Electrical Power and Energy Systems 67 (2015) 152–160

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

A new approach to eliminating of chaotic ferroresonant oscillations in power transformer

Hamid Reza Abbasi Fordoei [a,*], Ahmad Gholami [a], Seyyed Hamid Fathi [b], Ataollah Abbasi [b]

[a] Iran University of Science and Technology, Tehran, Iran
[b] Amir Kabir University, Tehran, Iran

ARTICLE INFO

Article history:
Received 30 August 2013
Received in revised form 28 September 2014
Accepted 21 November 2014
Available online 10 December 2014

Keywords:
Power transformer
Ferroresonance
Chaos
Nonlinear dynamics
Core loss model
Fault current limiter (FCL)

ABSTRACT

Ferroresonance is a complex phenomenon, which can result in thermal and electrical stresses on power system equipments. It can also cause chaotic oscillations in power system. In this paper, a new method is proposed to restrict and damp ferroresonant oscillations, which is based on a new of fault current limiter (FCL). In this method in order to restrict chaotic ferroresonance oscillations, a kind of fault current limiters (FCL) is used which has been used to restrict unwanted high current flow in power system before.

To study the ferroresonance nonlinear dynamics, in this paper, the chaos theory is used. By using this theory, the changes in system parameters which can cause chaotic ferroresonant oscillations, can be reviewed and analyzed in details. The behavior of the system during ferroresonance occurrence, with and without using proposed FCL, is discussed in bifurcation and phase plane diagrams. By using these diagrams, the behavioral changes of the system can be easily seen in two cases. The simulation results strongly show the effectiveness of using the proposed FCL for restricting the ferroresonant oscillations.

Introduction

Ferroresonance is an electrical complex nonlinear phenomenon, which can cause thermal and insulation failures in transmission and distribution systems. It may be initiated by contingency switching operation, lightning, routine switching, load shedding or capacitor banks connection to the secondary of the transformer winding involving a high voltage transmission line [1–5].

This phenomenon consists of multiple modes with different frequencies such as: base frequency, sub-harmonic, quasi-periodic and chaotic modes [6–8]. The abrupt transition or jump from one steady state to another is triggered by a disturbance, switching action or a gradual change in values of a parameter. The ferroresonance causes overvoltages and overcurrents in power networks which not only can damage transformers but also may cause severe damages to network devices like surge arresters [9–13].

Unlike the resonance, which occurs in RLC circuits with linear capacitances and inductances for a particular frequency, the ferroresonance is occurred in a circuit with a nonlinear inductance due to the core behavior of the transformer. The magnetic core of the voltage transformer can be considered as a nonlinear inductance and composition of line to line and line to earth capacitances and grading capacitors of circuit breakers can be considered as a linear capacitance [14,15].

The ferroresonant oscillations are dependent of not only frequency but also other factors; such as system voltage magnitude, initial magnetic FCLux condition of transformer iron core, total core losses in the circuit and the switching moment [16,17].

Because of the nonlinear nature of the ferroresonance, these systems are considered to be nonlinear dynamic systems and linear methods cannot be used to analyze them. Analytical approaches based on graphical solutions have been proposed to show bifurcations in single-phase ferroresonance circuits [18,19]. 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, the fixed points lose their stability and regain accordingly.

The bifurcation theory is a useful method for identifying system parameters conducive to ferroresonance [20,21]. It enables us to describe and analyze qualitative properties of the solutions, i.e., the fixed points, when system parameters change. The researches based on bifurcation theory need has been relatively high computational burden and are only valid for limited cases. Some of these methods are valid only in limited cases while creating a bifurcation However, by using a continuation method, they can be more systematic and save computational efforts [22,23].

* Corresponding author at: Electrical & Electronic Engineering, Iran University of Science and Technology, 1684613144 Narmak, Tehran, Iran. Tel.: +98 2177240540.
E-mail address: habbasi@iust.ac.ir (H.R.A. Fordoei).

http://dx.doi.org/10.1016/j.ijepes.2014.11.021
0142-0615/

Up to now, several methods have been proposed to restrict and damp ferroresonant oscillations; such as using metal oxide arresters [2] and neutral point resistance application in transformers [24]. One of the problems of arresters is that during ferroresonant oscillations in distribution systems, they may burst [24–27].

In the first section of simulation result section, for analyzing the ferroresonance, a nonlinear model of core losses are derived. An algorithm for calculating core losses from no-load characteristics is given in [28]. Bifurcation diagrams, phase plans, Feigenbaum numbers and Lyapunov exponents for analyzing route to chaos in ferroresonant behavior of the voltage transformer are used [29–31]. To obtain the eigenvalues, the method used is the multiple scales method [32]. Stability analysis by Lyapunov exponents and bifurcation diagrams is performed.

In second section of simulation result section, a new method is introduced to restrict ferroresonant oscillations. Up to now a fault current limiter (FCL) was used to limit fault current and increase power flow in power lines. In this paper a shielded core induction superconducting FCL (FCL) is used to restrict and control ferroresonant oscillations alongside the current limiting ability of FCL.

Whereas a ferroresonant system is a kind of chaotic systems, bifurcation theory should be used to specify the effect of FCL on chaotic ferroresonant oscillations. In final section, simulation results after the FCL was installed on the system, is achieved and its effect on the chaotic ferroresonant oscillations is survived.

Ferroresonance circuit and modeling

The three-phase diagram of the circuit studied in [33], is shown in Fig. 1. The ferroresonance occurres in phase A, when this phase is switched off on the low-voltage side of the transformer; phase C is not connected to the transformer at that time.

The transformer is modeled by a T-equivalent circuit with all impedances referred to the high voltage side. The magnetization branch is modeled by a nonlinear inductance in parallel with a nonlinear resistance, which represented by nonlinear saturation characteristic $(\lambda - i_{\mathrm{Lm}})$ and nonlinear hysteresis and eddy current characteristics $(v_m - i_{\mathrm{Rm}})$, respectively. The hysteresis and eddy current characteristics are calculated using the no-load characteristics and applying the algorithm given in [28]. The iron core saturation characteristic is given by the following equation:

$$i_{\mathrm{Lm}} = a\lambda + b\lambda^q \tag{1}$$

The dynamics of the equivalent circuit can be described by the following nonlinear differential equation;

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

For $q = 11$, the flux linkage curve via magnetization current in saturation section has less slope than what can be seen for $q = 5$ and 7. Thus, ferroresonance effects appear earlier. Besides, increasing q will increase both the number of stable and unstable points. Then changing control parameters may expose unstable points like saddle points and chaotic attractors as well.

The core losses are modeled by a switched resistor; which effectively reduced the core losses resistance by a factor of four at the time of the ferroresonance occurrence. In this paper, the core loss model adopted is described by a third order power series whose coefficients are fitted to matches the hysteresis and eddy current nonlinear characteristics as Eq. (3).

$$i_{\mathrm{Rm}} = h_0 + h_1 v_m + h_2 v_m^2 + h_3 v_m^3 \tag{3}$$

hi	coefficient for core loss nonlinear function
a	coefficient for linear part of magnetizing curve
b	coefficient for nonlinear part of magnetizing curve
ω	frequency of voltage source
q	index of nonlinearity of the magnetizing curve
Cser	series linear capacitor

(continued on next page)

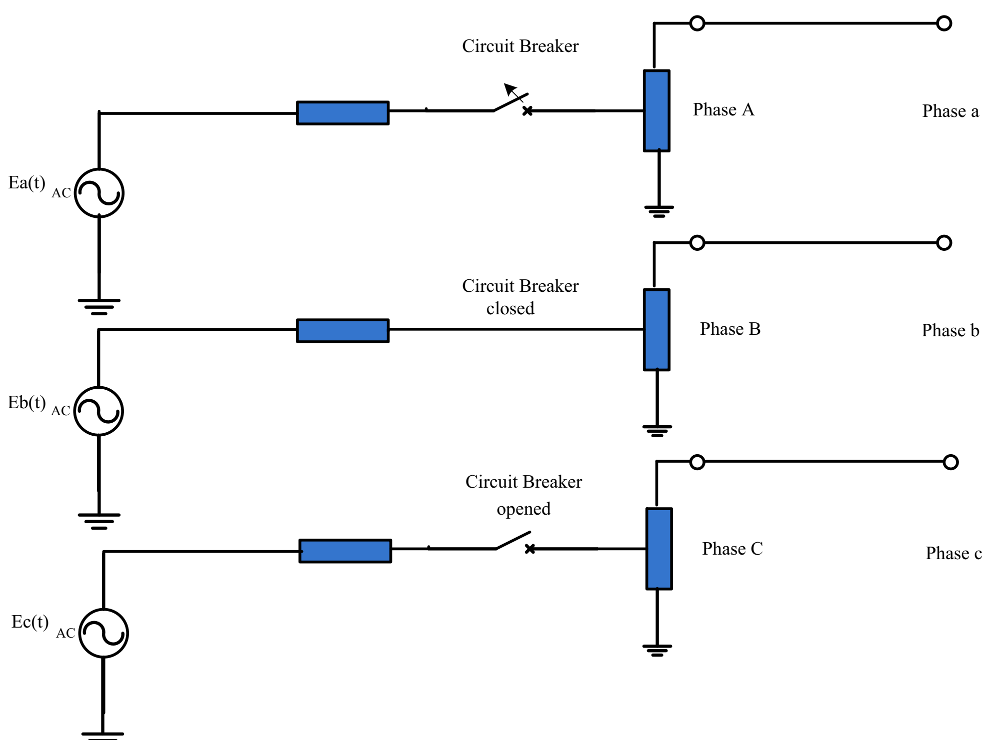

Fig. 1. Ferroresonance circuit in unloaded transformer.