Electrical Power and Energy Systems 47 (2013) 280–294

Contents lists available at SciVerse ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Chaotic oscillations control in the voltage transformer including nonlinear core loss model by a nonlinear robust adaptive controller

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ARTICLE INFO

Article history:
Received 25 August 2012
Received in revised form 2 November 2012
Accepted 9 November 2012
Available online 12 December 2012

Keywords:
Chaos theory
Chaotic ferroresonant oscillation
Robust adaptive control
Period doubling bifurcation
Chaos control
Feigenbaum number

ABSTRACT

In this paper, control of chaos is done in presence of ferroresonant oscillations in a voltage transformer with nonlinear model of core losses. In order to control the chaotic oscillations, nonlinear adaptive approach is employed. Moreover, a Time Delay Feedback Controller (TDFC) is implemented to stabilize Unstable Periodic Orbits (UPOs). Also multiple scales method to analyze chaotic behavior and types of fixed points in ferroresonance occurrence at voltage transformers considering different types of core loss models is applied. In the literature ferroresonance phenomenon in voltage transformers is proved to be classified in chaotic dynamics systems. In this contribution, chaos occurs in the system from a sequence of Period Doubling Bifurcation (PDB). This phenomenon consists of different types of bifurcations such as Period Doubling Bifurcation (PDB), Saddle Node Bifurcation (SNB), Hopf Bifurcation (HB) and chaos. Dynamic analysis of ferroresonant circuit is performed using bifurcation theory. bifurcation diagrams and phase plane diagrams are illustrated using a continuation method for linear and nonlinear core loss models. For analyzing ferroresonance phenomenon, Lyapunov exponents are calculated using multiple scales method and feigenbaum numbers are obtained. Bifurcation diagrams illustrate variation of parameter control and as a result chaos is created and increased in the system.

1. Introduction

Ferroresonance is a complex nonlinear electrical phenomenon [1], which can causes – thermal – danger to insulators as well as problems in transmission and distribution systems. Due to nonlinear nature of ferroresonance, ferroresonant systems are considered as nonlinear dynamic system, thus linear methods cannot be implemented to analyze them. So, analysis of this behavior is done applying more complex numerical methods [2,3]. These methods are used in transient analyzing programs such as MATLAB, EMTP, PSCAD [4–8]. Ferroresonance behavior occurs in circuits which contain a linear capacitance and a nonlinear inductance. For example, when circuit breaker between main bus and reserve bus is opened, ferroresonance is created in voltage transformer connected to reserve bus. When ferroresonance occurs over voltages, over currents and chaos are created in various frequencies in a power system. Magnetic core of voltage transformer can be considered as a nonlinear inductance and composition of line to line capacitances and line to earth capacitances and grading capacitors of circuit breaker can be considered as a linear capacitance. Ferroresonance should not be understood like linear resonance which occurs in circuits having a linear capacitance and inductance. In the linear resonance, voltage and current change linearly and depend on the frequency of the electrical source. But in the ferroresonance because of nonlinear characteristics of circuit elements the number of fixed points is more than one. Thus by variation of system parameters fixed points lose their stability and regain accordingly. This behavior depends not only on the frequency of electrical source but also on the amplitude of the voltage source, initial conditions and core loss [9–12]. Although methods such as harmonics balance can be used for analyzing the nonlinear differential equations, but solving them leads to a set of complex algebraic equations [13]. An alternative solution is the bifurcation theory which some articles use from this method [14–17]. It enables us to describe and analyze qualitative properties of the solutions, i.e., fixed points, when system parameters change. Studying ferroresonance using bifurcation theory has been performed [18–21]. Although study of ferroresonance exists in the recent literature, they demand relatively high computational resources and their results are only valid for limited cases. For example, the method which is used in [18] is valid only in limited cases while plotting a bifurcation diagram by continuous method could be more systematic and could reduce computational effort [13]. Ferroresonance in power systems have been reported in [5,21,22].

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http://dx.doi.org/10.1016/j.ijepes.2012.11.013

Nomenclature

h_i	coefficient for core loss nonlinear function	μ	damping coefficient
a	coefficient for linear part of magnetizing curve	$K\varepsilon$	amplitude of voltage source
b	coefficient for nonlinear part of magnetizing curve	δ	external detuning
ω	frequency of voltage source	λ	eigenvalue
q	index of nonlinearity of the magnetizing curve	M	mondoromy matrix
C_{ser}	series linear capacitor	$\psi(t)$	fundamental matrix
C_{sh}	shunt linear capacitor	i_R	loss current of core
x	state variable	V_m	magnetization voltage
$i(t)$	instantaneous value of branch current	$R_{\min}$	minimum resistance of circuit
$v(t)$	instantaneous value of the voltage	ϕ_{rated}	nominal flux
ϕ	flux linkage in the nonlinear inductance	σ	constant more than 1
$R_{\max}$	maximum resistance of circuit	Vin	input voltage
χ	feigenbaum constant	z_1, z_2, z_3	states of the nonlinear observer
α	nonlinearity constant		
ε	small positive parameter		

Chaotic ferroresonant behavior depends on various parameters of the system: voltage source amplitude, capacitance and resistance, core loss, initial conditions [6,18,19,23]. Also Metal Oxide Arrester (MOA) and neutral resistance effect on elimination and damping of chaotic oscillations. Chaotic behavior and routes to chaos can be changed when MOAs are connected to terminals of transformer [20–22,24,25]. In this paper a nonlinear models for core loss are derived. Bifurcation diagrams, phase plans [6,26], Feigenbaum numbers and Lyapunov exponents are used to analyze routing to chaos in ferroresonant behavior of the voltage transformer. Lyapunov exponents and the routes to chaos are analyzed by using multiple scales method and bifurcation theory, respectively. In this study, the effects of nonlinear models – of coreloss – are illustrated using bifurcation diagram. Stability analysis is done using Lyapunov exponents and bifurcation diagrams. In bifurcation diagrams, stable and unstable solutions and type of bifurcation are shown. Finally, stability of periodic solutions is investigated using solution's characteristic.

Stabilizing the Unstable Periodic Orbits (UPOs) is an important topic in chaos control research. The first control which is known as the Ott–Grebogi–Yorke (OGY) method proposed by Ott et al. [27], that stabilizes UPOs using small discontinuous parameter perturbation. Some further extensions of this method have lately been proposed [28,29], and they are quite popular in the fields of nonlinear dynamics today. As an alternative to the OGY method to control chaos, a linear Time Delayed Feedback Control (TDFC) method has been proposed to stabilize the UPOs in chaotic systems [30–33].These investigations have some problems. For example in [34], the resistance is considered as parameter of bifurcation, while increasing of input voltage and amount of capacitance is the main reason of ferroresonance in transformer. Also core loss model has been considered linear. The aim of this paper is presentation of a control method for chaotic ferroresonant oscillations. It is supposed that some uncertainties are present in the model. Because of this assumption, the robust stabilization is considered too. Also amplitude of voltage source and capacitors are considered as parameters of bifurcation and bifurcation diagrams and are used for stability analysis. Core loss model is considered nonlinear and a comparison between uncontrolled and controlled system is presented.

2. System description

Ferroresonance occurs in circuits having a linear capacitance and nonlinear inductance. In high voltage systems the capacitance is due to reserve busbars that are near of main busbars and the nonlinear inductance is due to the voltage transformer. Single line diagram of circuit is shown in Fig. 1.

When voltage is induced in the reserve busbar and disconnectors in both side of circuit breaker are opened and circuit breaker is closed, electromagnetic force of ferroresonance is generated. Grading capacitors and capacitors between main busbar and reserve busbar are caused to value of this induced voltage increases to the nominal voltage nearly. When disconnectors are closed capacitors are connected to under voltage busbar, i.e., main busbar and also reserve busbar. Because of low thermal capacity of voltage transformers ferroresonance can damage to its insulation severely. Equivalent circuit of Fig. 1 is shown in Fig. 2.

In Fig. 2 grading capacitors are series in the equivalent circuit. Capacitors between main and reserve busbars and between busbars and ground are modeled as a shunt capacitor with voltage transformer.

The amplitude of voltage source is equal to voltage of main busbar. The core of voltage transformer is magnetization section of transformer modeled by a nonlinear inductance and a resistance for modeling core loss considered as an important parameter in investigation of ferroresonance [10]. Parameters of the proposed case study in this paper are shown in Table 1.

In this paper the magnetization curve of transformer is modeled by a polynomial function as Eq. (1).

$$i_l = a\lambda + b\lambda^q \tag{1}$$

where i_l and λ is the current and flux of transformer respectively. In fact, the $a\lambda$ term is to model the linear behavior and the $b\lambda^q$ term is considered due to the saturation effect of the core. Coefficients used in Eq. (1) are as following:

$$q = 7 \rightarrow a = 3.42,\ b = 0.41$$
$$q = 11 \rightarrow a = 3.42,\ b = 0.14$$

Using these coefficients, the nonlinear magnetization curve of the voltage transformer is shown in Fig. 3.Fig. 3 shows that the increase of q causes the voltage transformer's core to be saturated earlier. Also, knee point of the saturation diagram is reached at lower values of current amplitudes. The dynamics of equivalent circuit can be described as the nonlinear differential equations.

$$\frac{d^2\lambda}{dt^2} + \frac{1}{R(C_{sh}+C_{ser})}\frac{d\lambda}{dt} + \frac{1}{(C_{sh}+C_{ser})}(a\lambda + b\lambda^q) = \frac{C_{ser}\omega}{(C_{sh}+C_{ser})}\left(\sqrt{2}V_{rms}Cos\theta\right) \tag{2}$$

X_1, X_2, ε, μ and k are defined as the Eqs. (3)–(7):