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Impact of the system parameters on the ferroresonant modes

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Abstract. The ferorresonance is a complicated and hard to predict phenomenon, and because of its harmful impact on the electrical equipment very interesting to be known in a greater detail. The ferroresonance occurs in several modes: fundamental, subharmonic, quasi-periodic and chaotic. This paper analyses the impact of the system parameters on obtaining the different ferroresonance modes. The analysis is carried out by simulating the behavior of one of the most common examples of the ferroresonance occurrence: unloaded single-phase transformer which is, when switched on, energized over the grading capacitor. The ferroresonant modes are indentified and represented by three different techniques: the spectral-density analysis, the phase-plane analysis and the Poincaré map.

Keywords: ferroresonance, analysis, modes, techiques.

Vpliv sistemskih parametrov na feroresonančne pojave

Feroresonanca je zapleten in težko predvidljiv pojav, ki je zaradi možnega škodljivega vpliva na električno opremo zelo zanimiv za analizo. Feroresonanca se pojavlja na različne načine: osnovni, podharmonski, kvazi-periodični in kaotični. V članku obravnavamo vpliv sistemskih parametrov na različne feroresonančne pojave. Analizo smo izvedli s simulacijo delovanja neobremenjenega enofaznega transformatorja, enega izmed najbolj pogostih primerov pojavov feroresonance. Feroresonančni vplivi so predstavljeni s tremi različnimi tehnikami: z analizo spektralne gostote, z analizo v fazni ravnini in s Poincarovo analizo.

1 INTRODUCTION

The ferroresonance is a nonlinear phenomenon that is sensitive to the parameters and initial conditions of the system.
The basic element of the ferroresonant circuit is a nonlinear inductance, but for the ferroresonance to occur, the electrical circuit must also contain a capacitor, voltage source (usually sinusoidal) and low losses [1], [2]. Due to the existence of many sources of capacitors and non-linear inductances, and a wide range of operating states, configurations under which the ferroresonance takes place are innumerable. One of these configurations is an unloaded single-phase transformer which is, when switched on, energized over the grading capacitor (Fig. 1), [3]-[5].

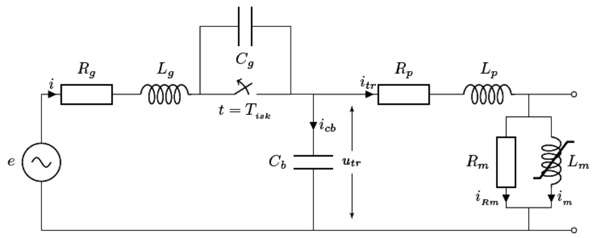

Figure 1. Equivalent scheme of the ferroresonant serial electrical circuit

The waveforms of magnitudes occurring in a power system and experiments carried out on a reduced system model together with numerical simulations enable the ferroresonant modes to be divided into four types: fundamental, subharmonic, quasi-periodic and chaotic.
In the fundamental mode, the voltage or current waveforms are distorted, but their period of oscillation is equal to the period of the source. The subharmonic mode is characterized by the periodic voltage or current signals, but the period of its oscillation is an integer multiple of the source period. In the quasi-periodic mode, the voltage or current signals are not periodic and in the chaotic mode, the voltage or current signals show an unpredictable behavior [6], [7].

The different ferroresonant modes can be obtained by changing the system parameters, which are: sizes that define the transformer magnetizing curve, grading capacitor, switching time, system initial states, amplitude of the voltage source, etc. [8].

By changing the grading capacitor C_g, the resistance of the transformer magnetizing branch R_m and the amplitude of the voltage source U_m, the different ferroresonant modes can be obtained.
The ferroresonant behavior of the dynamic systems can be analyzed on the basis of three different methods: the

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spectral-density analysis, the phase-plane analysis and the Poincaré map [3], [6].
Our presentation of the ferroresonant modes will be made by using these techniques.

2 FERRRORESONANT MODES

To simulate the single-phase transformer ferroresonance, the software ATP (Alternative Transient Program) [10] is used. It is a version of EMTP (Electromagnetic Transient Program) [11], the software for the analysis of the electromagnetic transient phenomena taking place in the power system. The program has a graphical user interface implemented in the graphic preprocessor ATPDraw [12], enabling a relatively simple construction of models of the electrical circuits.

The single-phase transformer is represented by its equivalent scheme, where the magnetizing branch of the transformer is represented by a linear resistance R_m and nonlinear inductance. Resistance R_g and inductance L_g represent the network participation. The simulation duration is $T_{sim} = 0.2\ sec$, while the step time is $\Delta t = 10^{-6}\ sec$.
The ATPDraw simulation scheme of the serial ferroresonant electrical circuit is shown in Fig. 2, [13].

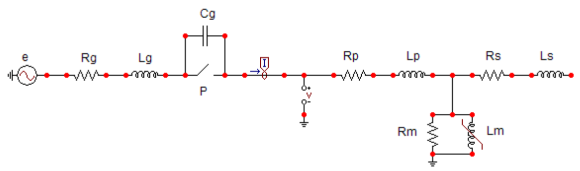

Figure 2. ATPDraw simulation scheme of the serial ferroresonant electrical circuit

2.1 *Fundamental ferroresonance*

The fundamental ferroresonance occurs when the values of the system parameters are the ones shown in Table 1.

Table 1: System parameter values - fundamental ferroresonance

Fundamental ferroresonance	
R_m [Ω]	2180,9
C_g [μF]	3,75
U_m [V]	325,27

The transformer voltage waveform of the fundamental ferroresonance is shown in Fig. 3.

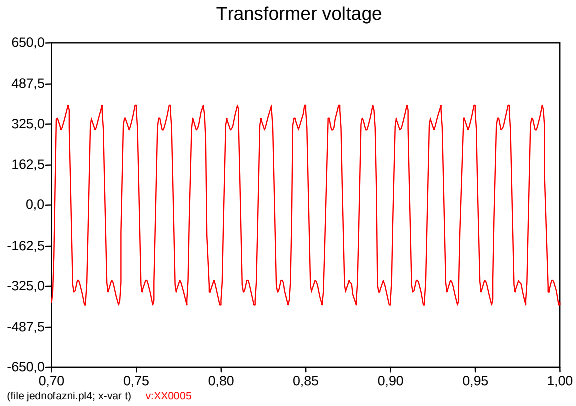

Figure 3. Transformer voltage waveform – fundamental ferroresonance

The harmonic components of the voltage and current signals are analyzed by using the spectral density method. This method is used to obtain the characteristic frequencies that are present in the signal. The presence of more than one characteristic frequency indicates the multiple periodicity, which is common in some ferroresonant states. The spectral analysis used for the transformer voltage waveform is shown in Fig. 4.

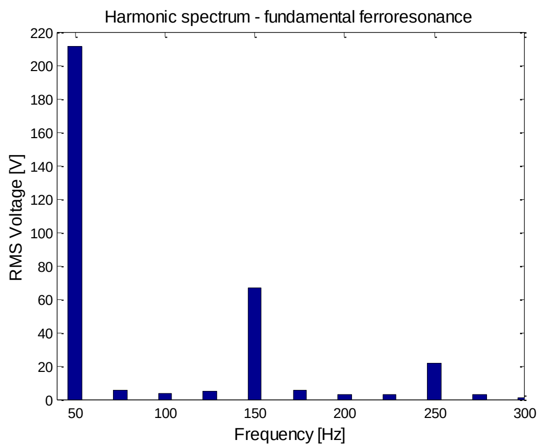

Figure 4. Spectral analysis of the transformer voltage waveform – fundamental ferroresonance

Based on the results of the spectral analysis of the transformer voltage waveform, we can conclude that the voltage spectrum consists of a basic harmonic (f_0 = 50 *Hz*), and its harmonics ($3f_0, 5f_0$, etc.).
The phase plane is a diagram which consists of two state variables: transformer voltage and current (Fig. 5). The result is a shift of the point in the time that follows the trajectory. The periodic solutions correspond to the closed trajectories.

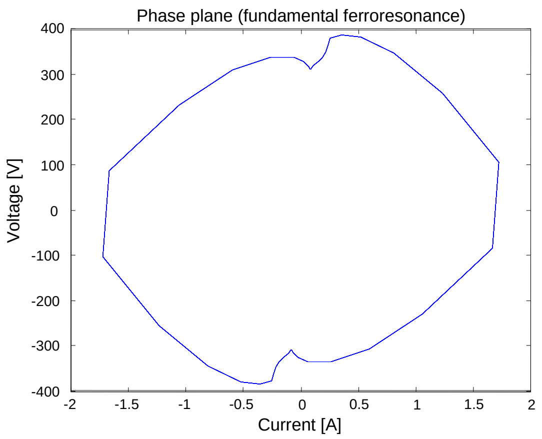

Figure 5. Phase- plane analysis – fundamental ferroresonance

The phase-plane is represented by a closed trajectory which tells us that this is a periodic voltage signal. The Poincaré map is a diagram of the two state variables voltage and current, but the system period (frequency) is taken for a sampling period (frequency). Because of that, the Poincaré map of the periodic solution consists of only one point (Fig. 6). The Poincaré map for the case of the fundamental ferroresonance is shown in Fig. 6.

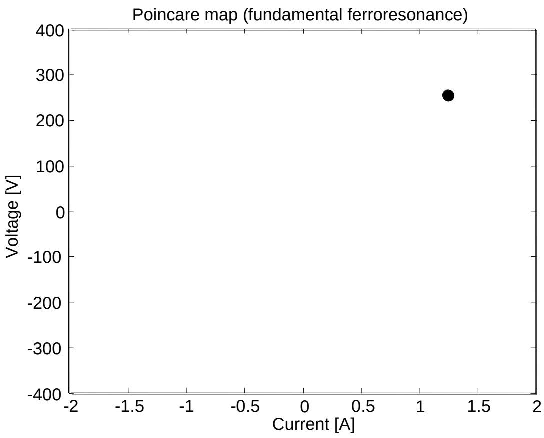

Figure 6. Poincaré map – fundamental ferroresonance

The Poincaré map shows the point far away from the point representing the normal state [3], [6].

2.2 *Subharmonic ferroresonance*

The subharmonic ferroresonance occurs when the values of the system parameters have values are the ones shown in Table 2.

Table 2: System parameter values - subharmonic ferroresonance

Subharmonic ferroresonance	
R_m [Ω]	12500
C_g [μF]	10
U_m [V]	325,27

The transformer voltage waveform of the subharmonic ferroresonance is shown in Fig. 7.

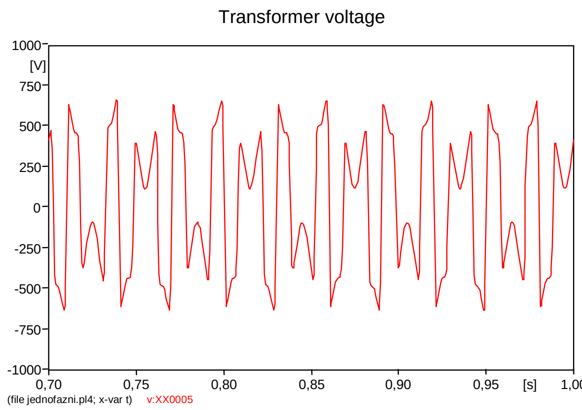

Figure 7. Transformer voltage waveform – subharmonic ferroresonance

A spectral analysis of the transformer voltage waveform is shown in Fig. 8.

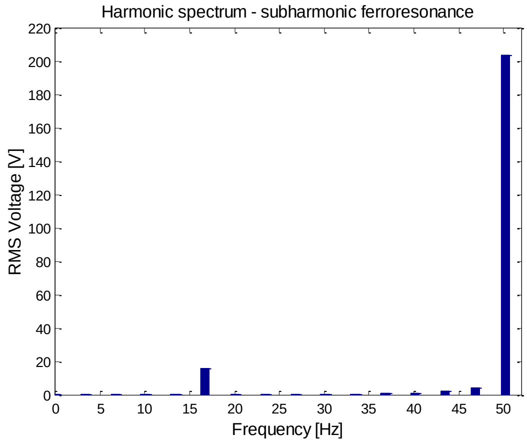

Figure 8. Spectral analysis of the transformer voltage waveform – subharmonic ferroresonance

From results of the spectral analysis of the transformer voltage waveform we see that the voltage spectrum consists of a basic harmonic (f_0 = 50 Hz) and its subharmonics, of which the most dominant is the third subharmonic component $\frac{f_0}{3}$.

The phase plane for the case of the subharmonic ferroresonance is shown in Fig. 9.

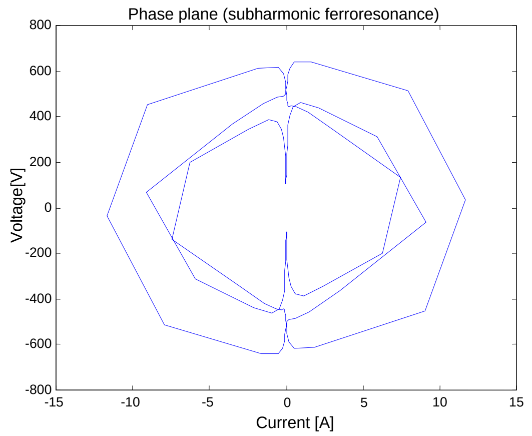

Figure 9. Phase plane analysis – subharmonic ferroresonance

The phase plane is represented by a close trajectory with three sizes and a period of 3T or 60 ms.
The Poincaré map for the case of the subharmonic ferroresonance is shown in Fig. 10.

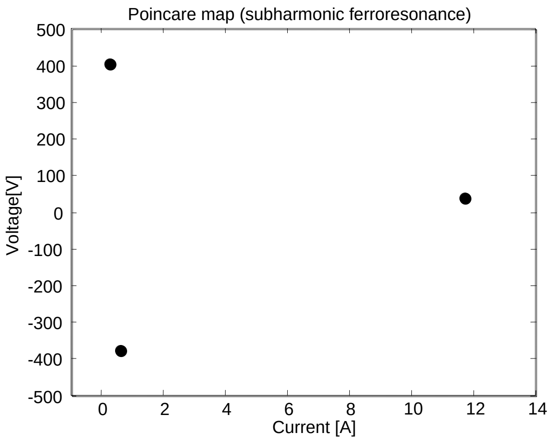

Figure 10. Poincaré map – subharmonic ferroresonance

Because of the dominance of the third harmonic in the harmonic spectrum of the voltage signal, the Poincaré map consists of three points [3], [6].

2.3 Chaotic ferroresonance

The chaotic ferroresonance occurs when the values of the system parameters are the ones shown in Table 3.

Table 3: System parameter values - chaotic ferroresonance

Chaotic ferroresonance	
R_m [Ω]	12500
C_g [μF]	48
U_m [V]	600

The transformer voltage waveform of the chaotic ferroresonance is shown in Fig. 11.

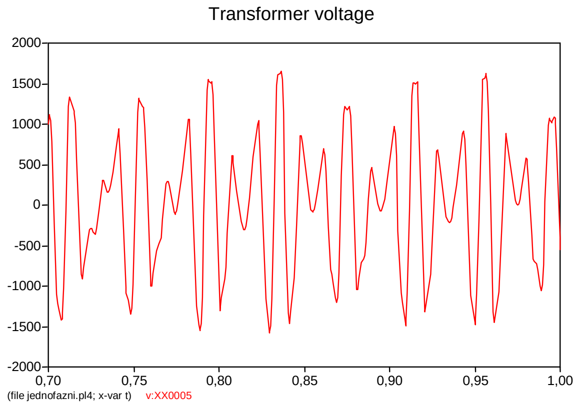

Figure 11. Transformer voltage waveform – chaotic ferroresonance

A spectral analysis of the transformer voltage waveform is shown in Fig. 12.

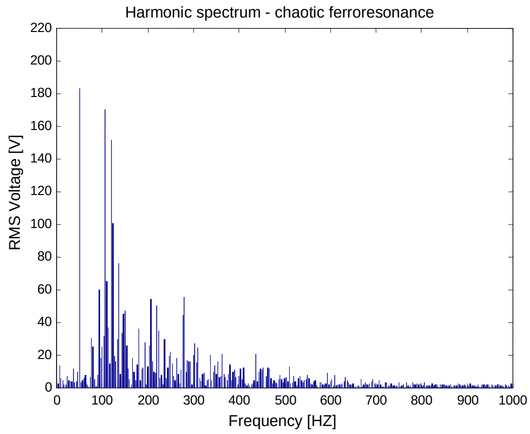

Figure 12. Spectral analysis of the transformer voltage waveform – chaotic ferroresonance

From the results of the spectral analysis of the transformer voltage waveform we see that the voltage spectrum is not discrete, i.e. it is a continuous signal which shows on irregular and unpredictable behavior.
The phase plane for the case of the chaotic ferroresonance is shown in Fig. 13.

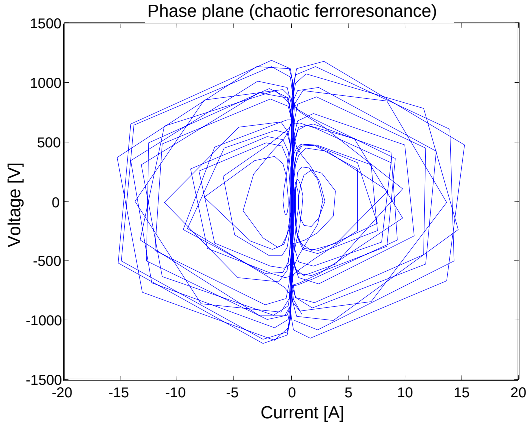

Figure 13. Phase-plane analysis – chaotic ferroresonance

The phase plane is represented by a trajectory that is never closed to itself.

The Poincaré map for the case of the chaotic ferroresonance is shown in Fig. 14.

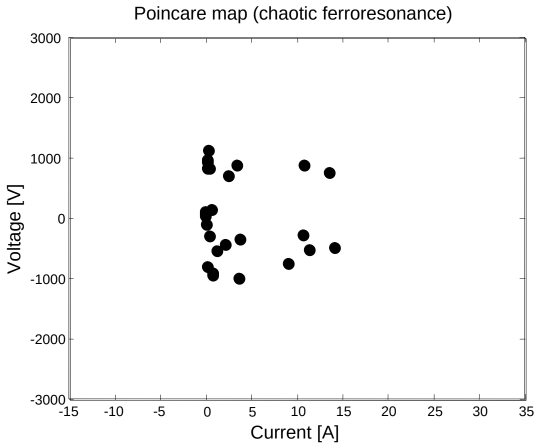

Figure 14. Poincaré map – chaotic ferroresonance

The Poincaré map shows the points forming an undefined character [3], [6].

3 Conclusion

In this paper we show that by changing the system parameters such as grading capacitor C_g, resistance of the transformer magnetizing branch *Rm* and amplitude of voltage source *Um*, different ferroresonant modes are obtained. The ferroresonance phenomenon is analyzed on the example of a single-phase unloaded transformer that is energized over a grading capacitor. To allow for our investigation and experiments, a software model is developed on the basis of the test data and the ferroresonant modes are obtained with satisfactory results. Our simulations of the ferroresonant electrical circuit are made by using the EMTP - ATP software package enabling us to analyze the electromagnetic transient phenomena taking place in the power system. The type of the ferroresonance is identified by using three different methods: the spectral density analysis, the phase-plane analysis and the Poincaré map. These methods confirm the existence of different ferroresonant modes.

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