Hindawi Publishing Corporation
Advances in Power Electronics
Volume 2012, Article ID 529178, 6 pages
doi:10.1155/2012/529178

Research Article

Resistive Ferroresonance Limiter for Potential Transformers

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Received 10 July 2012; Revised 4 October 2012; Accepted 12 October 2012

Academic Editor: Hadi Y. Kanaan

The ferroresonance or nonlinear resonance is a complex phenomenon, which may cause overvoltage in the electrical power system and endangers the system reliability and operation. The ability to predict the ferroresonance in the transformer depends on the accuracy of the transformer model used. In this paper, the effect of the new suggested ferroresonance limiter on the control of the chaotic ferroresonance and duration of chaotic transients in a potential transformer including nonlinear core losses is studied. To study the proposed ferroresonance limiter, a single phase 100 VA, 275 kV potential transformer is simulated. The magnetization characteristic of the potential transformer is modeled by a single-value two-term polynomial. The core losses are modeled by third order power series in terms of voltage and include core nonlinearities. The simulation results show that the ferroresonance limiter has a considerable effect on the ferroresonance overvoltage.

1. Introduction

The ferroresonance is typically initiated by saturable magnetizing inductance of a transformer and a capacitive distribution cable or transmission line connected to the transformer. In most practical situations, ferroresonance results in dominated currents, but in some operating "mode", may cause significant high value distorted winding voltage waveform, which is typically referred to as ferroresonance [1]. Although occurrences of the "resonance" involves a capacitance and an inductance, there is no definite resonant frequency. In this phenomenon, more than one response is possible for the same set of parameters, and drifts or transients may cause the response to jump from one steady-state response to another one. Its occurrence is more likely to happen in the absence of adequate damping [1]. Researches on ferroresonance in transformers have been conducted for more than 80 years. The word ferroresonance first appeared in the literature in 1920. Nonlinear dynamical tools for studying ferroresonance have been used in [2]. Practical interests have shown that the use of series capacitors for voltage regulation could cause ferroresonance in distribution systems [3]. Ferroresonant behavior of a 275 kV potential transformer, fed from a sinusoidal supply via circuit breaker grading capacitance, has been studied in [4, 5]. The potential transformer ferroresonance from an energy transfer point of view has been presented in [6]. A systematical method for suppressing ferroresonance at neutral-grounded substations has been studied in [7]. A sensitivity analysis on power transformer ferroresonance of a 400 kV double circuit transmission line has been reviewed in [8]. A novel analytical solution to the fundamental ferroresonance has been given in [9, 10]. In that paper, the problem with the traditional excitation characteristic (TEC) of nonlinear inductors has been investigated. The TEC contains harmonic voltages and/or currents. The stability domain calculations of the period-1 ferroresonance have been investigated in [11]. The application of the wavelet transform and MLP neural network for the ferroresonance identification has been used in [12]. The impact of the transformer core hysteresis on the stability domain of ferroresonance modes has been studied in [13, 14]. A 2D finite-element electromagnetic analysis of an autotransformer experiencing ferroresonance is given in [15, 16]. In [17], a new modeling of transformers enabling to simulate slow transients more accurate than the existing models has been presented. In the current paper,

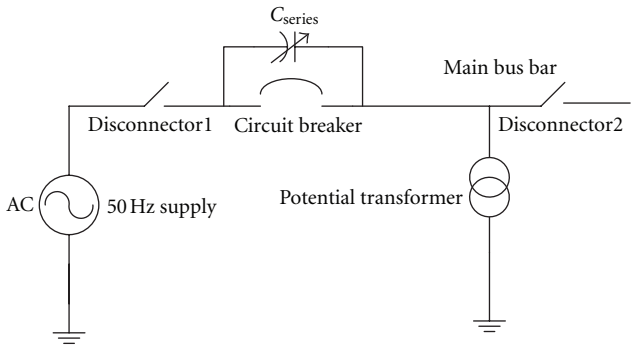

Figure 1: Power system single-line diagram.

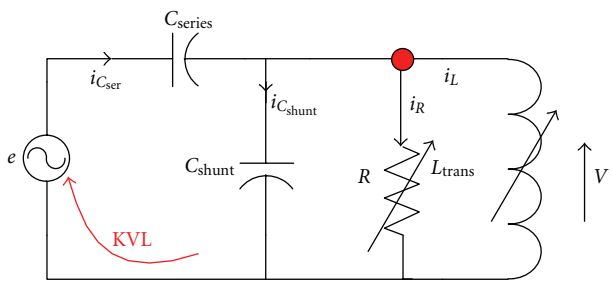

Figure 2: Basic reduced equivalent ferroresonance circuit.

new ferroresonance limiter is suggested as a compact circuit including one resistor, power electronic switch, and control circuit for limiting and stabilizing the unstable and high amplitude ferroresonance oscillations. The resistance is connected to the grounding point of the potential transformer (PT) and during ferroresonance occurrence, the power electronic switch connects the resistor to the transformer. In this paper the simulation results of the case study confirm that system states lead to chaos, and bifurcation occurs in the proposed model. The presence of the proposed ferroresonance limiter tends to clamp the ferroresonance overvoltage. The ferroresonance limiter successfully reduces the chaotic region for higher exponents.

2. System Modeling

The ferroresonance or nonlinear resonance can occur on circuits with power transformers connected to overhead lines and also potential transformers connected to isolated sections of bus bars. Energy is coupled via intercircuit capacitance of parallel lines or open circuit breaker grading capacitance [18].

By careful system design or PT placement it may be possible to increase the phase-to-earth capacitance of the PT ferroresonance circuit, for example, using a longer bus bar, short cables, CVTs, and bushing capacitance. Specifically, the connection of PTs to isolated section of bus, bar, that is, to a low capacitance, should be avoided. Figure 1 shows circuit diagram of the system components at a 275 kV substation. PT is isolated from sections of bus bars via disconnector. In Figure 2, C_{series} models the circuit breaker grading capacitance and C_{shunt} is the total bus bar capacitance to earth. The ferroresonance condition occurs upon closure of disconnector 1 and circuit breaker, leading to a system fault caused by the failure of the voltage transformer primary winding. This figure shows the basic ferroresonance equivalent circuit used to analyze the ferroresonance phenomena. The resistor, R, represents the transformer nonlinear core losses.

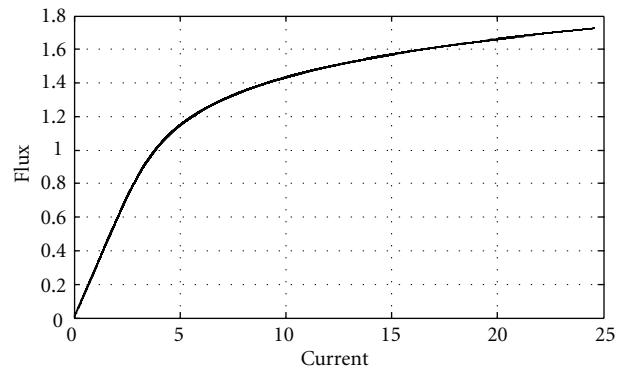

Figure 3: Flux-current characteristic of transformer core.

In Figure 2, E is the rms supply phase voltage. The nonlinear resistor R is an important factor in the initiation of the ferroresonance. In the peak current range for steady-state operation, the flux-current linkage can be approximated by a linear characteristic such as $i_L = a\lambda$, where the coefficient of the linear term (a) corresponds closely to the reciprocal of the inductance ($a \cong 1/L$). However, for very high currents the iron core might be driven into saturation and the flux-current characteristic becomes highly nonlinear, here the $\lambda - i$ characteristic of the potential transformer is modeled as in [20] by the following polynomial:

$$i = a\lambda + b\lambda^7, \tag{1}$$

where, $a = 3.14$, and $b = 0.41$. Figure 3 shows the $\lambda - i$ iron core characteristic for $q = 7$.

The basic ferroresonance circuit of the PT can be presented by the differential equation. A small change in the value of the system voltage, capacitance, or losses may lead to dramatic changes in PT behavior. A more suitable representation for studying the ferroresonance and other nonlinear systems is provided by nonlinear dynamic methods based on phase plan diagram, time domain simulation, and bifurcation diagram.

3. System Dynamic and Equation

Mathematical analysis of the equivalent circuit by applying *KVL* and *KCL* laws the equations of the system can be expressed by the following equations:

$$e = \sqrt{2}E\sin(\omega t),$$

$$i_L = a\lambda + b\lambda^7,$$

$$v_L = \frac{d\lambda}{dt},$$
$$i_{C_{\text{series}}} = C_{\text{ser}} \frac{d}{dt}(e - v_L),$$
$$i_{C_{\text{shunt}}} = C_{\text{sh}} \frac{dv_L}{dt} = C_{\text{sh}} \frac{d^2\lambda}{dt^2},$$
$$i_R = h_0 + h_1 v_L + h_2 v_L^2 + h_3 v_L^3, \tag{2}$$

$$\frac{(C_{\text{ser}} + C_{\text{sh}})}{C_{\text{ser}}} \frac{d^2\lambda}{dt^2} = -\frac{1}{C_{\text{ser}}}\left(h_0 + h_1 v_L + h_2 v_L^2 + h_3 v_L^3\right) - \frac{1}{C_{\text{ser}}}(a\lambda + b\lambda^7) + \sqrt{2}E\omega \cos \omega t, \tag{3}$$

where, ω is the supply frequency, and E is the rms supply phase voltage. The time behavior of the basic ferroresonance circuit is described by (3). The results for two different parameter sets showing the two possible types of ferroresonance are discussed. Table 1 listed base values of parameters and the parameters are given in Table 2. Also, the coefficient values of the nonlinear core model are presented in Table 3.

For the initial conditions, we have

$$\lambda(0) = 0.0, \qquad v_l = \frac{d\lambda}{dt}(0) = \sqrt{2}. \tag{4}$$

4. System Analysis Considering Ferroresonance Limiter

The system, which has been simulated, is shown in Figure 4. In this figure, the ferroresonance limiter is connected to the transformer via power electronic switches (sw_1 and sw_2). In this case, the system time domain simulations have been carried out by using fourth order Runge-Kutta method and validated against MATLAB SIMULINK.

The primary purpose of inserting ferroresonance limiter between the neutral point of the transformer and the earth is to limit the ferroresonance overvoltage and overcurrent. Low impedance earthing is conventionally defined as impedance that limits the prospective ferroresonance current to the full load current of the transformer. The value of the impedance required is easily calculated to a reasonable approximation by dividing the rated phase voltage by the rated phase current of the transformer. The ferroresonance limiter impedance is conventionally achieved using resistors rather than inductors, to limit the tendency for the fault arc to persist due to the inductive started energy. In Figure 4, R_{FLR} is the ferroresonance limiter resistance. The typical values for system parameters, presented in Table 2, are used for the simulations, while the ferroresonance limiter is added to the system and its value is equal to:

$$R_{\text{FLR}} = 50\,\text{k}\Omega. \tag{5}$$

The power electronic switches need proper switching pulse, in order to connect and disconnect the ferroresonance limiter resistance to the grounding point of the transformer.

Table 1: Simulation parameters base values.

Base value of input voltage	(275/square3) kV
Base value of volt-amperes	100 VA
Base angular frequency	($2\pi 50t$) rad/sec

Table 2: Parameters of simulations without using ferroresonance limiter effect.

C_{shunt} (nf)	C_{series} (nf)	ω (rad/sec)	E (kV)	R_{FLR} (kΩ)
3	0.5	314	275	50

Table 3: Parameters of nonlinear core model [19].

h_0	h_1	h_2	h_3
$-3.5213E-03$	$5.7869E-07$	$-1.4167E-12$	$1.21105E-18$

Figure 5 shows the switching process diagram with one decision box. V_{ref} is adjusted between 0.9–1.2 p.u of the source voltage and this reference voltage is compared with the measurement voltage on the transformer coil. When reference and measurement voltages are equal, then the decision box generates the pulse for sw_1 and in other cases, this circuit can operate the second switch. To protect the power electronic switches against overvoltages, the step down transformer is used here. The differential equation for the ferroresonance circuit, shown in Figure 4, can be written as follows:

$$\begin{aligned} C_{\text{ser}} C_{\text{sh}} R_n \frac{d^2 v_L}{dt^2} &= C_{\text{ser}} \sqrt{2} E\omega \cos \omega t \\ &\quad - (C_{\text{ser}} + C_{\text{sh}} + C_{\text{ser}} R_n h_1 \\ &\qquad + 2C_{\text{ser}} R_n h_2 v_L + 3C_{\text{ser}} R_n h_3 v_L^2) \frac{dv_L}{dt} \\ &\quad - (C_{\text{ser}} R_n a + C_{\text{ser}} R_n q b \lambda^6 + h_1) v_L \\ &\quad - \left(h_0 + h_2 v_L^2 + h_3 v_L^3 + a\lambda + b\lambda^7\right). \end{aligned} \tag{6}$$

5. Simulation Results

5.1. Ferroresonance in Potential Transformer. The phase space and waveform of the ferroresonance overvoltage are shown in Figures 6 and 7, respectively. The phase plan diagram clearly shows the chaotic trajectory characteristic of a periodic waveform and it can be seen in Figure 7 that the amplitude of the overvoltage reaches to 6 p.u, which is very dangerous for the system equipments; especially, it can cause the PT failure.

5.2. Effect of Ferroresonance Limiter. This section discusses the effect of ferroresonance limiter on the ferroresonance overvoltage by using bifurcation and phase plan diagram. The previous case with the same parameters but with

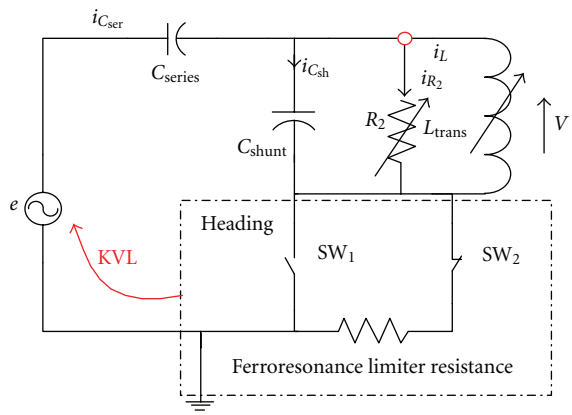

Figure 4: Equivalent ferroresonance circuit and ferroresonance limiter.

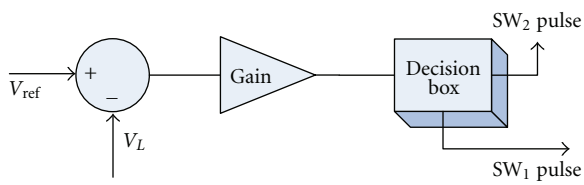

Figure 5: Controlling diagram of switching pulses.

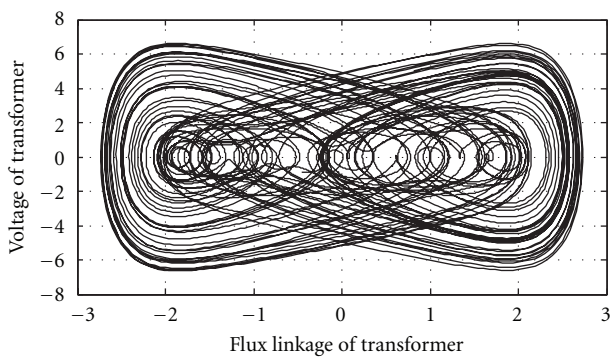

Figure 6: Phase plan diagram for chaotic motion (without using ferroresonance limiter).

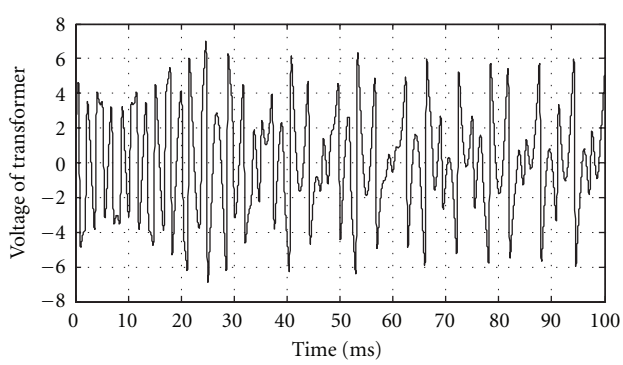

Figure 7: Time domain simulation for chaotic motion (without using ferroresonance limiter).

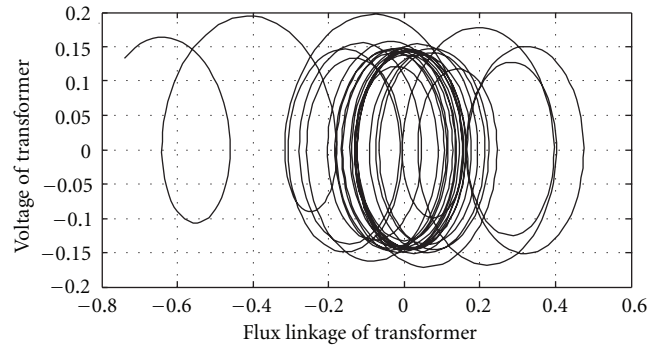

Figure 8: Phase plan diagram for quasiperiodic motion, after using ferroresonance limiter.

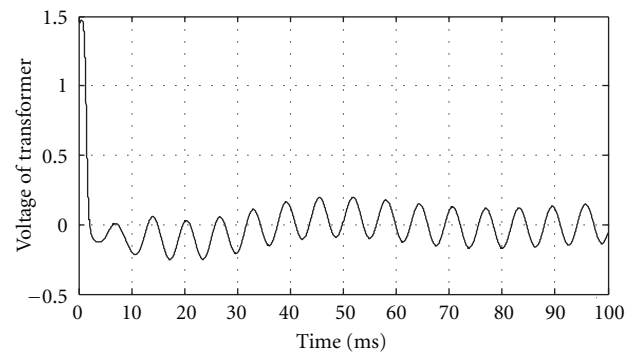

Figure 9: Time domain simulation for quasiperiodic motion, after using ferroresonance limiter.

the ferroresonance limiter is modeled in this section. The simulation results indicate that the chaotic ferroresonance is changed to the periodic oscillation, and the amplitude of the overvoltage is decreased to 1.5 p.u. By considering the ferroresonance limiter effect, the chaotic signal shown in Figure 6 is changed to signal shown in Figure 8. Also, time domain simulation for quasiperiodic motion, after using ferroresonance limiter has been shown in Figure 9. According to this plot, system behavior is changed to the torus oscillation, and the amplitude of the overvoltage, shown in Figure 10, is highly controlled and reaches 0.2 p.u.

5.3. Bifurcation Diagram Analysis. Another tool that is used for studying nonlinear equations is the bifurcation diagram [13]. Figure 10(a) clearly shows the ferroresonance overvoltage in PT when the nominal voltage of the power system increases to 5 p.u.

According to this plot, the chaotic trajectory and the amplitude of the ferroresonance overvoltage reach 2.5 p.u. This overvoltage can cause PT failure. Figure 10(b) shows that there is no chaotic region in the system behavior after using the ferroresonance limiter. Also, the fundamental resonance in the system and the amplitude of the overvoltage decreases less than 2 p.u and the system can work in the safe operation region.

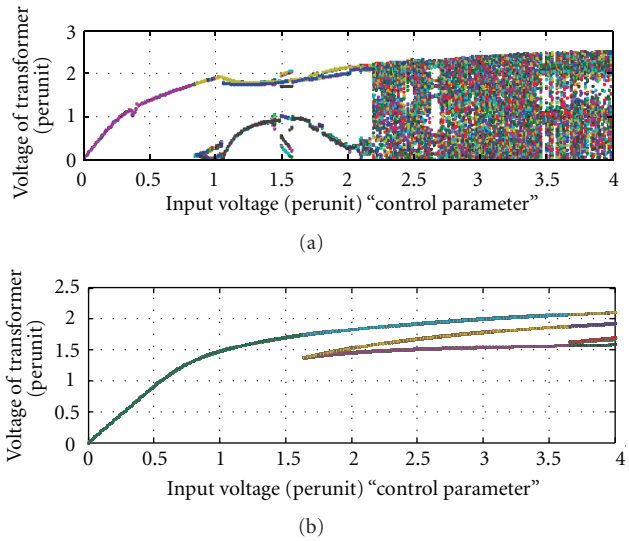

Figure 10: (a) Bifurcation diagram for voltage of transformer versus voltage of system, without using ferroresonance limiter. (b) Bifurcation diagram for voltage of transformer versus voltage of system, after using ferroresonance limiter.

6. Conclusion

In this paper, one of the nonlinear phenomena in the power transformer, known as ferroresonance, has been studied. The ferroresonance overvoltages are temporary overvoltages and they can cause insulation failures. This paper has suggested a new ferroresonance limiter for PTs. The proposed ferroresonance limiter results in reduction of the amplitude of the overvoltage and successfully eliminates chaotic behaviours. Based on simulations, it has been shown that after using ferroresonance limiter, the periodic oscillation was obvious and the chaotic oscillation has been changed to the fundamental and periodic resonances.

Nomenclature

h_0, h_1, h_2, h_3: Coefficients for core losses nonlinear function (per unit)
n: Index for the neutral connection
a: Coefficient for linear part of magnetizing curve (per unit)
b: Coefficient for nonlinear part of magnetizing curve (per unit)
q: Index of nonlinearity of the magnetizing curve
C_{series}: Linear capacitor of circuit breaker (F)
C_{shunt}: Linear capacitor of the power system (F)
R_m: Core losses resistance (ohm)
i: Instantaneous value of branch current (A)
v: Instantaneous value of the voltage across a branch element (V)
E: Instantaneous value of driving source (V)
φ: Flux linkage in the nonlinear inductance (Weber)
ω: Angular frequency of the driving force (rad/sec)
PT: Potential transformer
C.B: Circuit breaker
N.R: Neutral earth resistance
DS1: Disconector1
DS2: Disconnector2
MOSA: Metal oxide
FLR: Ferroresonance limiter resistance.

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