreted as a result of the ferroresonance phenomenon and, then, considering the ferroresonance part of the overall data, Figure 6 shows these effects with other details.
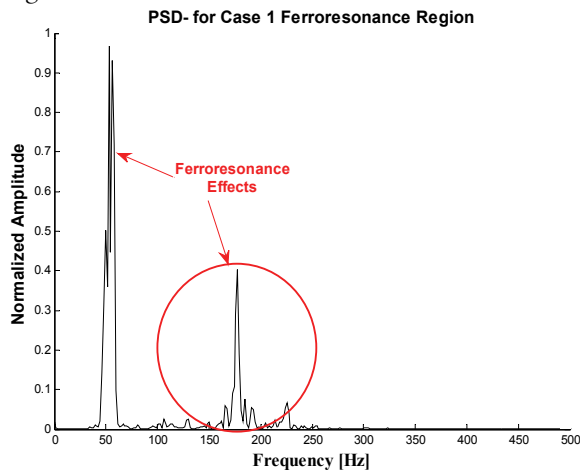

Figure 6. PSD for the ferroresonance part of the all data.

In terms of the comparisons of the ferroresonance and non ferroresonance parts of the overall data in spectral domain, which are shown in Figure 7, the most important features of the ferroresonance phenomena are defined by the bifurcations around 50 Hz and the additional frequency components observed in the frequency range of 100-200 Hz, which has a central frequency at 150 Hz. Similar results are obtained for cases 2, 3 and 4 defined in Table 1. The effects of these cases can be detailed through the coherence analysis approach as indicated in section 5 and 6.
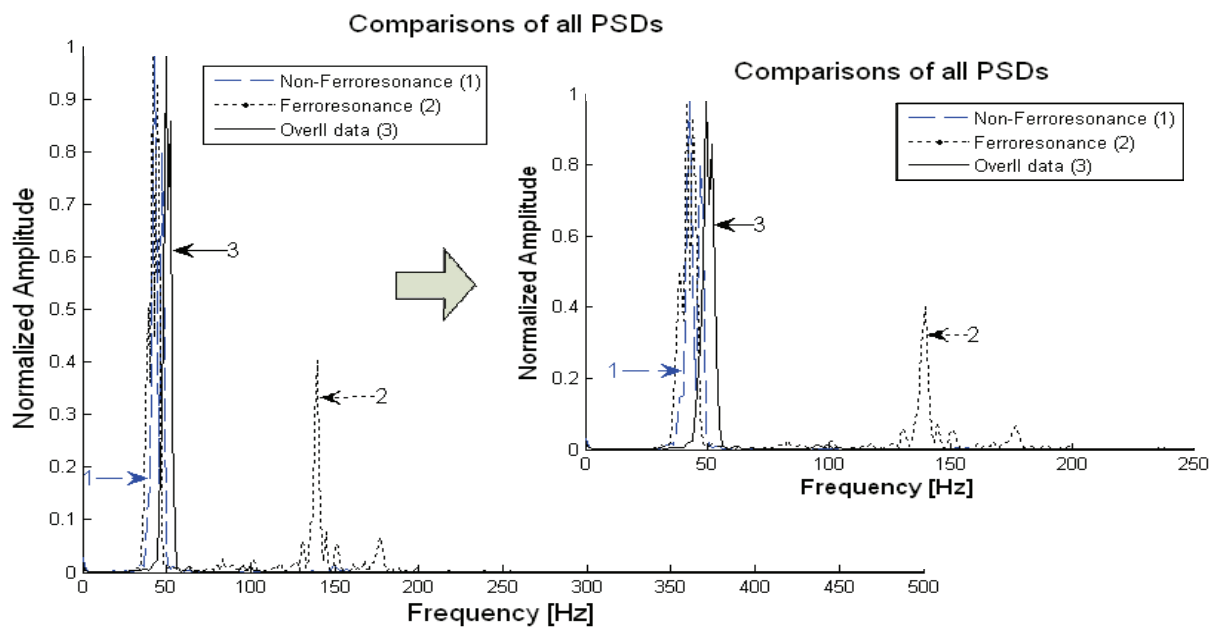
Coherence analysis

In the simplified model of the power system shown in Figure 1, two switches (S_1 and S_2) are used to disjoint the loads from the system. The different combinations of operational modes of the switches can be shown in different cases as indicated in Table 1.

In these cases, switch-on and off positions can be arranged for same switching times or different switching times, considering a specific time delay according to each other. Under these scenarios, the measurements are taken from the different buses (Bus 2 and 3) to show the ferroresonance effects. Hence, the coherence functions are based on the measurements taken from Bus-2 and 3 for cases 1, 2, 3 and 4 and the related results are interpreted through Figure 8.
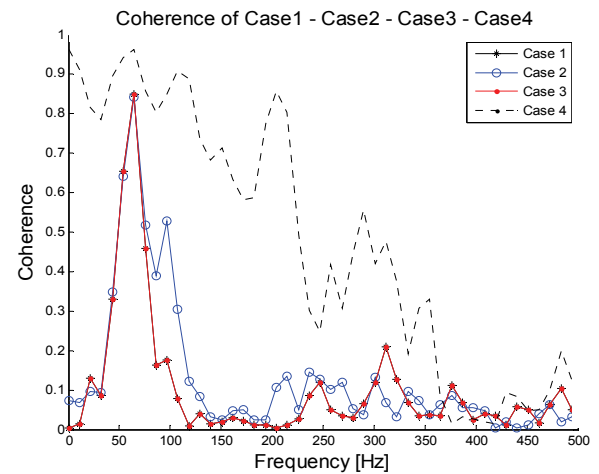

Figure 8. Coherences for all data in case 1, 2, 3 and 4.

Figure 7. Comparisons of the PSDs for partial and overall data.

The coherence analysis results, shown in cases 1 and 3, give the same results in this sense; the most different state is case 4, which uses the time delay in switching. In case 4, the time delay related to the switching causes higher correlated results.

In terms of the symbolic description of the coherence analysis, the coherence functions can be described by the functions $\{C_{j,k}^{i}(f)\}$: $i=1, 2, 3, 4$ and $j, k=1, 2$ for $j \neq k$. Here subscripts j and k are bus numbers while the index i indicates the cases.

These functions show the relationships between the measurement pairs taken from Bus 2 and Bus 3 using index cases. According to these measurement pairs, the highly correlated results can be given for case 4 as mentioned above. In case 4, the time delay Δt is different from zero, namely switching the time between S_1 and S_2. Case 4 is positive, and this time difference causes the high correlation levels, for $\Delta t = 0$ is defined in case 3 and case 1. The correlation functions reflect the same characteristics.

Conclusion

In this study, the ferroresonance phenomena are considered under the modeling of the West Anatolian Electric Power Network of 380 kV in Turkey. Ferroresonance and non-ferroresonance parts of the voltage variations for single phase are compared with each other using the PSD functions. In the coherence approach, the most impressive results are related to the time delaying of the switching used to remove the loads. However, the switch (S_2) is on the line of load L_2. For this reason, the effect of this load in the switching duration will be stronger than the L_1. Thus, the switching mode (S_2) plays a more dominant role over the S_1. Also, if $\Delta t \neq 0$, it will cause high correlation levels. Therefore, the effect of case 4 is observed between 0 and 500 Hz with high correlated frequency components. These are also interpreted as 3rd, 5th and 7th harmonics of the fundamental frequency.

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