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Laboratory ferroresonance measurements in power transformers

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Abstract. The paper analyzes laboratory ferroresonance measurements taken on an example of a three-phase three-legged power transformer. Ferroresonance occurrs due to a nonlinear inductance, capacitance and periodic voltage source in the network. A transformer becomes ferroresonant during an irregular circuit-breaker operation, when the interaction between the transformer nonlinear magnetizing inductances and phase-to-ground capacitances generate sustained distorted overvoltages. The measurement results and voltage waveforms show the presence of high and sustained ferroresonant overvoltages and a harmonic spectrum containing higher harmonics.

Keywords: measurements, ferroresonance, three phase three legged transformer

Laboratorijske meritve feroresonance v močnostnih transformatorjih

V članku predstavljamo rezultate laboratorijskih meritev feroresonance na primeru trifaznega tristebrnega transformatorja. Za pojav feroresonance v električnem omrežju so potrebni nelinearna induktivnost in kapacitivnost ter periodični napetostni vir. Transformator preide v feroresonančno stanje med nepravilnim delovanjem odklopnikov, ko se zaradi interakcije med nelinearno induktivnostjo in kapacitivnostjo pojavi prenapetost. Eksperimentalni rezultati so potrdili prisotnost visoke in trajne feroresonančne prenapetosti. V frekvenčnem spektru so vidne tudi višje harmonske komponente.

1 INTRODUCTION

Ferroresonance is a relatively complicated dynamical problem described as the energy oscillations between a nonlinear inductance and linear capacity in the electrical system with a periodic power supply. A nonlinear inductance is caused by the saturation effect of the power- or voltage-transformer iron-core while the linear capacity comes from power lines, cables or equipment capacities. The ferroresonance consequences are deformed current and voltage signals in the system that distort the power-quality parameters [1]. Ferroresonance practically occurs in the analysis of single-phase transformers [2] - [3], voltage transformers [4] - [5] and three-phase transformers [6] - [7]. The basic methods for the ferroresonance investigation in electrical systems are the Fast Fourier Transform [8], Wavelet Transform [9], Galerkin's method [10] or a corresponding numerical method used to simulate a ferroresonant system [11]. Ferroresonance occurs as a polyharmonic, subharmonic or chaotic mode [3], resulting in [12]: (a) steady-state signals containing exclusively odd higher-harmonic components, (b) steady-state signals containing both even and odd higher-harmonic components, and (c) chaotic voltage or current signals. The main focus of this paper is on ferroresonance measurements in a three-phase three-legged power transformer during an irregular operation of a circuit breaker. Two different power-transformer configurations are analyzed, leading to different ferroresonant occurrence types.

The remainder of this paper is organized as follows. Section 2 presents the used laboratory measurement setup for ferroresonance initiation. Section 3 shows the measured results for different configurations of a three-phase power transformer and analyzed harmonic spectrum of voltage waveforms. Section 4 shows conclusions of our research.

2 MEASUREMENT SETUP

Ferroresonance is measured on an example of a three-phase three-legged power transformer shown in Figure 1. The parameters of the transformer are:

- primary voltage: 500 *V*,
- secondary voltage: 380 *V*,
- rated power: 2,4 *kVA*,
- short circuit voltage: 3.05 %,
- windings connection: *Y* - *Y* with an insulated neutral.

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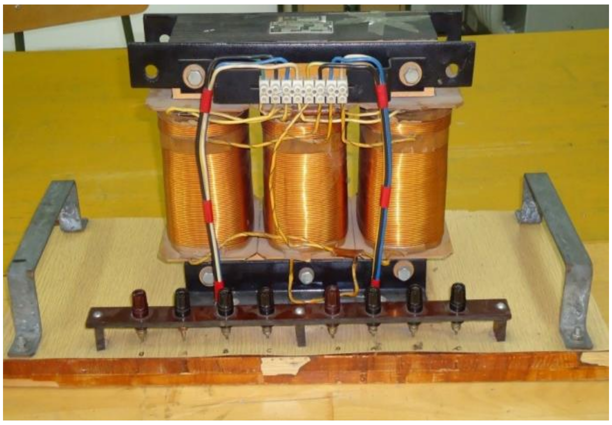

Figure 1. Three-phase three-legged transformer

The ferroresonat circuit (Figure 2) consists of phase-to-ground capacitors which, after switching operations, interact with the magnetizing inductances of the transformer-core legs. The circuit is supplied with a three-phase source of a 50 Hz frequency. The power quality analyzer Fluke 434 is used for monitoring and recording the ferroresonant voltage. For the asynchronous switching operations, three-single phase switches are used.

Figure 2. Laboratory setup

Ferroresonance of a three-phase three-legged power transformer occurs due to an irregular-circuit breaker operation, where the capacitors represent the capacitance of over-head power lines, cables or capacitor banks. The measurements are conducted on an example of two configurations of interest.

3 MEASUREMENT RESULTS

3.1 Configuration 1

The capacitances of the phase-to-ground capacitors are: C_1 = 9.48 µ*F*, C_2 = 9.46 µ*F*, C_3 = 9.36 µ*F*. At time $t = T_{close}$, the switch in phase 1 closes, while the switches in phases 2 and 3 remain open. The ferroresonant circuit is closed over the phase-to-ground capacitors of the open phases (phases 2 and 3) and nonlinear magnetizing inductances of the transformer-core legs (Figure 3).

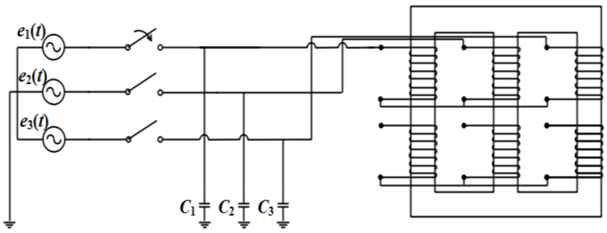

Figure 3. Ferroresonance of a three-phase three-legged trasformer – phase 1 switching on

The waveforms of the phase and neutral voltages are shown in Figures 4 -7:

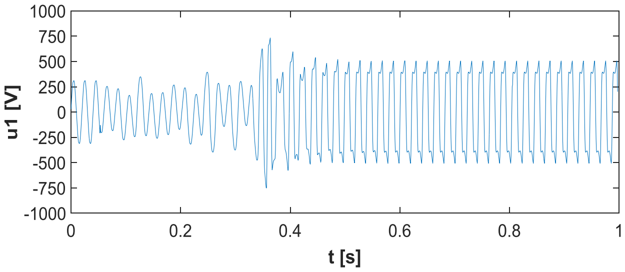

Figure 4. Phase 1 voltage

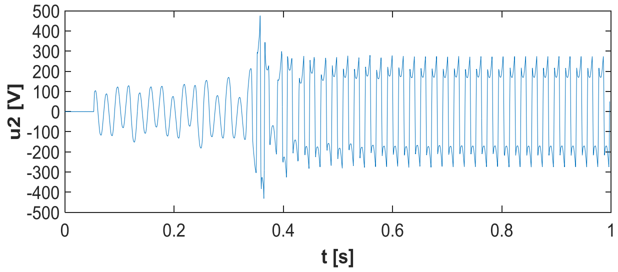

Figure 5. Phase 2 voltage

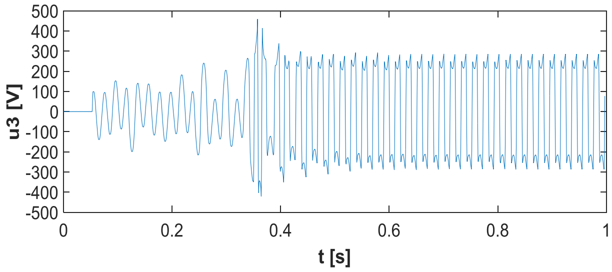

Figure 6. Phase 3 voltage

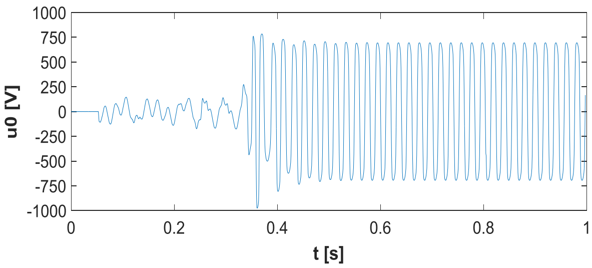

Figure 7. Neutral voltage

One of the ways of identifying the steady states is to find the harmonic spectrum of a state variable (transformer voltages). In the analyzed ferroresonant steady-state phase voltage, there is an evident dominance of both the fundamental frequency and odd higher harmonics, meaning that this steady-state is polyharmonic with odd harmonics (Figure 8).

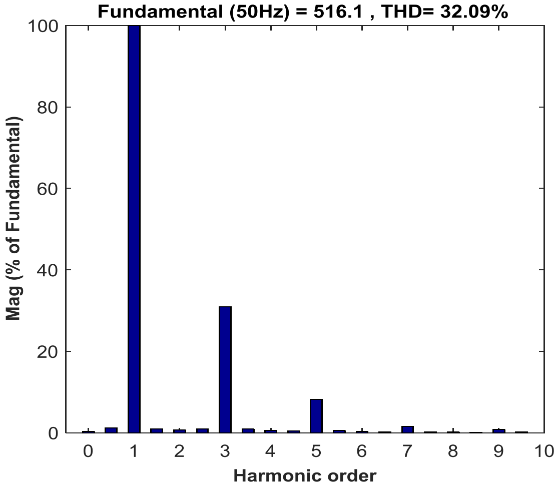

Figure 8. Harmonic spectrum of a ferroresonant steady-state phase voltage

3.2 *Configuration 2*

The capacitances of the phase-to-ground capacitors are: C_1 = 10.35 µ*F*, C_2 = 10.5 µ*F*, C_3 = 10.45 µ*F*. At time $t = T_{open}$, the switches in phases 1 and 3 open simultaneously, while the switch in phase 2 remains closed. The ferroresonant circuit is closed over the phase-to-ground capacitors of the open phases (phases 1 and 3) and nonlinear magnetizing inductances of the transformer-core legs (Figure 9).

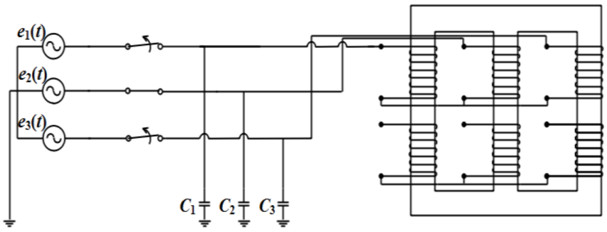

Figure 9. Ferroresonance of a three-phase three-legged trasformer – phases 1 and 3 switching off

The waveforms of the phase and neutral voltages are shown in Figures 10 -13:

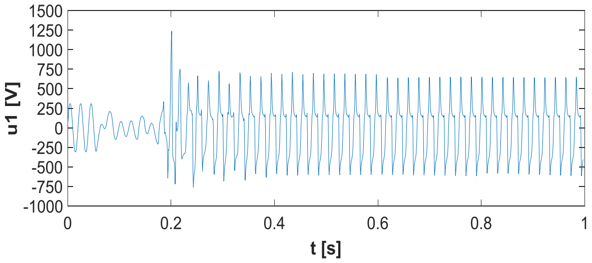

Figure 10. Phase 1 voltage

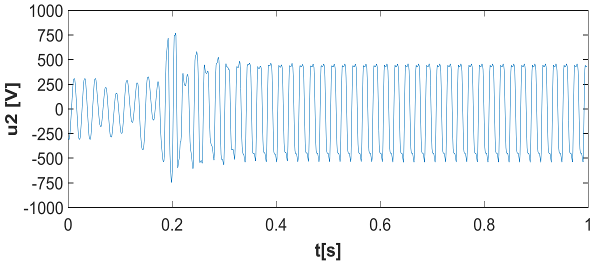

Figure 11. Phase 2 voltage

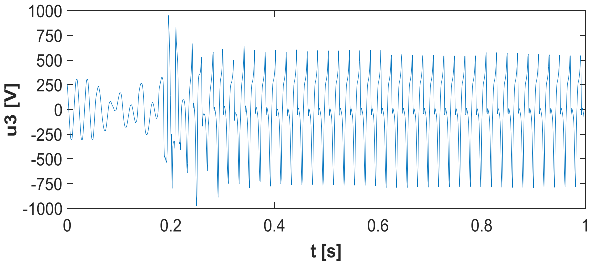

Figure 12. Phase 3 voltage

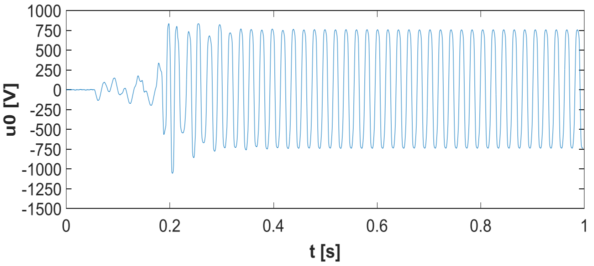

Figure 13. Neutral voltage

Unlike Configuration 1, the harmonic spectrum of the ferroresonant steady-state phase voltage of Configuration 2 contains both, the fundamental frequency and the odd and even higher harmonics, meaning that this steady-state is polyharmonic with odd and even harmonics (Figure 14).

Table 1 shows a comparison between the peak values of the transformer phase and neutral voltages before switching and during the steady-state ferroresonance occurrence.

In Configuration 1, during ferroresonance, the phase 1 voltage increases by 1.63 times, while in phases 2 and 3, the induced voltages are very high. A significant increase of 2.21 times in the phase 1 voltage is registered at a neutral voltage. In Configuration 2, during ferroresonance, the phase 1 voltage increases by 2.31 times, the phase 2 voltage by 1.49 times and phase 3 voltage by 1.96 times compared to the corresponding phase voltage in a normal operating state. The neutral voltage also shows a high increase of 2.46 times the phase 1 voltage before switching.

4 CONCLUSION

Ferroresonance is a nonlinear phenomenon occurring in electrical systems due to energy oscillations between the nonlinear inductance and linear capacity. Affected by ferroresonance, the voltage changes from a steady monoharmonic state to a polyharmonic state with significantly increased amplitude oscillations. A laboratory setup to perform ferroresonance measurements in a three-phase power transformer is presented. Two different configurations of an irregular circuit-breaker operation are analyzed. Their voltage waveforms and harmonic spectra are shown and described. Both configurations give rise to the occurrence of ferroresonant voltages with the amplitude peaks significantly higher than in a normal transformer operation. However, there are certain variations in the harmonic spectrum of the ferroresonant voltage signals. The steady-state phase voltage of Configuration 1 consists of odd higher-harmonic components, and the steady-state phase voltage of Configuration 2 consists of both, the odd and even higher harmonic components. The focus of our future work will be on the development of an EMTP-ATP model to be validated on the basis of presented measurement results. The model will serve to predict the ferroresonance occurrence as a function of different power-system parameters.

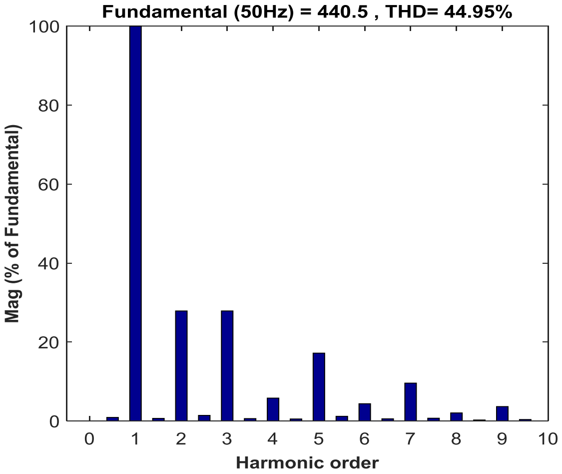

Figure 14. Harmonic spectrum of a ferroresonant steady-state phase voltage

REFERENCES

[1] Tokić, V. Milardić, "Power Quality", Printcom, Grafički inženjering, Tuzla, 2015.

[2] WG on Modelling and Analysis of System Transients Using Digital Programs. "Modelling and Analysis Guidelines for Slow Transients – Part III: "The Study of Ferroresonance", *IEEE Trans. on Power Delivery*, 15 (1), pp. 255-265, Jan. 2000.

Table 1. A comparison of the voltage-peak values

	Configuration 1				**Configuration 2**			
	Phase 1 voltage [*V*]	Phase 2 voltage [*V*]	Phase 3 voltage [*V*]	Neutral voltage [*V*]	Phase 1 voltage [*V*]	Phase 2 voltage [*V*]	Phase 3 voltage [*V*]	Neutral voltage [*V*]
Before switching	313.9	0	0	0	307.7	307.1	306.5	4.8
Ferroresonance	511.4	284.7	290.8	695.1	711	457.1	601.1	757

[3] M. Pejić, A. Tokić, “Impact of the System Parameters on the Ferroresonant Modes”, *Elektrotehniški vestnik*, 80 (1-2), pp. 8-12, 2013.

[4] W. Piasecki, M. Florkowski, M. Fulczyk, P. Mahonen, W. Nowak, “Mitigating Ferroresonance in Voltage Transformers in Ungrounded MV Networks”, *IEEE Trans. on Power Delivery*, 22 (4), pp. 2362-2369, Oct. 2007.

[5] A. Tokić, M. Kasumović, D. Demirović, I. Turković, “Ferroresonance in 35 kV Isolated Networks: Causes and Mitigations”, *Elektrotehniški vestnik*, 83 (5), pp. 259-265, 2016.

[6] A Tokić, V Madžarević, I Uglešić, “Numerical Calculations of Three-phase Transformer Transients”, *IEEE Trans. on Power Delivery*, 20 (4), 2493-2500, Oct. 2005.

[7] B. A. Mork, D. L. Struehm, “Application of non-linear dynamics & chaos to Ferroresonance in Distribution Systems,”, *IEEE Trans. Power Delivery*, 9 (2), pp. 1009–1017, Apr. 1994.

[8] K. Milicevic, D. Vulin, D. Vinko, “Experimental Investigation of Symmetry-Breaking in Ferroresonant Circuit”, *IEEE Trans. on Circuits and Systems I*, 61 (5), pp. 1543-1552, Jan. 2014.

[9] T. C. Akinci, N. Ekren, S. Seker, S. Yildirim, “Continuous Wavelet Transform for Ferroresonance Phenomena in Electric Power Systems”, *International Journal of Electrical Power & Energy Systems*, 44 (1), pp. 403-409, Jan. 2013.

[10] Kieny, C. Le Roy, G. and Sbai, A., “Ferroresonance Study Using Galerkin Method with Pseudo-Arclength Continuation Method”. *IEEE Trans. on Power Delivery*, 6 (4), pp. 1841-1847. Oct. 1991.

[11] A. Tokić, J. Smajić, “Modeling and Simulations of Ferroresonance by Using BDF/NDF Numerical Methods”, *IEEE Trans. on Power Delivery*, 30 (1), pp. 342-350, Jan. 2015.

[12] K. Miličević, Ferroresonance: “Systems, Analysis and Modeling”, *Wiley Encyclopedia of Electrical and Electronics Engineering*, pp. 1-8, Dec. 2014.

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