EKSPERIMENTALNI FEROREZONANTNI KRUG KAO FIZIČKI MODEL FEROREZONANTNOG DIJELA ELEKTROENERGETSKE MREŽE
EXPERIMENTAL FERRORESONANT CIRCUIT AS A PHYSICAL MODEL OF A FERRORESONANT PART OF THE ELECTRICAL POWER NETWORK

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Članak prikazuje vrste ferorezonancije kao i dio elektroenergetske mreže u kojemu je ferorezonancija moguća. Eksperimentalno istraživanje ferorezonantnih dijelova elektroenergetske mreže nije praktički moguće. Stoga je u laboratoriju realiziran eksperimentalni ferorezonantni krug kao fizički model ferorezonantnog dijela elektroenergetske mreže na temelju vrijednosti parametara 230 kV-ne transformatorske stanice Dorsey (Manitoba, Kanada). Normirani parametri eksperimentalnog ferorezonantnog kruga i 230 kV-ne transformatorske stanice Dorsey uspoređeni su kao i dobiveni rezultati mjerenja.

The paper presents types of ferroresonance as well as a part of the electrical power network in which the ferroresonance could occur. The experimental investigation of the ferroresonant parts of the electrical power network is not practically possible. Therefore, an experimental ferroresonant circuit is realized in the laboratory as a physical model of a ferroresonant part of the electrical power network, based on the 230-kV Converter Station Dorsey (Manitoba, Canada). Per-unit parameter values of the experimental ferroresonant circuit and 230-kV Converter Station Dorsey are compared as well as the results obtained from the measurements.

Ključne riječi: elektroenergetska mreža; ferorezonancija; ferorezonantni krug; fizički model; vrste ustaljenih stanja
Keywords: electrical power network; ferroresonance; ferroresonant circuit; physical model; steady-state types

1 UVOD

Ferorezonancija je složena nelinearna električna pojava koja može uzrokovati napone transformatora nekoliko puta veće od nazivnih vrijednosti. Dijelovi elektroenergetske mreže u kojima je ferorezonancija moguća ovdje će se zvati ferorezonantni dijelovi elektroenergetske mreže.

Ferorezonantni dijelovi elektroenergetske mreže sastoje se od nelinearne zavojnice sa željeznom jezgrom koja je napajana preko komponente ili dijela elektroenergetske mreže, kapacitivnost kojih nije zanemariva. Pritom nelinearna zavojnica može biti jednofazni transformator u praznom hodu ili faza trofaznog transformatora u praznom hodu.

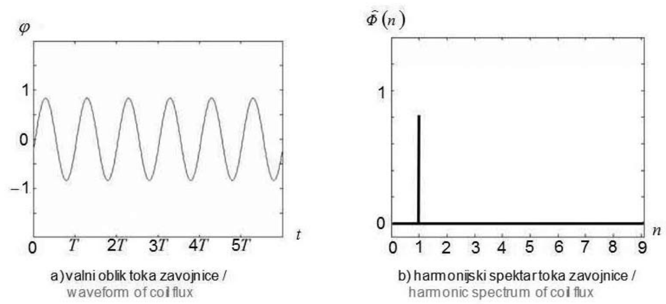
Promjena vrste ustaljenog stanja uzrokovana malom promjenom vrijednosti parametara naziva se bifurkacija. U ferorezonantnom krugu, sve bifurkacije koje uzrokuju promjenu jednoharmonijskog (slika 1) u bilo koje višeharmonijsko ustaljeno stanje sa značajno većim vrijednostima varijabli stanja naziva se ferorezonancija.

1 INTRODUCTION

Ferroresonance is a complicated nonlinear electrical phenomenon which can lead to transformer voltages several times the normal equipment ratings. Parts of electrical power network in which ferroresonance can occur are called here the ferroresonant parts of the electrical power network.

Ferroresonant parts of the electrical power network comprise a nonlinear coil with an iron core that is fed through a component or a part of the electrical power network, the capacitance of which is not negligible. Thereby, the nonlinear coil can be an unloaded single phase transformer, or a phase of an unloaded three-phase transformer.

Sudden change of steady-state types caused by a small change made to the parameter values is called a bifurcation. In a ferroresonant circuit, bifurcations that cause a change from monoharmonic (Figure 1) to any polyharmonic steady state with significantly higher state-variable values are usually named a ferroresonance.



Slika 1 — Primjer jednoharmonijskog ustaljenog stanja

Figure 1 — Example of monoharmonic steady state

Identificirane su tri osnovne vrste ferorezonancije [1] i [2]: ferorezonancija osnovne frekvencije, podharmonijska ferorezonancija i kaotična ferorezonancija. Svaka od vrsta ferorezonancije rezultira višeharmonijskim ustaljenim stanjem s različitim harmonijskim spektrom odabrane varijable stanja, npr. toka zavojnice φ gdje je $\hat{\Phi}(n)$ vršna vrijednost n-tog harmonika:

— ferorezonancija osnovne frekvencije rezultira ustaljenim stanjem koje sadrži više harmonike, frekvencije kojih su neparni višekratnici frekvencije izvora ω (slika 2):

Three basic types of ferroresonance have been identified [1] and [2]: the fundamental frequency ferroresonance, subharmonic ferroresonance and chaotic ferroresonance. Each type of ferroresonance results in a higher harmonic steady state with a different harmonic spectrum of a chosen state variable, e.g. of coil flux φ with the peak value $\hat{\Phi}(n)$ of the n-th harmonic:

— fundamental frequency ferroresonance results in a steady state which contains higher harmonics, frequencies of which are odd multiples of source frequency ω (Figure 2):

$$\varphi = \sum_n \hat{\Phi}(n) \cdot \sin(n\omega t + \alpha_n), \quad n = 1,\ 3,\ 5,\ 7,\ \dots, \tag{1}$$

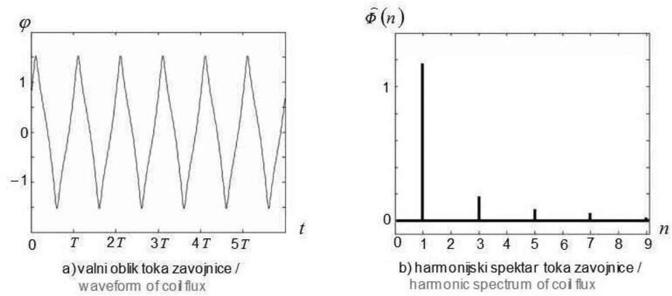
ili ustaljenim stanjem koje sadrži sve cjelobrojne više harmonike (slika 3):

or in a steady state which contains all integer higher harmonics (Figure 3):

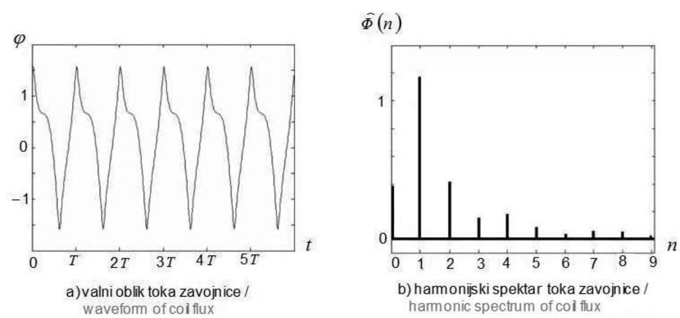
$$\varphi = \sum_{n} \hat{\Phi}(n) \cdot \sin(n\omega t + \alpha_n), \quad n = 0, 1, 2, 3, 4, \dots \tag{2}$$

Promjena jednoharmonijskog ustaljenog stanja u ustaljeno stanje s neparnim višim harmonicima (1) naziva se ferorezonantni skok. Pojava ustaljenog stanja (2) naziva se lom simetrije ili viljuškasta bifurkacija [3] i [4].

The change from monoharmonic steady state into a steady state with odd higher harmonics (1) is called the ferroresonant jump. Occurrence of a steady state (2) is called the symmetry-breaking or the pitchfork bifurcation [3] and [4].



Slika 2 — Primjer ustaljenog stanja s neparnim višim harmonicima
Figure 2 — Example of odd higher harmonic steady state



Slika 3 — Primjer ustaljenog stanja s parnim i neparnim višim harmonicima
Figure 3 — Example of even and odd higher harmonic steady state

— podharmonijska ferorezonancija rezultira ustaljenim stanjem koje sadrži jedan od podharmonika k i njegove višekratnike:

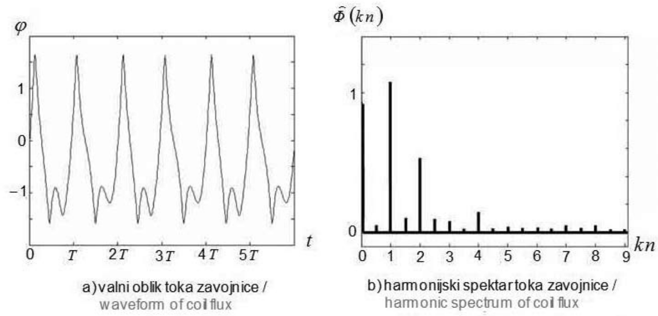
— subharmonic ferroresonance results in a steady-state which contains a subharmonic k and its multiples:

$$\varphi = \sum_{n} \hat{\Phi}(kn) \cdot \sin(kn\omega t + \alpha_{kn}), \quad n = 0, 1, 2, 3, \dots, 1/k = 2, 3, 4, 5, \dots \tag{3}$$

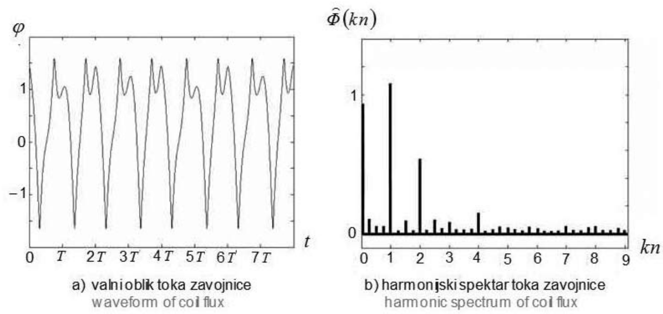
S obzirom na najmanji podharmonik k u harmonijskom sadržaju varijable stanja, nastalo ustaljeno stanje naziva se $1/k$-struko periodičko ustaljeno stanja (slike 4 i 5). Promjena ustaljenog stanja s najmanjim podharmonikom k u ustaljeno stanje

Regarding the smallest subharmonic k in a harmonic content of a state-variable, the resulting steady state is called period-$1/k$ steady state (Figures 4 and 5). The change from a steady state with the lowest subharmonic k into a steady state s najmanjim podharmonikom $k/2$ naziva se udvostručenje periode.

with the lowest subharmonic $k/2$ is called period-doubling.



Slika 4 — Primjer ustaljenog stanja s podharmonicima (dvostruko periodičko ustaljeno stanje)
Figure 4 — Example of subharmonic steady state (period-2 steady state)



Slika 5 — Primjer ustaljenog stanja s podharmonicima (četverostruko periodičko ustaljeno stanje)
Figure 5 — Example of subharmonic steady state (period-4 steady state)

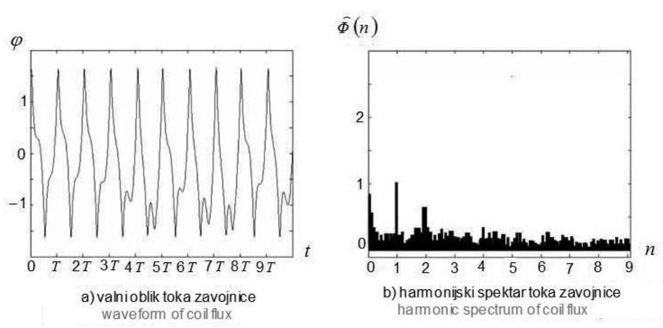
— kaotična ferorezonancija rezultira ustaljenim stanjem kontinuiranog harmonijskog spektra [5]:

— chaotic ferroresonance results in a steady state which has a continuous harmonic spectrum [5]:

$$\varphi = \int_{n=0}^{\infty} \hat{\Phi}(n) \cdot \sin(n\omega t + \alpha_n) \mathrm{d}\, n, \tag{4}$$

tj. oscilacije se čine stohastičkim (slika 6).

i.e. the oscillations appear to be random (Figure 6).



Slika 6 — Primjer kaotičnog ustaljenog stanja
Figure 6 — Example of chaotic steady-state

Zajedničko svojstvo svih ustaljenih stanja nastalih spomenutim vrstama ferorezonancije jest visoki napon transformatora ferorezonantnog dijela elektroenergetske mreže. Pritom napon može biti nekoliko puta veći od nazivnog napona.

A common property of all steady states resulting from the mentioned types of ferroresonance is the high transformer voltage of a ferroresonant part of the electrical power network. Thereby, the voltage can be a few times higher than the nominal transformer voltage.

2 PRIMJER FEROREZONANTNOG DIJELA ELEKTROENERGETSKE MREŽE

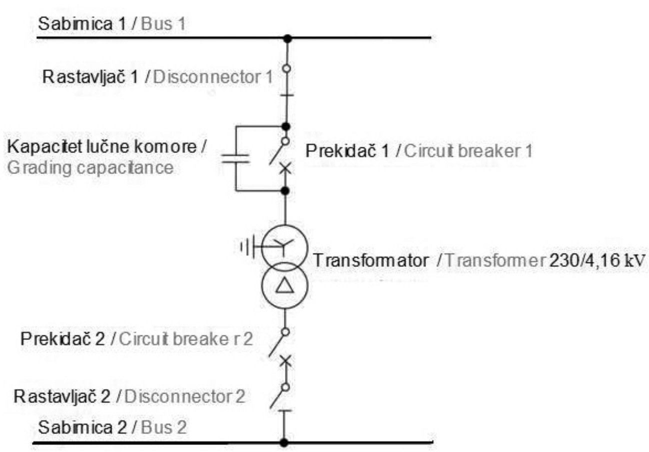
Slika 7 prikazuje jednopolni dijagram ferorezonantnog dijela elektroenergetske mreže u kojemu je faza trofaznog transformatoru u praznom hodu, tj. nelinearna zavojnica, napajana preko kapaciteta lučne komore prekidača. Elektroenergetska mreža prikazana na slici 7 jednaka je 230 kV-tnoj transformatorskoj stanici Dorsey u kojoj se pojavila ferorezonancija, kao što je opisano u [6] do [8].

Ova je transformatorska stanica odabrana za analizu, jer su vrijednosti parametara značajnih za ferorezonanciju poznate za tu stanicu [8], za razliku od transformatorskih stanica elektroenergetske mreže Hrvatske i većine transformatorskih stanica općenito.

2 EXAMPLE OF A FERRORESONANT PART OF ELECTRICAL NETWORK

Figure 7 shows the single-line diagram of a ferroresonant part of the electrical power network in which the phase of an unloaded three-phase transformer, as a nonlinear coil, is fed through a grading capacitance of a circuit breaker. The electrical power network shown in Figure 7 is equivalent to the Manitoba Hydro's 230 kV Dorsey Converter Station in which the ferroresonance has occurred, as it is described in [6] to [8].

This station is chosen for the analysis, because the parameter values of importance for the ferroresonance are known for this station [8], unlike the converter stations of electrical power network in Croatia and unlike most of the converter stations in general.



Slika 7 — Ferorezonantni dio elektroenergetske mreže
Figure 7 — Ferroresonant part of electrical power network

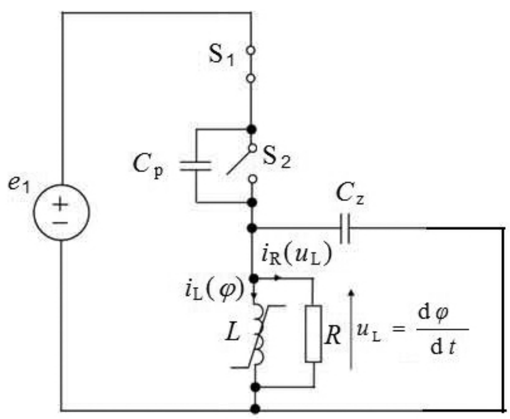
Za ferorezonantni dio elektroenergetske mreže prikazan na slici 7 ferorezonancija se može pojaviti u svakoj fazi sklapanjem polova prekidača 1. Primjerice, ako je pol rastavljača 1 faze 1 uklopljen i pol prekidača 1 u istoj fazi isklopljen, faza je transformatora napajana kroz kapacitet lučne komore prekidača 1. Pritom su svi polovi prekidača 2 i rastavljača 2 isklopljeni, tj. transformator je u praznom hodu. Stoga je cijeli se-

For the ferroresonant part of the electrical power network shown in Figure 7, the ferroresonance can occur in each phase by switching of poles of the circuit breaker 1. For instance, if the pole of the disconnector 1 in phase 1 is closed and the pole of the circuit breaker in the same phase is open, the phase of the transformer is fed through a grading capacity of the circuit breaker 1. Thereby, all the poles of circuit breaker 2 and disconnector 2 kundarni krug, koji se sastoji od sekundarnih namota trofaznog transformatora, prekidača 2, rastavljača 2 i sabirnice 2, zanemariv u daljnjoj analizi.

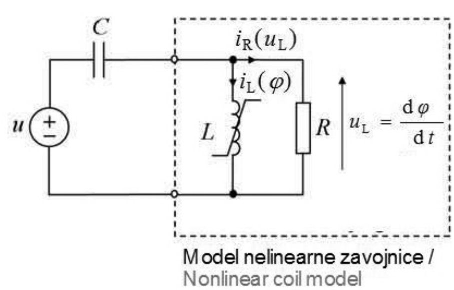
Slika 8 prikazuje model faze 1 elektroenergetske mreže prikazane na slici 7. Nelinearni induktivitet opisan funkcijom $i_L(\varphi)$ i paralelni otpor opisan funkcijom $i_R(u_L)$ predstavljaju zavojnicu sa željeznom jezgrom faze 1 transformatora u praznom hodu, gdje su i_L i φ struja i tok induktiviteta, a i_R i u_L struja i napon otpora. Ukupni gubici u željezu, pri čemu je zanemaren utjecaj viših harmonika, modelirani su linearnim otporom. Pritom je zanemarena magnetska veza između faza trofaznog transformatora, tj. trofazni je transformator modeliran kao tri jednofazna transformatora. C_p je kapacitet lučne komore prekidača, a C_z je ukupni dozemni kapacitet, uključujući kapacitet voda i međukapacitet zavoja namota transformatora. Idealni izvor napajanja e_1 predstavlja napon faze 1. Polovi prekidača 1 i rastavljača 1 faze 1 modelirani su sklopkama S_1 i S_2.

are open, i.e. the transformer is unloaded. Thus, the entire secondary circuit, being composed of secondary windings of the three-phase transformer, circuit breaker 2, disconnector 2 and bus 2, is negligible for the further analysis.

Figure 8 shows a model of phase 1 of the electrical power network shown in Figure 7. A nonlinear inductance described by the function $i_L(\varphi)$ and a parallel resistance described by the function $i_R(u_L)$ represent the iron core coil of the unloaded phase 1 of power transformer, where i_L and φ are the current and flux of inductance, i_R and u_L are the current and voltage of the resistance. Total iron-core losses, disregarding the effects of higher harmonics, are modelled by the linear resistance. Thereby, the paper disregards the magnetic coupling between the phases in a three-phase transformer, i.e. the three phase transformer is modelled as three single-phase transformers. C_p is the circuit breaker grading capacitance and C_z is the total phase-to-earth capacitance, including bus-bar capacitance to earth and transformer winding capacitance. An ideal source equivalent e_1 represents the system voltage of phase 1. Poles of the circuit breaker 1 and disconnector 1 of phase 1 are modelled as switches S_1 and S_2, respectively.



Slika 8 — Model ferorezonantnog dijela elektroenergetske mreže
Figure 8 — Model of the ferroresonant part of electrical power network



Slika 9 — Ferorezonantni krug
Figure 9 — Ferroresonant circuit

Slika 9 prikazuje ekvivalentni krug – ferorezonantni krug. Jednadžbe stanja ferorezonantnog kruga su:

The Figure 9 shows the equivalent circuit, named here as the ferroresonant circuit. The state-equations of the ferroresonant circuit are:

$$\frac{\mathrm{d}\varphi}{\mathrm{d}t} = \dot{\varphi} = -u_\mathrm{C} + u, \quad (5a)$$

$$\frac{\mathrm{d}u_\mathrm{C}}{\mathrm{d}t} = \dot{u}_\mathrm{C} = \frac{1}{RC}(u - u_\mathrm{C}) + \frac{1}{C} i_\mathrm{L}(\varphi), \quad (5b)$$

gdje su:

where:

$$u = e_1 \frac{C_\mathrm{p}}{C_\mathrm{p} + C_\mathrm{Z}} = \hat{U} \sin \omega t, \quad (6a)$$

$$\hat{U} = \frac{C_\mathrm{p}}{C_\mathrm{p} + C_\mathrm{Z}} \hat{E}_1, \quad (6b)$$

$$C = C_\mathrm{p} + C_\mathrm{Z}. \quad (6c)$$

3 EKSPERIMENTALNI FEROREZONANTNI KRUG

Ferorezonancija može uništiti dijelove elektroenergetske mreže [6] do [10]. Stoga bi bilo preskupo istraživati ferorezonanciju na sâmim ferorezonantnim dijelovima elektroenergetske mreže, primjerice, mijenjajući vrijednosti parametara.

U svrhu kontroliranog istraživanja utjecaja vrijednosti parametara, bez opasnosti od uništenja komponenata, u laboratoriju je realiziran ferorezonantni krug koji se sastoji od linearnog kondenzatora $C = 20\ \mu\mathrm{F}$ i nelinearne zavojnice, slika 10. Krug je ovdje nazvan eksperimentalni ferorezonantni krug.

3 EXPERIMENTAL FERRORESONANT CIRCUIT

The ferroresonance can destroy parts of electrical power network [6] to [10]. Thus, it would be too expensive to investigate the ferroresonance on a ferroresonant part of electrical power network by varying its parameter values.

In order to investigate impact of parameter values in a controlled manner, without the danger of destruction of components, the ferroresonant circuit, being composed of the linear capacitor $C = 20\ \mu\mathrm{F}$ and the nonlinear coil, is realized in the laboratory, Figure 10. The circuit is named here as the experimental ferroresonant circuit.

Slika 10 — Eksperimentalni ferorezonantni krug
Figure 10 — Experimental ferroresonant circuit

Primarni namot toroidnog dvonamotnog transformatora sa željeznom jezgrom (Trafoperm N3) upotrijebljen je kao nelinearna zavojnica. Transformator je nazivne prividne snage 200 VA i nazivnog primarnog napona 30 V.

The primary winding of the toroidal iron-cored (Trafoperm N3) two-winding transformer was used as a nonlinear coil. The transformer was designed for the nominal apparent power of 200 VA and for the nominal primary voltage of 30 V.

Karakteristike nelinearnog induktiviteta:

The characteristics of nonlinear inductance

$$i_{\mathrm{L}}(\varphi)=\mathrm{sgn}(\varphi)\sqrt{0{,}1244\cdot\varphi^{2}+2{,}3\cdot10^{16}\cdot\varphi^{20}+4{,}93\cdot10^{31}\cdot\varphi^{38}},\quad i_{\mathrm{L}},\ \mathrm{A},\quad \varphi,\ \mathrm{Vs} \tag{7a}$$

i linearnog otpora

and linear resistance

$$i_{\mathrm{R}}(u_{\mathrm{L}})=u_{\mathrm{L}}/R, \tag{7b}$$

$$R=320\ \Omega, \tag{7c}$$

nelinearne zavojnice temelje se na rezultatima dobivenim standardnim ispitivanjem transformatora: na efektivnoj vrijednosti struje zavojnice kao funkciji efektivne vrijednosti napona zavojnice $I_{\mathrm{T}}(U_{\mathrm{T}})$ i na gubicima zavojnice kao funkciji efektivne vrijednosti napona zavojnice $P_{\mathrm{T}}(U_{\mathrm{T}})$ [11] i [12].

Autotransformator prividne snage 10 kVA upotrijebljen je kao promjenljivi naponski izvor u svim provedenim eksperimentima. Pritom je vršna vrijednost napona mijenjana u rasponu $0<\hat{U}<90$, V.

Analizirani eksperimentalni ferorezonantni krug najjednostavniji je električki krug u kojemu je ferorezonancija moguća. Pritom su shema spoja i jednadžbe stanja eksperimentalnog ferorezonantnog kruga ekvivalentne shemi spoja prikazanoj na slici 9 i jednadžbama stanja (5).

Eksperimentalni ferorezonantni krug može biti fizički model ferorezonantnog dijela elektroenergetske mreže ako omogućuje istraživanje pojave značajne za original, tj. ako se mjerenjem na eksperimentalnom ferorezonantnom krugu identificiraju vrste ustaljenih stanja karakteristične za ferorezonanciju. Rezultati mjerenja prikazani su u 5 poglavlju.

U 4 poglavlju uspoređene su normirane vrijednosti parametara eksperimentalnog ferorezonantnog kruga i ferorezonantnog dijela elektroenergetske mreže. Time su utvrđene razlike normiranih vrijednosti parametara koje bi mogle imati utjecaj na razlike rezultata mjerenja dobivenih na eksperimentalnom ferorezonantnom krugu i transformatorskoj stanici Dorsey, na kojoj se eksperimentalni ferorezonantni krug, kao fizički model ferorezonantnog dijela elektroenergetske mreže, temelji.

of the nonlinear coil are based on the results obtained by the standard measurements: the RMS coil current as a function of RMS coil voltage $I_{\mathrm{T}}(U_{\mathrm{T}})$ and the coil loss as a function of RMS coil voltage $P_{\mathrm{T}}(U_{\mathrm{T}})$ [11] and [12].

The autotransformer of 10 kVA nominal apparent power was used as a variable voltage source in all the experiments. Thereby, the peak voltage value was varied in the range of $0<\hat{U}<90$, V.

The analyzed experimental ferroresonant circuit is the simplest electrical circuit in which ferroresonance can occur. Thereby, the circuit scheme and state equations of the experimental ferroresonant circuit are equivalent to the circuit scheme shown in Figure 9 and state-equations (5), respectively.

The experimental ferroresonant circuit can be a physical model of the ferroresonant part of the electrical power network if it enables an investigation of a phenomenon that is important for the original, i.e. if it is possible to identify steady-state types that are characteristic for ferroresonance using the results of measurements carried out on the experimental ferroresonant circuit. Results of the measurement are presented in Section 5.

The per-unit values of parameters of the experimental ferroresonant circuit and ferroresonant part of the electrical power network, respectively, are compared in Section 4. In this way, the disagreement is determined between the per-unit values that could have an impact on the disagreement of measurement results obtained at the experimental ferroresonant circuit and Converter Station Dorsey, on which the experimental ferroresonant circuit is based as a physical model of the ferroresonant part of the electrical power network.

4 NORMIRANI PARAMETRI

4 PER-UNIT PARAMETERS

Normirane varijable i parametri izraženi su s obzirom na referentne (bazne) vrijednosti napona, snage, frekvencije i struje:

Per-unit variables and parameters are expressed in relation to reference quantities of voltage, power, frequency and current:

$$U_{\mathrm{ref}}, S_{\mathrm{ref}}, \omega_{\mathrm{ref}}, I_{\mathrm{ref}} = \frac{S_{\mathrm{ref}}}{U_{\mathrm{ref}}}. \tag{8}$$

Normirane konstitutivne relacije elemenata ferorezonantnog kruga prikazanog na slici 9 jesu:

Per-unit constitutive relations of elements of a ferroresonant circuit shown in Figure 9 are:

$$\bar{u} = \bar{\hat{U}} \sin \frac{\omega}{\omega_{\mathrm{ref}}} \tau, \quad \bar{\hat{U}} = \frac{\hat{U}}{U_{\mathrm{ref}}}, \quad \tau = \omega_{\mathrm{ref}} \cdot t, \tag{9a}$$

$$\bar{i}_{\mathrm{C}} = \bar{C} \frac{\mathrm{d}\bar{u}_{\mathrm{C}}}{\mathrm{d}\tau}, \quad \bar{C} = C \frac{U_{\mathrm{ref}} \cdot \omega_{\mathrm{ref}}}{I_{\mathrm{ref}}}, \tag{9b}$$

$$\bar{u}_{\mathrm{R}} = \bar{R} \cdot \bar{i}, \quad \bar{R} = R \frac{I_{\mathrm{ref}}}{U_{\mathrm{ref}}}, \tag{9c}$$

$$\bar{i}_{\mathrm{L}} = \bar{f}(\bar{\varphi}), \quad \bar{f}(\bar{\varphi}) = \frac{1}{I_{\mathrm{ref}}} f\left(\frac{U_{\mathrm{ref}} \cdot \bar{\varphi}}{\omega_{\mathrm{ref}}}\right). \tag{9d}$$

Stoga su jednadžbe stanja normiranog ferorezonantnog kruga:

Thus, the state equations of the per-unit ferroresonant circuit are:

$$\dot{\bar{\varphi}} = -\bar{u}_{\mathrm{C}} + \bar{\hat{U}} \cdot \sin \tau, \tag{10a}$$

$$\dot{\bar{u}}_{\mathrm{C}} = \frac{1}{\bar{R}\bar{C}}\left(\bar{\hat{U}} \sin \tau - \bar{u}_{\mathrm{C}}\right) + \frac{1}{\bar{C}} \bar{i}_{\mathrm{L}}(\bar{\varphi}). \tag{10b}$$

4.1 Normirani parametri ferorezonantnog dijela elektroenergetske mreže

4.1 Per-unit parameters of a ferroresonant part of electrical power network

Kao što je već spomenuto u drugom poglavlju, ferorezonantni dio elektroenergetske mreže opisan u tom poglavlju ekvivalentan je 230 kV-tnoj transformatorskoj stanici Dorsey (Manitoba, Kanada). Pritom, prema [8], ferorezonancija se pojavila za sljedeće vrijednosti parametara stanice:

As already mentioned in Section 2, the ferroresonant part of the electrical power network described in that chapter is equivalent to the Manitoba Hydro's 230 kV Dorsey Converter Station. Thereby, according to [8], the ferroresonance occurred at the following parameter values of the transformer station Dorsey:

$$\begin{aligned}
&\left.\begin{aligned} C_{\mathrm{p}} &\approx 6{,}6 \ \ \mathrm{nF} \\ C_{\mathrm{Z}} &\approx 12{,}5 \ \ \mathrm{nF} \\ \hat{E}_1 &= 188 \ \ \mathrm{kV} \end{aligned}\right\} \rightarrow \left\{\begin{aligned} \hat{U} &= \frac{C_{\mathrm{p}}}{C_{\mathrm{p}} + C_{\mathrm{Z}}} \hat{E}_1 = 65 \ \ \mathrm{kV} \\ C &= C_{\mathrm{p}} + C_{\mathrm{Z}} = 19{,}1 \ \ \mathrm{nF} \end{aligned}\right. \\
&\omega = 2\pi \cdot 60 \ \ \mathrm{Hz} \\
&u_{\mathrm{R}} = R \cdot i, \quad R = 3{,}11 \ \ \mathrm{M\Omega} \\
&i_{\mathrm{L}} = 1{,}43 \cdot 10^{-4} \varphi + 7{,}2 \cdot 10^{-37} \varphi^{13}, \quad i_{\mathrm{L}}, \mathrm{A}, \quad \varphi, \mathrm{Vs}\ .
\end{aligned} \tag{11}$$

Izraženo s obzirom na referentne vrijednosti:

Expressed in relation to reference quantities

$$U_{ref} = 188 \ \text{kV}, \quad S_{ref} = 6{,}7 \ \text{MVA}, \quad \omega_{ref} = 60 \ \text{Hz}, \tag{12}$$

normirani parametri ferorezonantnog dijela transformatorske stanice Dorsey su:

the per-unit parameters of the ferroresonant part of the Dorsey transformer station are:

$$\overline{u} = \overline{\hat{U}} \sin \tau, \quad \overline{\hat{U}} = 0{,}35, \quad \tau = \omega_{ref} \cdot t, \tag{13a}$$

$$\overline{i}_C = \overline{C} \frac{d\overline{u}_C}{d\tau}, \quad \overline{C} = 0{,}04, \tag{13b}$$

$$\overline{u}_R = \overline{R} \cdot \overline{i}, \quad R = 588 \tag{13c}$$

$$\overline{i}_L = 0{,}002 \cdot \overline{\varphi} + 0{,}0024 \cdot \overline{\varphi}^{13}. \tag{13d}$$

4.2 Normirani parametri eksperimentalnog ferorezonantnog kruga

4.2 Per-unit parameters of the experimental ferroresonant circuit

Vrijednosti parametara eksperimentalnog ferorezonantnog kruga su:

The values of parameters of the experimental ferroresonant circuit are:

$$\begin{aligned} &u = \hat{U} \sin \omega t, \quad 0 \ \text{V} < \hat{U} < 90 \ \text{V}, \quad \omega = 2\pi \cdot 60 \ \text{Hz}, \\ &i_C = C \frac{du_C}{dt}, \quad C = 20 \ \mu\text{F}, \\ &u_R = R \cdot i, \quad R = 320 \ \Omega, \\ &i_L = \text{sgn}(\varphi) \sqrt{0{,}1244 \cdot \varphi^2 + 2{,}3 \cdot 10^{16} \cdot \varphi^{20} + 4{,}93 \cdot 10^{31} \cdot \varphi^{38}} \end{aligned} \tag{14}$$

Izraženo s obzirom na referentne vrijednosti:

Expressed in relation to reference quantities

$$U_{ref} = 29 \ \text{V}, \quad S_{ref} = 90 \ \text{VA}, \quad \omega_{ref} = 50 \ \text{Hz}, \tag{15}$$

normirani parametri eksperimentalnog ferorezonantnog kruga su:

that is, in a per-unit system, the parameters of the experimental ferroresonant circuit are:

$$\overline{u} = \overline{\hat{U}} \sin \tau, \quad 0 < \overline{\hat{U}} < 3{,}1, \quad \tau = \omega_{ref} \cdot t, \tag{16a}$$

$$\overline{i}_C = \overline{C} \frac{d\overline{u}_C}{d\tau}, \quad \overline{C} = 0{,}06, \tag{16b}$$

$$\overline{u}_R = \overline{R} \cdot \overline{i}, \quad \overline{R} = 34{,}2, \tag{16c}$$

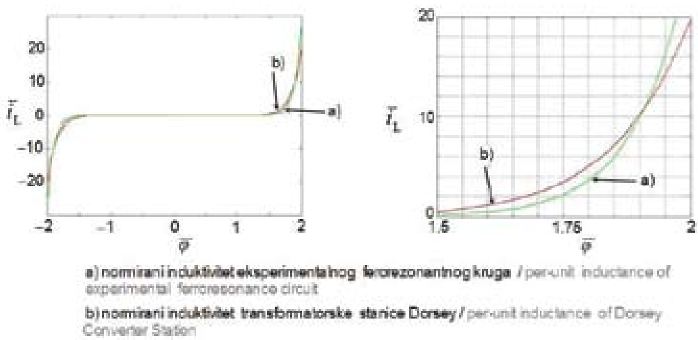
$$\overline{i}_L = \text{sgn}(\overline{\varphi}) \sqrt{1{,}1 \cdot 10^{-4} \cdot \overline{\varphi}^2 + 4{,}82 \cdot 10^{-6} \cdot \overline{\varphi}^{20} + 2{,}44 \cdot 10^{-9} \cdot \overline{\varphi}^{38}} \ . \tag{16d}$$

4.3 Usporedba normiranih parametara

Usporedbom normiranih vrijednosti (13) i (16) razlika između vrijednosti normiranih otpora, (13c) i (16c), pokazuje se najznačajnijom. Pritom su karakteristike normiranih induktiviteta uspoređene samo za praktički mogući raspon vrijednosti toka, $|\overline{\varphi}| \leq 2$. Iz prikaza na slici 11 može se zaključiti da su, za navedeni raspon vrijednosti toka, razlike karakteristika zanemarive.

4.3 Comparison of per-unit parameters

By comparison of per-unit values (13) and (16), respectively, the difference between the values of per-unit resistances, (13c) and (16c) appears to be the significant one. Thereby, the characteristics of per-unit inductance are compared for a practically possible range of flux values, $|\overline{\varphi}| \leq 2$, only. From the depictions in Figure 11 it can be concluded that the disagreement between the characteristics, for the mentioned range of flux values, is negligible.



Slika 11 — Karakteristike normiranih induktiviteta $\bar{i}_L(\overline{\varphi})$ za praktički mogući raspon vrijednosti toka

Figure 11 — Characteristics of per-unit inductance $\bar{i}_L(\overline{\varphi})$ for a practically possible range of flux values

Normirani otpor je u eksperimentalnom ferorezonantnom krugu značajno manji od otpora u transformatorskoj stanici Dorsey. Dakle, normirani gubici u eksperimentalnom ferorezonantnom krugu veći su od gubitaka u transformatorskoj stanici Dorsey. Utjecaj odstupanja vrijednosti normiranih otpora utvrdit će se usporedbom rezultata mjerenja izvršenih na eksperimentalnom ferorezonantnom krugu i transformatorskoj stanici Dorsey, na kojoj se eksperimentalni ferorezonantni krug temelji.

The per-unit resistance in the experimental ferroresonant circuit is significantly lower than the one in Dorsey Converter Station. Consequently, the per-unit losses in the experimental ferroresonant circuit are higher than in the Dorsey Converter Station. The impact of the deviation of per-unit resistance values will be determined by comparison of the results of the measurements carried out on the experimental ferroresonant circuit and on the Dorsey Converter Station, on which the experimental ferroresonant circuit is based.

5 REZULTATI MJERENJA

Kao što je već spomenuto, praktički je nemoguće istraživati ferorezonanciju na sâmim ferorezonantnim dijelovima elektroenergetske mreže, tj. na transformatorskoj stanici Dorsey, mijenjanjem vrijednosti parametara stanice. Dakle, kao jedini rezultat mjerenja na transformatorskoj stanici Dorsey može se upotrijebiti primijećenu pojavu ferorezonancije za vrijednosti parametara (13).

Mjerenja na eksperimentalnom ferorezonantnom krugu sa vrijednostima parametara (16) provedena su, u Laboratoriju za energetsku elektroniku na Elektrotehničkom fakultetu Osijek, u svrhu identifikacije pojave ferorezonancije i utvrđivanja utjecaja odstupanja vrijednosti

5 RESULTS OF THE MEASUREMENTS

As already said, it is practically impossible to investigate the ferroresonance on a ferroresonant part of electrical power network, i.e. on the Dorsey Converter Station, by varying its parameter values. Consequently, we can take the noticed occurrence of ferroresonance for given parameter values (13) as the only result of the measurements on the Dorsey Converter Station.

The measurements on the experimental ferroresonant circuit with given parameter values (16) are carried out in the Laboratory for Power Electronics at the Faculty of Electrical Engineering Osijek in order to identify the occurrence of ferroresonance and to determine the impact of deviation of per-unit resistance normiranih otpora (13c) i (16c). Na taj način će eksperimentalni ferorezonantni krug biti vrednovan kao fizički model ferorezonantnog dijela elektroenergetske mreže. Pritom, kao što je već spomenuto u 3 poglavlju, eksperimentalni ferorezonantni krug može biti fizički model ferorezonantnog dijela elektroenergetske mreže ako se mjerenjem na eksperimentalnom ferorezonantnom krugu identificiraju vrste ustaljenih stanja karakteristične za ferorezonanciju.

Vrste ustaljenih stanja identificirane su s pomoću harmonijskog spektra toka zavojnice φ. Harmonijski je spektar dobiven brzom Fourierovom transformacijom primijenjenom na 20 perioda T valnog oblika toka zavojnice φ, $T = 20$ ms. Pritom je valni oblik toka zavojnice φ izračunat, prema Faradayevom zakonu, kao integral mjerenog napona zavojnice u_L. Vrijednosti napona zavojnice u_L uzorkovani su i pohranjeni s pomoću osciloskopa Tektronix TDS3012B. Valni oblik toka zavojnice φ, kao integral pohranjenih vrijednosti napona zavojnice u_L, i harmonijski spektar toka zavojnice φ izračunati su s pomoću Matlaba 7.0.

Tijekom mjerenja je jedini promjenljivi parametar vršna vrijednost napona napajanja $\hat{U}$ (16a). Kao što je prikazano u tablici 1, povećanjem vršne vrijednosti napona napajanja, ferorezonantni skok pojavio se za vrijednost $\hat{U}\approx 1{,}1$. Daljnjim povećanjem vršne vrijednosti napona napajanja viljuškasta bifurkacija, podharmonijska i kaotična ferorezonancija identificirane su za vršne vrijednosti napona napajanja $\hat{U}=1{,}4$, $\hat{U}\approx 2{,}4$ i $\hat{U}\approx 2{,}7$. Smanjenjem vršne vrijednosti napona napajanja reverzni se ferorezonantni skok pojavio za vršnu vrijednost napona napajanja $\hat{U}\approx 0{,}75$. Dakle, u rasponu vrijednosti $0{,}75 \le \hat{U} \le 1{,}1$, ferorezonancija se može pojaviti ovisno o vrijednostima početnih uvjeta [13]. U nastavku teksta će se raspon vršnih vrijednosti napona napajanja u kojemu pojava ferorezonancije ovisi o početnim uvjetima nazivati ferorezonantni raspon. Slike 12 prikazuju valne oblike i harmonijske spektre toka zavojnice dobivene mjerenjem. Slika 13 prikazuje bifurkacijski dijagram dobiven mjerenjem [14].

U transformatorskoj stanici Dorsey ferorezonancija osnovne frekvencije pojavila se za vrijednost $\hat{U}\approx 0{,}35$. Budući da mjerenja na sâmoj transformatorskoj stanici nisu moguća, u sljedećem će se poglavlju ferorezonantni raspon matematičkog modela transformatorske stanice Dorsey, (10) i (13), odrediti simulacijom. Usto će biti određene vrste ustaljenih stanja dobivene povećavanjem i smanjenjem vršnih vrijednosti napona napajanja u rasponu $0 < \hat{U} \le 3{,}1$. Ferorezonantni raspon i vrste ustaljenih stanja bit će određene simulacijom i za matematički model eksperimentalnog ferorezonantnog kruga, (10) i (16).

values, (13c) and (16c). In this way, the experimental ferroresonant circuit will be evaluated as a physical model of a ferroresonant part of the electrical power network. Thereby, as already mentioned in Section 3, the experimental ferroresonant circuit can be a physical model of the ferroresonant part of the electrical power network if it is possible to identify steady-state types that are characteristic for ferroresonance using the results of the measurements carried out on the experimental ferroresonant circuit.

Steady-state types are identified using the harmonic spectrum of the inductor flux φ. The harmonic spectrum is obtained using the fast Fourier transformation that is applied to 20 periods T of the inductor flux φ, $T = 20$ ms. Thereby, the waveform of the inductor flux φ is calculated, according to the Faraday's law, as an integral of the measured inductor voltage u_L. The values of inductor voltage u_L were sampled and stored using the Tektronix TDS3012B oscilloscope. The waveform of the inductor flux φ, as an integral of the stored values of inductor voltage u_L, and its harmonic spectrum are calculated using Matlab 7.0.

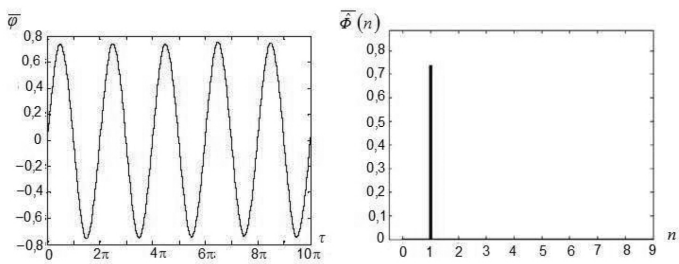
During the measurements, the only variable parameter was the peak value of source voltage $\hat{U}$ (16a). As it is shown in Table 1, by increasing the peak value of source voltage, the ferroresonant jump occurred at the value of $\hat{U}\approx 1{,}1$. By further increasing the peak value of source voltage pitchfork bifurcation, subharmonic and chaotic ferroresonance are identified at peak values of source voltage of $\hat{U}=1{,}4$, $\hat{U}\approx 2{,}4$ and $\hat{U}\approx 2{,}7$, respectively. By decreasing the peak value of the source voltage, reverse ferroresonant jump occurred at the peak value of source voltage $\hat{U}\approx 0{,}75$. Thus, in the range $0{,}75 \le \hat{U} \le 1{,}1$, ferroresonance can occur depending on the values of initial conditions [13]. In the rest of the paper, the range of peak values of source voltage in which initiation of ferroresonance depends on the values of initial conditions is called a ferroresonant range. Figures 12 show waveforms and harmonic spectra of coil flux obtained by measurements. Figure 13 shows the bifurcation diagram obtained by measurements [14].

At the Dorsey Converter Station, fundamental frequency ferroresonance occurred at the value of $\hat{U}\approx 0{,}35$. Because it is practically impossible to investigate the ferroresonance on the converter station, in next chapter, the ferroresonant range of the mathematical model of the Dorsey Converter Station, (10) and (13), will be determined by simulation. Thereby, steady-state types obtained by increasing and decreasing the peak value of source voltage inside the range $0 < \hat{U} \le 3{,}1$ will be determined. Ferroresonant range and steady-state types of the mathematical model of experimental ferroresonant circuit, (10) and (16), will be determined using the simulation as well.

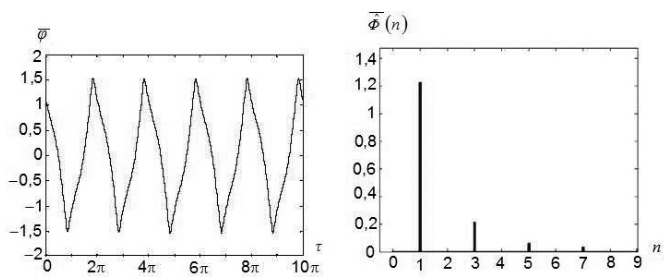
Tablica 1 – Vrste ustaljenih stanja i vrste ferorezonancija/bifurkacija eksperimentalnog ferorezonantnog kruga dobivene mjerenjem

Table 1 – Steady-state types and types of ferroresonance/bifurcations of the experimental ferroresonant circuit obtained by measurements

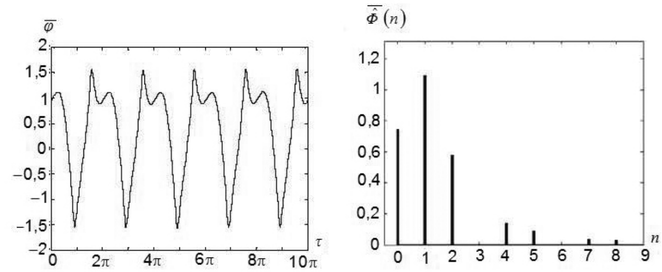
Povećanje / Increasing $\hat{U}$, p.u.	Smanjenje / Decreasing $\hat{U}$, p.u.	Ustaljena stanja i bifurkacije / Steady-states and bifurcations
$0 < \hat{U} < 1,1$	$0 < \hat{U} < 0,75$	Jednoharmonijsko ustaljeno stanje / Monoharmonic steady-state
$\hat{U} = 1,1$	-	Ferorezonantni skok (ferorezonancija osnovne frekvencije) / Ferroresonant jump (fundamental frequency ferroresonance)
-	$\hat{U} = 0,75$	Reverzni ferorezonantni skok / Reverse ferroresonant jump
$1,1 < \hat{U} < 1,4$	$0,75 < \hat{U} < 1,4$	Ustaljeno stanje s neparnim višim harmonicima / Odd higher harmonic steady-state
$\hat{U} = 1,4$		Viljuškasta bifurkacija / Pitchfork bifurcation
$1,4 < \hat{U} < 2,4$		Ustaljeno stanje s parnim i neparnim višim harmonicima / Even and odd higher harmonic steady-state
$\hat{U} = 2,4$		Podharmonijska ferorezonancija (udvostručenje periode) / Subharmonic frequency ferroresonance (period-doubling)
$2,4 < \hat{U} < 2,7$		Dvostruko periodičko ustaljeno stanje / Period-two steady-state
$\hat{U} = 2,7$		Kaotična ferorezonancija / Chaotic ferroresonance
$2,7 < \hat{U} \leq 3,1$		Kaotično ustaljeno stanje / Chaotic steady-state



a) Jednoharmonijsko ustaljeno stanje dobiveno za / Monoharmonic steady-state obtained at $\hat{U} = 0,73$

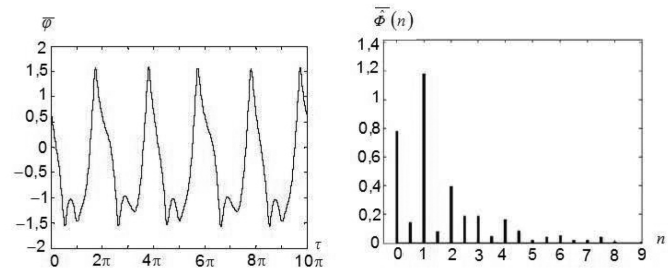


b) Ustaljeno stanje s neparnim višim harmonicima dobiveno za / Odd higher harmonic steady-state obtained at $\hat{U} = 1,22$



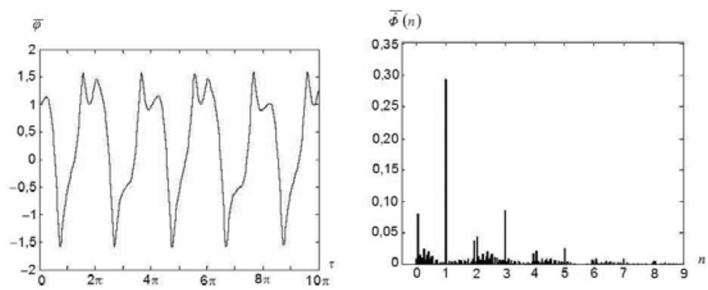
c) Ustaljeno stanje s parnim i neparnim višim harmonicima dobiveno za / Even and odd higher harmonic steady-state obtained at

$\hat{\overline{U}}$ = 1,95



d) Ustaljeno stanje s podharmonicima (dvostruko periodičko ustaljeno stanje) dobiveno za / Subharmonic steady-state (period-two steady-state) obtained at

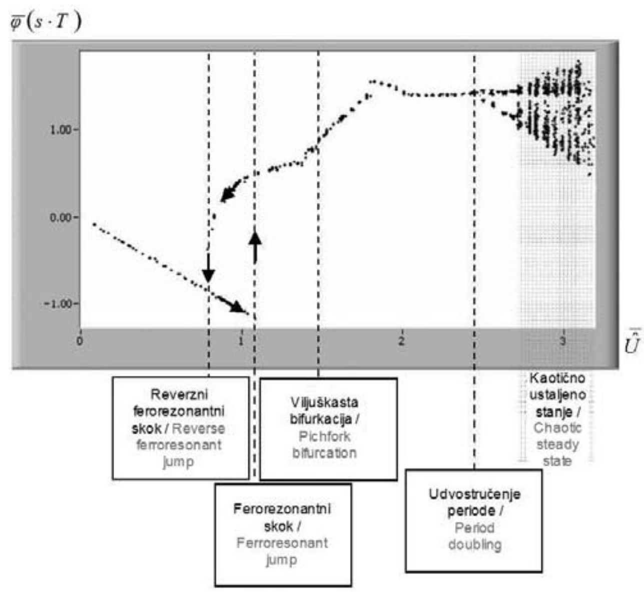
$\hat{\overline{U}}$ = 2,58



e) Kaotično ustaljeno stanje dobiveno za
Chaotic steady-state obtained at

$\hat{\overline{U}}$ = 2,95

Slika 12 — Valni oblici i harmonijski spektri toka zavojnice dobiveni mjerenjem
Figure 12 — Waveforms and harmonic spectra of coil flux obtained by measurements



Slika 13 — Bifurkacijski dijagram dobiven mjerenjem (s = 50, 51, ..., 99, 100)

Figure 13 — Bifurcation diagram obtained by measurements (s = 50, 51, ..., 99, 100)

6 REZULTATI SIMULACIJE

Matematički modeli transformatorske stanice Dorsey, (10) i (13), i eksperimentalnog ferorezonantnog kruga, (10) i (16), realizirani su u Matlab Simulinku. Kao metoda numeričke integracije odabrana je Dormand-Prince metoda s promjenljivim korakom integracije [15].

U tablicama 2 i 3 prikazana su ustaljena stanja dobivena povećanjem i smanjenjem vršnih vrijednosti napona napajanja u rasponu $0 < \hat{U} \leq 3{,}1$. Pritom je ferorezonantni raspon transformatorske stanice Dorsey $(0{,}05 \leq \hat{U} \leq 0{,}95)$ značajno širi od ferorezonantnog raspona eksperimentalnog ferorezonantnog kruga $(0{,}75 \leq \hat{U} \leq 1{,}13)$, tj. ferorezonancija je moguća za značajno manje vršne vrijednosti napona napajanja u transformatorskoj stanici Dorsey.

Vrste ustaljenih stanja dobivene za vršne vrijednosti napona napajanja veće od onih u ferorezonantnom rasponu značajno se razlikuju u transformatorskoj stanici Dorsey, tablica 2, i eksperimentalnom ferorezonantnom krugu, tablica 3. Međutim, jedina značajna razlika između ferorezonantnih vrsta ustaljenih stanja jest gustoća harmonijskog spektra, slike 2-6, koja ima praktički zanemariv značaj u odnosu na značaj vršnih vrijednosti varijabli stanja koje mogu biti vrlo visoke. Stoga, u nastavku teksta razlika ferorezonantnih ustaljenih stanja bit će zanemarena te će razlika ferorezonantnih raspona biti smatrana jedinom značajnom razlikom.

6 SIMULATION RESULTS

The mathematical models of the Dorsey Converter Station, (10) and (13), and the experimental ferroresonant circuit, (10) and (16), are realized using the software package MATLAB/Simulink. Dormand-Prince method with variable integration step is used as a numerical integration method [15].

Tables 2 and 3 show steady-states obtained by increasing and decreasing the peak values of the source voltage in the range $0 < \hat{U} \leq 3{,}1$. Thereby, the ferroresonant range of the Dorsey Converter Station $(0{,}05 \leq \hat{U} \leq 0{,}95)$ is significantly wider than the ferroresonant range of the experimental ferroresonant circuit $(0{,}75 \leq \hat{U} \leq 1{,}13)$, i.e. ferroresonance is possible for a significantly lower peak values of source voltage at the Dorsey Converter Station.

The steady-state types obtained for peak values of source voltage that are higher than the ones in a ferroresonant range differ significantly at the Dorsey Converter Station, Table 2, and experimental ferroresonant circuit, Table 3. However, the only significant difference between the ferroresonant steady-state types is the density of their harmonic spectrum, Figures 2-6, which has negligible practical importance in comparison with the magnitudes of state variables that can be quite high. Therefore, in the rest of the paper the disagreement of ferroresonant steady-states will be disregarded and the disagreement of ferroresonant ranges will be taken as the only significant disagreement.

Tablica 2 – Vrste ustaljenih stanja transformatorske stanice Dorsey dobivene simulacijom
Table 2 – Steady-state types of the Dorsey Converter Station obtained by simulation.

Povećanje / Increasing $\hat{U}$, p.u.	Smanjenje / Decreasing $\hat{U}$, p.u.	Ustaljena stanja / Steady-states
$0 < \bar{U} < 0{,}95$	$0 < \bar{U} < 0{,}05$	Jednoharmonijsko ustaljeno stanje / Monoharmonic steady-state
$0{,}95 \le \bar{U} < 1{,}2$	$0{,}05 \le \bar{U} < 1{,}2$	Ustaljeno stanje s neparnim višim harmonicima / Odd higher harmonic steady-state
$1{,}2 \le \bar{U} < 1{,}62$		Ustaljeno stanje s parnim i neparnim višim harmonicima / Even and odd higher harmonic steady-state
$1{,}62 \le \bar{U} < 1{,}73$		Dvostruko periodičko ustaljeno stanje / Period-two steady-state
$1{,}73 \le \bar{U} < 1{,}75$		Kaotično ustaljeno stanje / Chaotic steady-state
$1{,}75 \le \bar{U} < 1{,}85$		Ustaljeno stanje s parnim i neparnim višim harmonicima / Even and odd higher harmonic steady-state
$1{,}85 \le \bar{U} < 1{,}9$		Dvostruko periodičko ustaljeno stanje / Period-two steady-state
$1{,}9 \le \bar{U} < 2{,}0$		Kaotično ustaljeno stanje / Chaotic steady-state
$2{,}0 \le \bar{U} < 2{,}73$		Ustaljeno stanje s parnim i neparnim višim harmonicima / Even and odd higher harmonic steady-state
$2{,}73 \le \bar{U} \le 3{,}1$		Kaotično ustaljeno stanje / Chaotic steady-state

Tablica 3 – Vrste ustaljenih stanja eksperimentalnog ferorezonantnog kruga dobivene simulacijom
Table 3 – Steady-state types of experimental ferroresonant circuit obtained by simulation

Povećanje / Increasing $\hat{U}$, p.u.	Smanjenje / Decreasing $\hat{U}$, p.u.	Ustaljena stanja / Steady-states
$0 < \bar{U} < 1{,}13$	$0 < \bar{U} < 0{,}75$	Jednoharmonijsko ustaljeno stanje / Monoharmonic steady-state
$1{,}13 \le \bar{U} < 1{,}94$	$0{,}75 \le \bar{U} < 1{,}94$	Ustaljeno stanje s neparnim višim harmonicima / Odd higher harmonic steady-state
$1{,}94 < \bar{U} < 2{,}64$		Ustaljeno stanje s parnim i neparnim višim harmonicima / Even and odd higher harmonic steady-state
$2{,}64 < \bar{U} < 3{,}05$		Dvostruko periodičko ustaljeno stanje / Period-two steady-state
$3{,}05 < \bar{U} \le 3{,}1$		Kaotično ustaljeno stanje / Chaotic steady-state

Simulacija je provedena za sve kombinacije vrijednosti parametara (13) i (16) te je s pomoću utvrđenih ferorezonantnih raspona, tablica 4, zaključeno da je jedino razlika u vrijednostima otpora, (13c) i (16c), značajna.

Simulation is carried out for all combinations of parameter values (13) and (16) in order to obtain ferroresonant ranges, Table 4. From these results it can be concluded that the disagreement between the resistance values, (13c) and (16c), is the significant one.

Tablica 4 – Ferorezonantni rasponi dobiveni simulacijom
Table 4 – Ferroresonant ranges obtained by simulation

	$i_L(\varphi)$, (13d)		$i_L(\varphi)$, (16d)	
	C, (13b)	C, (16b)	C, (13b)	C, (16b)
R, (13c)	$0{,}05 \le \bar{U} \le 0{,}95$	$0{,}04 \le \bar{U} \le 1{,}0$	$0{,}05 \le \bar{U} \le 0{,}83$	$0{,}04 \le \bar{U} \le 0{,}95$
R, (16c)	$0{,}98 \le \bar{U} \le 1{,}25$	$0{,}68 \le \bar{U} \le 1{,}15$	$1{,}04 \le \bar{U} \le 1{,}22$	$0{,}75 \le \bar{U} \le 1{,}14$

Dakle, uzrok razlike ferorezonantnih raspona transformatorske stanice Dorsey i eksperimentalnog ferorezonantnog kruga jest razlika normiranih otpora $\overline{R}$, tj. normiranih gubitaka, eksperimentalnog ferorezonantnog kruga i transformatorske stanice Dorsey. Međutim, nije moguće realizirati eksperimentalni ferorezonantni krug s normiranim gubicima približno jednakim normiranim gubicima ferorezonantnog dijela elektroenergetske mreže. Prema [9, 16] veći gubici, kao u eksperimentalnom ferorezonantnom krugu, smanjuju ferorezonantni raspon, tj. vjerojatnost pojave ferorezonancije. Stoga, za pojavu ferorezonancije potrebno je napajati eksperimentalni ferorezonantni krug značajno većom vršnom normiranom vrijednošću napona napajanja nego u slučaju transformatorske stanice Dorsey.

Usto se zbog značajno manjih normiranih gubitaka u transformatorskoj stanici Dorsey ustaljeno stanje s parnim i neparnim višim harmonicima, dvostruko periodičko ustaljeno stanje i kaotično ustaljeno stanje pojavljuju na značajno manjim normiranim vršnim vrijednostima napona napajanja nego u eksperimentalnom ferorezonantnom krugu.

Consequently, the cause for the disagreement of ferroresonant ranges of the Dorsey Converter Station and experimental ferroresonant circuit is the disagreement of per-unit resistance values $\overline{R}$, i.e. per-unit losses of the Dorsey Converter Station and experimental ferroresonant circuit. However, it is impossible to realize an experimental ferroresonant circuit with per-unit losses that would be approximately equal to the per-unit losses of a ferroresonant part of the electrical network. According to [9] and [16] higher losses, as the ones in the experimental ferroresonant circuit, decrease the ferroresonant range, i.e. the possibility of ferroresonance initiation. Therefore, in order to initiate the ferroresonance, it is necessary to feed the experimental ferroresonant circuit with significantly higher peak value of source voltage than in the case of the Dorsey Converter Station.

Furthermore, due to the significantly lower per-unit losses at the Dorsey Converter Station, even and odd higher harmonic steady state, period-two steady state and chaotic steady state occur at significantly lower peak values of source voltage than in the case of the experimental ferroresonant circuit.

7 ZAKLJUČAK

Ferorezonancija je pojava koja može uništiti dijelove elektroenergetske mreže. Može se pojaviti u dijelovima elektroenergetske mreže koji sadrže nelinearnu zavojnicu sa željeznom jezgrom koja je napajana preko komponente ili dijela elektroenergetske mreže, kapacitivnost kojih nije zanemariva. Vrste ferorezonancije određene su harmonijskim spektrom varijable stanja u ustaljenom stanju nastalom ferorezonancijom.

Eksperimentalno istraživanje ferorezonancije na ferorezonantnim dijelovima elektroenergetske mreže nije moguće bez opasnosti od uništenja komponenata mreže. U svrhu kontroliranog istraživanja ferorezonancije, u laboratoriju je realiziran eksperimentalni ferorezonantni krug na temelju vrijednosti parametara 230 kV-ne transformatorske stanice Dorsey, kao fizički model ferorezonantnog dijela elektroenergetske mreže. Pritom je transformatorska stanica Dorsey odabrana jer su za tu stanicu poznate vrijednosti svih parametara značajnih za pojavu ferorezonancije.

Usporedbom normiranih parametara te rezultata mjerenja i simulacije eksperimentalnog ferorezonantnog kruga i 230 kV-ne transformatorske stanice Dorsey zaključeno je da se eksperimentalni ferorezonantni krug može upotrebljavati kao fizički model ferorezonantnog dijela elektroenergetske mreže. Pritom je nužno uzeti u obzir da su

7 CONCLUSIONS

Ferroresonance is a phenomenon which can destroy parts of the electrical power network. It can occur in a part of the electrical power network which comprises a nonlinear coil with an iron core that is fed through a component or a part of the electrical power network, the capacitance of which is not negligible. The types of ferroresonance are defined by the harmonic spectrum of the state variable in steady state which has arisen after the ferroresonance.

The experimental investigation of ferroresonance on ferroresonant parts of the electrical power network is not possible without the risk of destroying network components. In order to investigate ferroresonance in a controlled manner, an experimental ferroresonant circuit is set up in the laboratory based on parameter values of 230 kV Dorsey Converter Station, as a physical model of a ferroresonant part of the electrical power network. Therefore, the Dorsey Converter Station is chosen because all parameter values significant for the phenomenon of ferroresonance are known for this station.

Comparison of per-unit parameters and results of measurements and simulation of the experimental ferroresonant circuit and 230 kV Dorsey Converter Station implies that the experimental ferroresonant circuit can be used as the physinormirani gubici eksperimentalnog ferorezonantnog kruga značajno veći od normiranih gubitaka 230 kV-ne transformatorske stanice Dorsey.

Na opisani bi se način mogao realizirati fizički model ferorezonantnih dijelova hrvatske elektroenergetske mreže. Pritom bi najveći problem bilo dobivanje vrijednosti parametara mreže značajnih za pojavu ferorezonancije.

cal model of a ferroresonant part of the electrical power network. Therefore, it is necessary to take into account that the per-unit losses of the experimental ferroresonant circuit are significantly higher than the per-unit losses of the 230 kV Dorsey Converter Station.

In the described manner, a physical model of ferroresonant parts of the Croatian electrical power network could be realized. In doing so, the major difficulty would be obtaining those values of network parameters that are significant for the initiation of ferroresonance.

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Uredništvo primilo rukopis:
2008-11-21

Prihvaćeno:
2009-06-11

Manuscript received on:
2008-11-08

Accepted on:
2009-03-02