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Determination of the Characteristics for Ferroresonance Phenomenon in Electric Power Systems

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***Abstract*—**Ferroresonance is an electrical phenomenon in nonlinear character, which frequently occurs in power system due to transmission line faults and single or more-phase switching on the lines as well as usage of the saturable transformers. In this study, the ferroresonance phenomena are investigated under the modeling of the West Anatolian Electric Power Network of 380 kV in Turkey. The ferroresonance event is observed as a result of removing the loads at the end of the lines. In this sense, two different cases are considered. At first, the switching is applied at 2^{nd} second and the ferroresonance affects are observed between 2^{nd} and 4^{th} seconds in the voltage variations of the phase-R. Hence the ferroresonance and non-ferroresonance parts of the overall data are compared with each others using the Fourier transform techniques to show the ferroresonance affects.

***Keywords*—**Ferroresonance, West Anatolian Electric Power System, Power System Modeling, Switching, Spectral Analysis.

I. 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. The Ferroresonance phenomenon composes to the high voltage levels because of the relative ratios of losses, magnetizing impedance and cable capacitance fall into its more favorable range. Also, the abnormal rates of harmonics and transient or steady-state over-voltages (can often be dangerous)dangerously for most electrical equipments in the power systems. 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]-[3].

In this sense, the ferroresonance phenomenon is known as a nonlinear phenomenon that cause to over voltages in power systems. The affect of the ferroresonance can not be only described as the jump to a higher fundamental 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 [4]. This term was first time used by P. Boucherot in 1920 to appellation of oscillations in circuits with nonlinear inductance and capacitance [5]-[8]. In this paper, West Anatolian Electric Power Network of 380kV 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 satisfied results are obtained to denote the frequency properties.

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II. Spectral Analysis Methods

Spectral Analysis methods include Short Time Fourier Transform (STFT) and Power Spectral Density (PSD) techniques.

A. Short Time Fourier Transform and Spectrogram

The short time Fourier transform 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 is 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 [9].

$$STFT\{x(t)\} \equiv X(\tau, f) = \int_{-\infty}^{+\infty} x(t)g(t-\tau)\exp[-j2\pi ft]dt \tag{1}$$

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 discrete case, it is;

$$STFT\{x(n)\} \equiv X(m, f) = \sum_{n=-\infty}^{+\infty} x(n)g(n-m)\, e^{-jwn} \tag{2}$$

The magnitude squared of the STFT yields the “spectrogram” of the function.

$$Spectrogram\{x(t)\} \equiv |X(\tau, f)|^2 \tag{3}$$

B. Power Spectral Density

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 [9]. For a block of data of length N samples the transform at frequency $m\Delta f$ is given by

$$X(m\Delta f) = \sum_{k=0}^{N-1} x(k\Delta t)\ \exp[-j2\pi km/N] \tag{4}$$

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

$$S_{xx}(f) = \frac{1}{N}|X(m\Delta f)|^2, f = m\Delta f \tag{5}$$

III. Ferroresonance Phenomena and System Modeling

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 a high overvoltage and random time duration, which can cause to 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:

- 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.

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

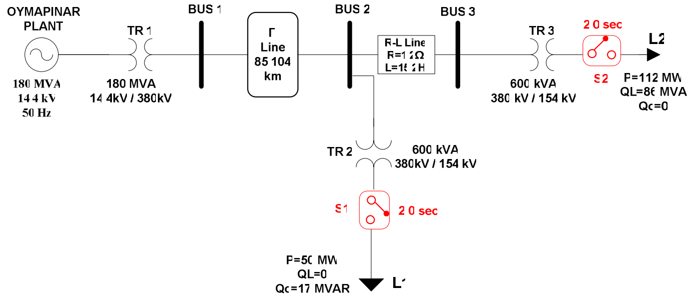

Fig. 1 Simplified Model of Oymapinar-Seydisehir line for West Anatolian Power Network in Turkey

The parameters of all electrical equipments can be shown in Table I.

TABLE I
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, 14.4kV/ 380kV TR_2: 600kVA, 380kV / 154kV TR_3: 600kVA, 380kV / 154kV
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=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

To indicate the ferroresonance affect, voltage variation for single phase (Phase R) in the model can be given by the following figure. Here, Fig. 2 shows the voltage variations to be occurred in the case of removing the load through the switch S_1 (at 2^{nd} sec.), which takes place at the end of the TR3.

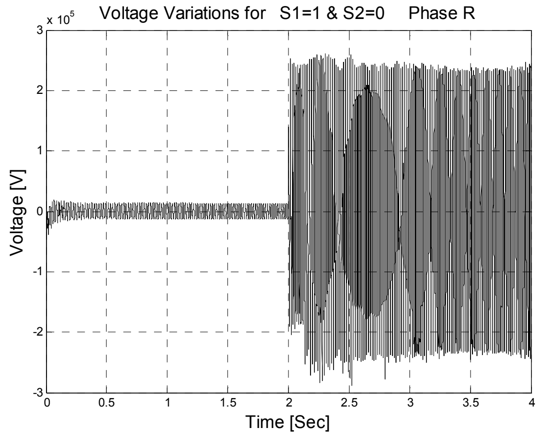

Fig. 2 Overall data of the voltage variation for phase-R

According to the Fig. 2, over voltage variations are observed as a result of the ferroresonance affect by switching.

IV. Time Frequency Properties of the Over Voltage Variation

Voltage variations, which are taken from the model, are analyzed in the time-frequency domain using the short time Fourier transform (STFT) techniques. Here, the sampling frequency is at 14 kHz. The data shown in Fig. 2 is processed and its time-frequency plane is represented by the Fig. 3.

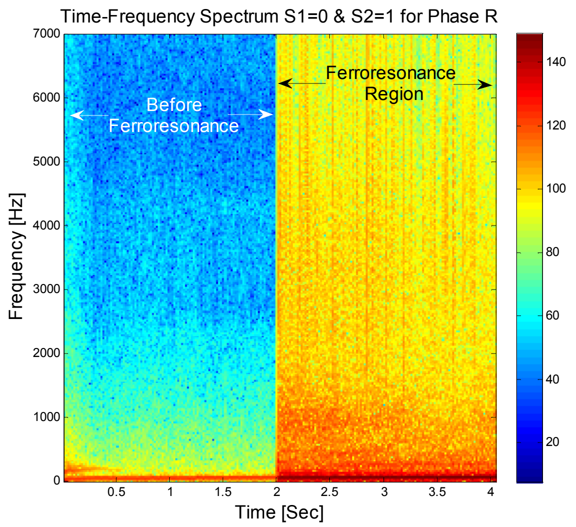

Fig. 3 Observations of the ferroresonance affect occurred after 2nd second

Here the time interval between 0 and 2 seconds indicates the sinusoidal variations at low frequency region, which covers the fundamental frequency of the system at around 50 Hz. After the 2nd sec., the ferroresonance affect appears with large amplitudes at high frequency values and then, it goes on until the 4th second. It is observed that the high amplitudes of the voltage variation occur for overall frequency band as a result of the ferroresonance phenomenon. Moreover, frequency contents of the ferroresonance phenomenon for overall data can be shown by the following Fig. 4.

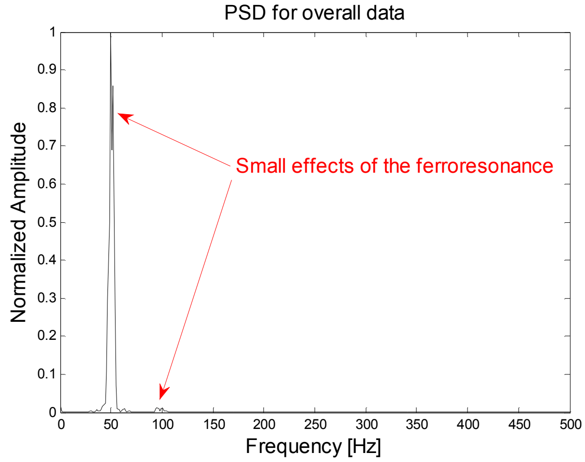

Fig. 4 PSD for overall data

According to the Fig. 4, small affects of the ferroresonance can be observed with bifurcation at 50 Hz and additional small frequencies at around 100 Hz. To show more detailed ferroresonance affects, the PSD techniques are applied to the ferroresonance region of the data, hence, in the Fig. 5, it is seen that these affects amplify and they are indicated between 50-250 Hz as well as several bifurcation at 50 Hz.

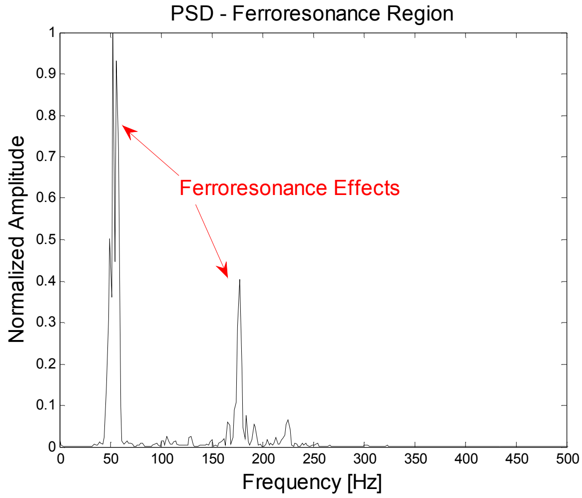

Fig. 5 PSD for ferroresonance region of the overall data

According to Fig. 4-5 strong affects of the ferroresonance are characterized by the frequency interval between the 100 and 250 Hz. However, to observe the initial part of the ferroresonance region, a very short duration is considered as shown in Fig. 6.

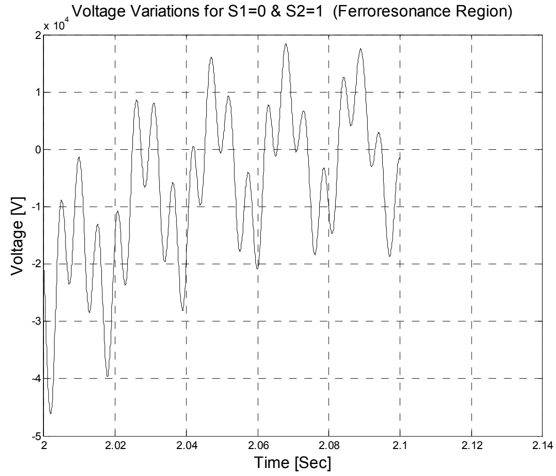

Fig. 6 Initial part of the ferroresonance affect in time domain

For the initial case of the ferroresonance event, its PSD variation is given by Fig. 7.

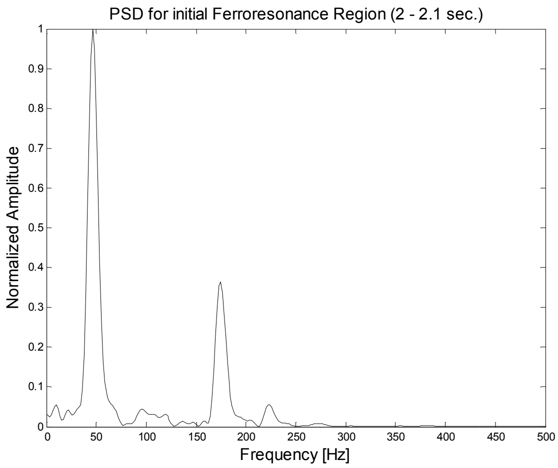

Fig. 7 PSD for the initial case of the ferroresonance region

As seen in Fig. 7, the PSD results are similar with the pure-ferroresonance region as given in Fig. 5. In this sense, if the initial region of the ferroresonance is compared with the pure ferroresonance region, the comparisons in the spectral domain can be shown by the Fig. 8. From this viewpoint, it can be said that there is no important difference with each others. So, the affect of the ferroresonance phenomenon instantly occurs and it goes on during the time.

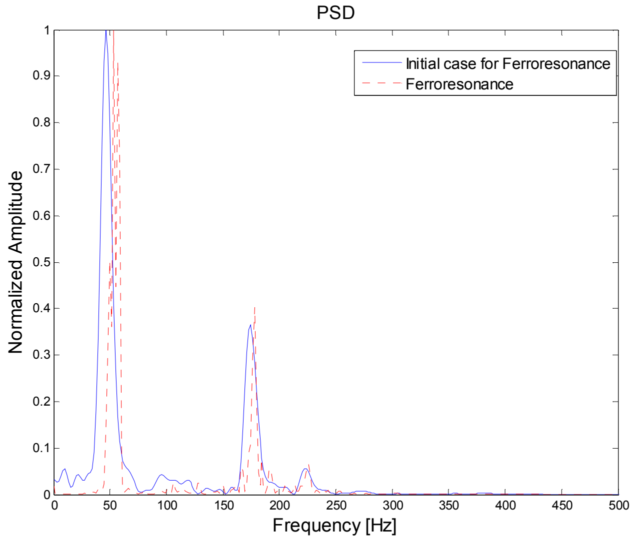

Fig. 8 Comparisons of the PSDs for ferroresonance regions

V. Concluding Remarks

With this study, the general characteristics of the ferroresonance phenomenon were aimed and modeling and simulation studies were realized using the MATLAB-Simulink for the small part of the electric power system of Turkey. In terms of the mathematical tools, time-frequency analysis and power spectral analysis techniques were considered, with these methods, the features of the ferroresonance phenomenon were extracted and they could be listed as below:

- The ferroresonance event causes over voltage variations in the power system.
- These over voltage variations have non-sinusoidal forms.
- The reason of the non sinusoidal forms in the voltage variations can be based on the harmonics and inter-harmonics of the ferroresonance phenomenon.
- PSD approach detects these harmonics and other properties of the voltage variations.
- The general characteristics can be defined with additional frequency components appeared between 100 and 250 Hz as well as bifurcations at around the fundamental frequency.
- All of the ferroresonance conditions occur at the beginning of the over voltage variation because the switching operation effects the system instantly. Nevertheless, this view depends on the load characteristics. For example, in nonlinear loads, it can be very different.

In future, this research will be supported with more powerful methods for feature extraction studies.

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