Electrical Power and Energy Systems 45 (2013) 1–9

Contents lists available at SciVerse ScienceDirect

Electrical Power and Energy Systems

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

Ferroresonance suppression in power transformers using chaos theory

Hamid Radmanesh [a,b,*], G.B. Gharehpetian [b]

[a] Department of Electrical Engineering, Islamic Azad University, Takestan Branch, Takestan, Iran
[b] Electrical Engineering Department, Amirkabir University of Technology, Tehran, Iran

ARTICLE INFO

Article history:
Received 8 October 2010
Received in revised form 16 August 2012
Accepted 19 August 2012
Available online 5 October 2012

Keywords:
Metal oxide varistor
Control of chaos
Bifurcation
Ferroresonance
Power transformers

ABSTRACT

The main goal of this paper is the determination of the effect of the metal oxide varistor (MOV) on various ferroresonance modes including fundamental resonance, subharmonic and chaos mode which are generated in electrical power systems. Chaos theory is used for analyzing this effect. Also, the bifurcation, phase plan diagram and time domain simulation are used for this purpose. The proposed power system contains a no-load or lightly loaded power transformer. The magnetization curve of the transformer core is modeled by a single-value two-term polynomial. The core loss is modeled based on the flux of the transformer. The MOV modeled as a nonlinear voltage dependent resistance. The suppression effect of MOV on chaotic ferroresonance in power transformer is studied in this paper. The simulation results confirm that connecting the MOV to the transformer has a considerable suppression effect on ferroresonance phenomena.

1. Introduction

The ferroresonance is a nonlinear resonance, which has result in multiple periodic and non-periodic modes in the system behavior. Considering system parameters and the initial condition of the ferroresonant circuit, it may settle to one of the following behaviors such as fundamental, subharmonic, quasi-periodic or chaotic resonances. Usually, the ferroresonance contains a nonlinear inductance and capacitances. The nonlinear inductance typically is a saturate magnetizing inductance of a transformer and the capacitance is a capacitive distribution cable or transmission line connected to the transformer. Ferroresonance phenomenon has been recognized and investigated in many papers as early as 1907 [1–4]. Isolated ferroresonant solutions in transmission lines have been investigated in [5], which presents the detailed analysis of the subharmonic mode of the ferroresonance and its sensitivity with respect to the length of the deenergised line. The study of the periodic ferroresonance in electrical power networks by bifurcation diagrams has been carried out in [6]. The analysis of the lightning-caused ferroresonance in capacitor voltage transformer (CVT) has been given in [7]. In the paper, a dynamic response to lightening and switching has been studied. So, the study investigates the effect of the lightning strike on a tower with a 132 kV CVT. The s-domain model of three winding transformer for modal analysis has been given in [8]. The influence of non-differential components to the power system small signal stability region has been studied in [9]. Considering the importance of the initial condition in the nonlinear systems, in [10], the impact of initial conditions on the initiation of the ferroresonance in the model of a 275 kV magnetic voltage transformer has been investigated. The transient response of a practical ferroresonant circuit has been studied in detail in [11]. The iterative approximation technique has been used for the determination of the transient response due to sudden application of a sinusoidal voltage. The analysis of subharmonic oscillations in a ferroresonant circuit with the focused on subharmonic (period-3) ferroresonant oscillations has been given in [12]. A novel analytical solution to the fundamental ferroresonance including power frequency excitation characteristic has been investigated in detail in [13]. A method of protecting the voltage transformer against ferroresonance overvoltages with a compact active load has been developed by [14]. The static VAR compensator (SVC) and the thyristor-controlled series capacitor (TCSC) analytical model, a systematical method for suppressing ferroresonance at neutral-grounded substations and the frequency response of the unfiled power flow controller (UPFC) has been simultaneously studied in [15]. A sensitivity study on power transformer ferroresonance in a 400 kV power system is presented in [16]. In that paper, the model of 1000 MV-400/275/13 kV power transformer has been described and the simulations have been compaired with field test results. The influence of supply, circuit and magnetic material parameters on the occurrence of the fundamental ferroresonance mode in a series inductance–capacitance–resistance (LCR) circuit with a nonlinear inductor has been discussed in [17,18]. The effect of the circuit breaker shunt resistance on the chaotic ferroresonance in voltage transformers

* Corresponding author at: Department of Electrical Engineering, Islamic Azad University, Takestan Branch, Takestan, Iran. Tel.: +98 2164543335; fax: +98 2188212072.

E-mail addresses: Hamid.Radmanesh@aut.ac.ir (H. Radmanesh), grptian@aut.ac.ir (G.B. Gharehpetian).

0142-0615/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijepes.2012.08.028

has been studied in [19]. The suppression technique of the ferroresonance phenomenon in the coupling capacitor of the voltage transformer has been given in [20]. The impact of hysteresis and magnetic couplings on the stability domain of ferroresonance in asymmetric three-phase three-leg transformers has been discussed in [21]. Mitigating the ferroresonance of 161 kV electromagnetic potential transformers by damping reactors in gas-insulated switchgear has been presented in [22]. The frequency domain analysis of a power transformer ferroresonance has been studied in [23]. The aim of the current paper is to show the controlling effect of MOV on clamping the ferroresonance overvoltages and the application of MOV as a practical solution for protecting power transformers against ferroresonance overvoltages.

2. Power system modeling

The ferroresonance phenomenon, in most situations, consists of a capacitance and an inductance and there is no definite resonant frequency, so more than one response is possible for the same set of parameters including fundamental, subharmonic and chaotic resonances [24]. In this section, the ferroresonance equivalent circuit is a power transformer connected to the power system. But, one of the three poles of the circuit breaker is open and only transformer two phases are energized. This switching action produces induced voltage in the opened phase. This voltage causes ferroresonance overvoltages, if the distribution line is capacitive. This case here consists of a source with one conductor being interrupted as shown in Fig. 1 [25]. Fig. 2 shows the circuit that feeds the disconnected coil trough the capacitive coupling of the power system [25].

The circuit shown in Fig. 2 has been analyzed using the venin's theorem. By shorting the two remaining voltage sources of phases 1 and 2 the capacitance of the remaining part of the power system can be derived. So, Cg and transformer windings are short circuited and phases 1 and 2 having the same voltage and can be omitted. So, the remaining circuit will consist of two C_m and one C_g. Thus, the equivalent capacitances can be given as Eq. (1) where C_g is ground capacitance and C_m is mutual capacitance of the power system.

$$C = C_g + 2C_m \tag{1}$$

And the equivalent source voltage is given by equation:

$$E = \frac{C_m}{C_g + 2C_m} V_l \tag{2}$$

In unloaded or very lightly loaded transformer, the current causes the flux flow through the iron core. This phenomenon increases the transformer core loss and therefore it should not be neglected. Fig. 3 shows the reduced equivalent circuit including R_2, where it modeles the core loss including eddy current and hysteresis loss. C models the total remaining capacitance and L_{core} represents the power transformer disconnected coil.

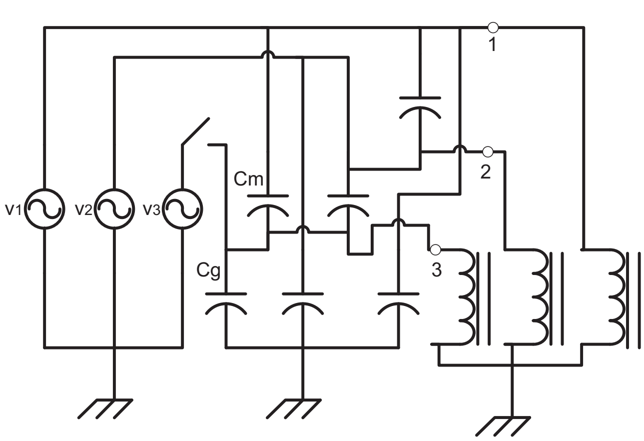

Fig. 1. Model of ferroresonance circuit including line capacitances.

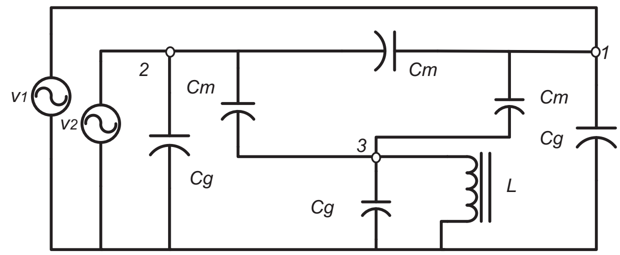

Fig. 2. Circuit that feeds disconnected coil.

The magnetization curve is modeled by a nonlinear inductance in parallel with a nonlinear resistor representing the saturation and hysteresis and eddy current characteristics, respectively. Any damping can be added to the circuit, which may cause the ferroresonance voltage and current elimination. This damping effect can be a resistive source impedance, transformer loss and corona loss. But, the load applied to the secondary of the transformer is much important. A lightly-loaded or unloaded transformer fed through capacitive source impedance is a major candidate for ferroresonance as shown in Fig. 1. Due to high currents and core fluxes, the ferroresonance can overheat the transformer. The high temperature may weaken the winding insulation and cause a transformer failure. In extra high voltage systems, ferroresonance voltages occur during the first cycles and cause insulation coordination problems. Because of non-linearity nature of these circuits, the analytical solution must be determined using time domain methods. So, a computer-based numerical integration method is applied using time domain simulation programs such as the MATLAB.

In this paper, the iron core saturation characteristic is modeled by equation:

$$i_{Lm} = a\varphi + b\varphi^q \tag{3}$$

where q depends on degree of saturation. The adequate value of saturation parameters of a power transformer have been derived by Watson and listed in Table 1 [26].

For deriving the differential equation of the ferroresonance circuit we have:

$$i_1 - i_2 - i_3 = 0 \tag{4}$$

$$V_l = \frac{d\varphi}{dt} = \dot{\varphi} = R_2(i_1 - i_2) \tag{5}$$

where V_l is voltage of transformer, φ is flux linkage, R_2 is transformer core loss, i_1 and i_2 has been shown in Fig. 1. The nonlinear

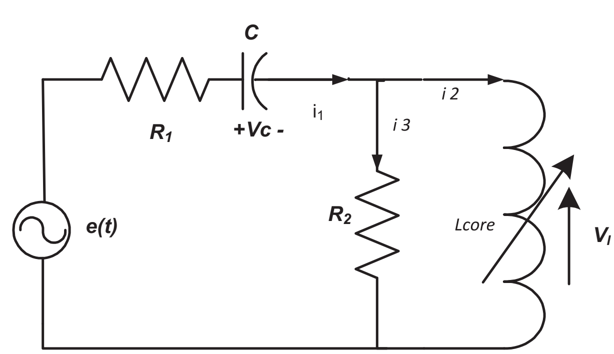

Fig. 3. Equivalent ferroresonance circuit.