Controlling Chaotic Oscillations in Electromagnetic Voltage Transformers including Nonlinear Core Losses Considering Neutral Earth Resistance Effect

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Abstract: *Ferroresonance or nonlinear resonance is a complex phenomenon, which may cause overvoltages in the electrical power system which endangers the system reliability and continuous safe operating. The ability to recognize or confirm ferroresonance depends on the accuracy of the transformer model used. This work, an overview of available paper to this area is provided, at first ferroresonance phenomenon is introduced and then two type of ferroresonance oscillation in a voltage transformer is simulated. Finally effect of the neutral resistance on the onset of chaotic ferroresonance and duration of chaotic transient in a voltage transformer including nonlinear core losses has been studied. It is expected that this resistance generally leads into ferroresonance 'control'.*

Key words: *ferroresonance oscillation, stabilizing, chaos control, voltage transformer, nonlinear core losses effect, Neutral Earth Resistance*

I. Introduction

Ferroresonance overvoltage on electrical power systems were recognized and studied as early as 1930s. Kieny first suggested applying chaos to the study of ferroresonance in electric power circuits [1]. Ferroresonant behavior of a 275 kV electromagnetic voltage transformer, fed from a sinusoidal supply via circuit breaker grading capacitance, has been studied in [2]. Voltage transformer ferroresonance from an energy transfer standpoint is given in [3]. Discussion of modeling and analysis guidelines for ferroresonance slow transients has been addressed in [4]. Fast ferroresonance suppression of coupling capacitor voltage transformers was investigated in [5]. A systematical method for suppressing ferroresonance at neutral-grounded substations is given in [6]. In this paper, the scheme for suppressing the ferroresonance is to insert resistance, made from parallel-connected resistors into the PT's wye connected secondary circuit. Sensitivity studies on power transformer ferroresonance of a 400 kV double circuit are given in [7]. Stability domain calculations of period-1 ferroresonance in a nonlinear resonant circuit have been investigated in [8]. The impact of transformer core hysteresis on stability domain of ferroresonance modes has been studied in [9]. A new modeling of transformers enabling to simulate slow transients more accurate than the existing models in Simulink/MATLAB is given in [10]. Controlling ferroresonance oscillations in voltage transformer including nonlinear core losses and considering the circuit breaker shunt resistance effect has been investigated in [11] and [12]. In all papers sited above, the effect of neutral resistance on ferroresonance oscillations in voltage transformer has not been studied yet. In this paper, controlling effect of the neutral earth resistance is studied on the ferroresonance oscillations.

II. Power System Modeling without Neutral Resistance

Ferroresonance or nonlinear resonance can occurs when energy is coupled via the inter-circuit capacitance of the parallel lines or open circuit breaker grading capacitance.

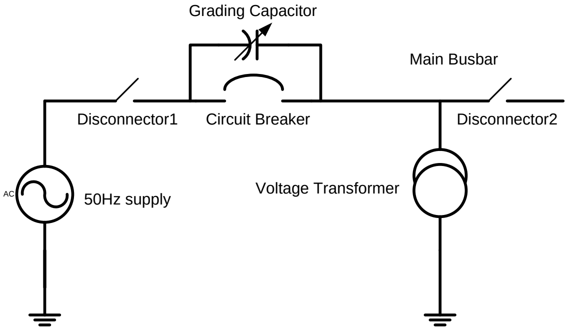

Fig. 1. Power System one line diagram arrangement resulting to VT Ferroresonance

Fig. 1 shows the circuit diagram of system components at the 275 KV substations. VT is isolated from sections of bus bars via disconnector. C_{series} is circuit breaker grading capacitance, and C_{shunt} is the total bus bar capacitance to earth.

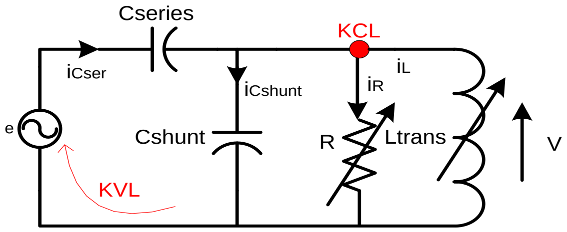

Fig. 2. Basic reduced equivalent ferroresonance circuit

Ferroresonance conditions occurred upon closure of DS_1 with C.B and DS_2 open, leading to a system fault caused by failure of the voltage transformer primary winding. Fig.2 shows the basic ferroresonance equivalent circuit used to analyzing ferroresonance phenomena in this paper. The resistor R represents transformer core losses which are considered as nonlinear losses in this paper. In Fig. 2, E is the rms supply phase voltage and R represents a voltage transformer core loss that has been found to be an important factor in the initiation of ferroresonance. The $\lambda - i$ characteristic of the voltage transformer is modeled as in [14] by the polynomial

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

where, $a = 3.14$, $b = 0.41$

Fig. 3 shows simulation of $\lambda - i$ iron core characteristic for q=7, also

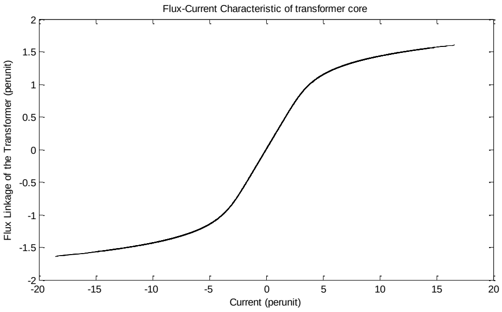

Fig. 3. Flux- current characteristic of the transformer core

The basic ferroresonance circuit of the voltage transformer can be presented by the differential equation. Mathematical tools that are used in this analysis are phase plan diagram, time domain simulation, and bifurcation diagram.

III. Power System Dynamic and Equation

Mathematical analysis of equivalent circuit by applying KVL and KCL has been done and Equations of system can be presented as below:

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

$$i_L = a\lambda + b\lambda^7 \tag{3}$$

$$v_L = \frac{d\lambda}{dt} \tag{4}$$

$$\frac{(C_{ser} + C_{sh})}{C_{ser}} \frac{d^2\lambda}{dt^2} = -\frac{1}{C_{ser}}\left(h_0 + h_1 v_L + h_2 {v_L}^2 + h_3 {v_L}^3\right) - \frac{1}{C_{ser}}\left(a\lambda + b\lambda^7\right) + \sqrt{2}E\omega\cos\omega t \tag{5}$$

where, ω is the supply frequency, and E is the rms supply phase voltage. In equation (1) a=3.4 and b=0.41 are the seven order polynomial sufficient. The time behavior of the basic ferroresonance circuit is described by (5).

Table (1): base values of the system used for simulation

Base value of the input voltage	$275/\sqrt{3}$ kV
Base value of volt-amperes	100 VA
Base angular Frequency	$2\pi 50$ rad/sec

Table.1 shows base values used in the analysis and parameters of different states are given in table (2).

Table (2): Parameters used for various states simulation without considering neutral resistance

System behavior *Parameters*	C_{shunt} *(nf)*	C_{series} *(nf)*	ω *(rad/sec)*	*E (kV)*	R_n *(kΩ)*
values	3	0.5	314	275	50

In the second case, power system behavior is analyzed in the case of considering neutral earth resistance effect. In the second case of analysis, periodic oscillation is obvious and chaotic oscillation is changed to the fundamental and periodic resonances. Nonlinear core losses values are given in Tables (3).

IV. Power System Descriptions with Considering Neutral Earth Resistance

In this case of power system modelling, time domain simulations were performed using fourth order Runge-Kutta method and validated against MATLAB SIMULINK, and power system which was considered for simulation is shown in Fig. 4.

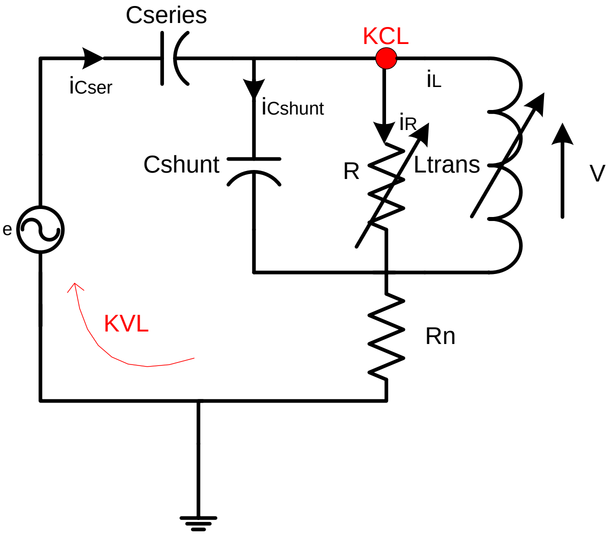

Fig.4. Basic reduced equivalent ferroresonance circuit with considering neutral earth resistance

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

Table (3): parameters value of nonlinear core model

h_0	-0.000001
h_1	0.0047
h_2	-0.0073
h_3	0.0039

Neutral earthling impedance is conventionally achieved using resistors rather than inductors, so as to limit the tendency for the fault arc to persist due to the inductive energy storage. In Fig. 4, R_n is the neutral earth resistance. Typical values for various system parameters, as presented in Table (2) have been considered for simulation, while the neutral resistance has been added to the system the value of which is given below:

$$R_{neutral} = 50K\Omega$$

And for the initial conditions, we have:

$$\lambda(0) = 0.0; \quad v_l = \frac{d\lambda}{dt}(0) = \sqrt{2} \qquad (7)$$

The differential equation for the ferroresonance circuit in Fig.5 can be presented in (6).

V. Simulation results

In this section of the paper, derivative differential equation of the previous case are studied in two states, and behavior of the voltage transformer is modeled in the first case of the simulation while neutral earth resistance is not considered on the system configuration.

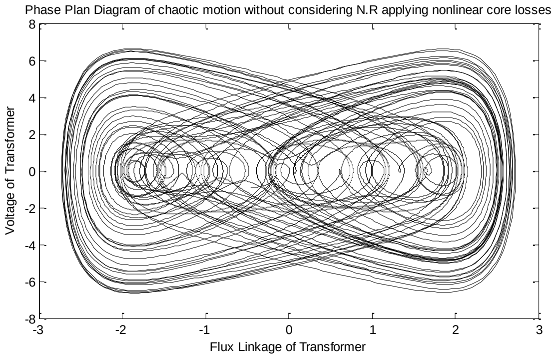

Fig. 5. a) Phase plan diagram for chaotic motion without considering neutral earth resistance

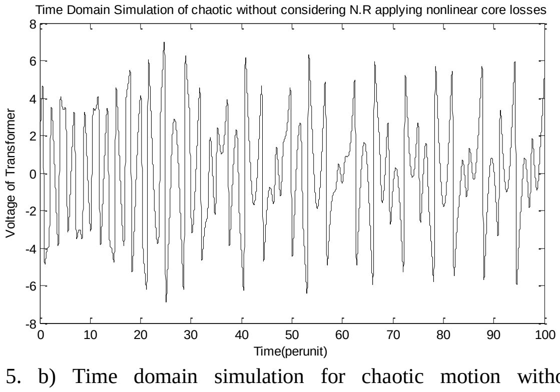

Fig. 5. b) Time domain simulation for chaotic motion without considering neutral earth resistance

MATLAB figures that are shown in the first part show the chaotic resonance of the power system while amplitude of the overvoltages is reached to 3.5p.u. Ferroresonance oscillation in this case has 6p.u amplitude and is very dangerous for the power system equipment especially it can cause voltage transformer failure. Studying the results of the simulation is derived due to the parameters value of the power system equipment that is given in table (2) for two sets of the parameters. In the second part of the simulation, these two chaotic ferroresonance oscillations have been greatly controlled by considering neutral earth resistance effect. Phase space and waveform of voltage for Chaotic Ferroresonance were shown in Figs. 5 (a, b). The phase plane diagram clearly shows the chaotic trajectory characteristic of a periodic waveform and amplitude of the overvoltages reach up to 6 p.u. In this case of simulation, effect of neutral earth resistance is considered on the simulation results, parameter values kept constant with the previous case, but neutral earth resistance is added to the power system structure. By considering earth resistance effects, chaotic signal is changed to the simulation results of Figs. 7 (a, b).

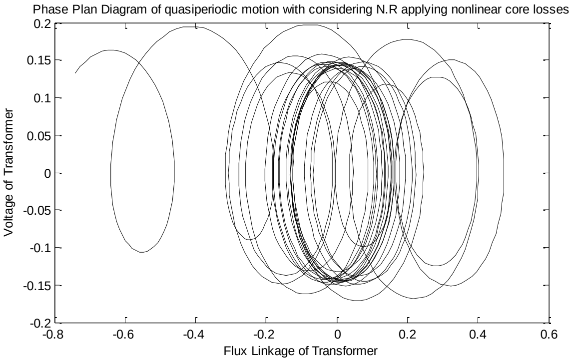

Fig. 6. a) Phase plan diagram for quasiperiodic motion with considering neutral earth resistance effect

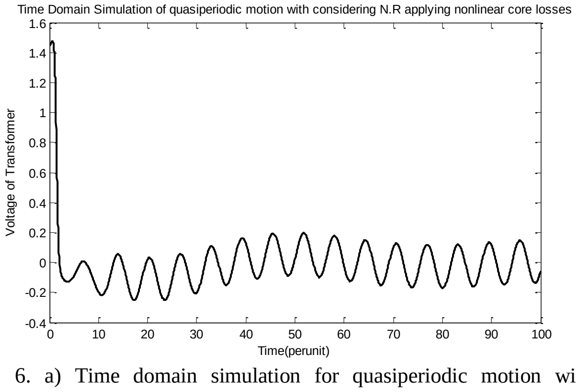

Fig. 6. a) Time domain simulation for quasiperiodic motion with considering neutral earth resistance effect

VI. Bifurcation Diagram Analysis

By using the bifurcation diagrams, Fig. 7 clearly shows the ferroresonance overvoltage in VT when voltage of system increase up to 5 p.u.

Table (4): Parameters used for plotting bifurcation diagrams

Power system parameters	C_{shunt} *(nf)*	C_{series} *(nf)*	R_n *(KΩ)*	*E* *(kV)*
Parameters value	0.1	3	50	275-1375

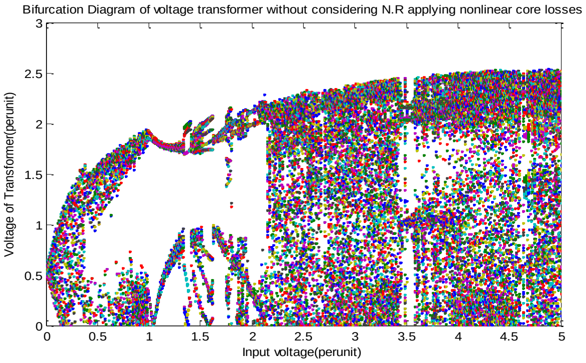

Fig. 7. Bifurcation diagram for voltage of transformer versus voltage of system, without considering neutral earth resistance

Table (4) shows the parameter values that are considered for plotting the bifurcation diagram with and without applying neutral earth resistance. Fig. 7 shows the bifurcation diagram of the voltage of transformer against the increasing input voltage to 5p.u. It shows chaotic trajectory, and amplitude of the overvoltages reach to 2.5p.u, this ferroresonance overvoltages can cause VT failure. By considering effect of earth resistance on the system, Fig. 8 clearly shows that ferroresonance overvoltage has been ignored and there is no chaotic region in the system behavior. It can see some fundamental resonance in the system and amplitude of the voltage is decreased less than 1 p.u.

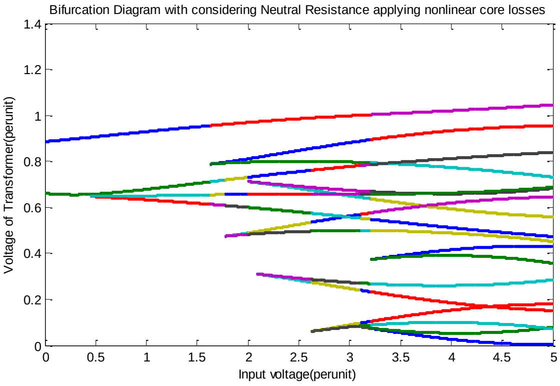

Fig. 8. Bifurcation diagram for voltage of transformer versus voltage of system, with considering neutral earth resistance

V. Conclusion

In this work it is shown that system behaviour has been greatly controlled by the neutral earth resistance. The presence of the neutral resistance results in clamping the amplitude of the ferroresonance overvoltages in the studied system. The neutral resistance successfully eliminates the chaotic behaviour of power system model.

References

[1] C. Kieny, Application of the bifurcation theory in studying and understanding the global behavior of a ferroresonant electric power circuit, *IEEE Transactions on Power Delivery, vol. 6,* 1991, pp. 866-872.

[2] Emin, Z.; Al Zahawi, B.A.T.; Tong, Y.K.; , "Voltage transformer ferroresonance in 275 kV substation," *High Voltage Engineering, 1999. Eleventh International Symposium on (Conf. Publ. No. 467)* , vol.1, no., pp.283-286 vol.1, 1999

[3] Andrei, R.G.; Halley, B.R.; , "Voltage transformer ferroresonance from an energy transfer standpoint," *Power Delivery, IEEE Transactions on* , vol.4, no.3, pp.1773-1778, Jul 1989

[4] Yunge Li; Wei Shi; Furong Li; , "Novel analytical solution to fundamental ferroresonance-part I: power frequency excitation characteristic," *Power Delivery, IEEE Transactions on* , vol.21, no.2, pp. 788- 793, April 2006

[5] Ajaei, F.B.; Sanaye-Pasand, M.; Rezaei-Zare, A.; Iravani, R.; , "Analysis and Suppression of the Coupling Capacitor Voltage Transformer Ferroresonance Phenomenon," *Power Delivery, IEEE Transactions on* , vol.24, no.4, pp.1968-1977, Oct. 2009

[6] Yunge Li; Wei Shi; Rui Qin; Jilin Yang; , "A systematical method for suppressing ferroresonance at neutral-grounded substations," *Power Delivery, IEEE Transactions on* , vol.18, no.3, pp. 1009- 1014, July 2003

[7] Charalambous, C.; Wang, Z.D.; Osborne, M.; Jarman, P.;, "Sensitivity studies on power transformer ferroresonance of a 400 kV double circuit," *Generation, Transmission & Distribution, IET* , vol.2, no.2, pp.159-166, March 2008

[8] Jacobson, D.A.N.; Lehn, P.W.; Menzies, R.W.; , "Stability domain calculations of period-1 ferroresonance in a nonlinear resonant circuit," *Power Delivery, IEEE Transactions on* , vol.17, no.3, pp. 865- 871, Jul 2002

[9] Rezaei-Zare, A.; Iravani, R.; Sanaye-Pasand, M.; , "Impacts of Transformer Core Hysteresis Formation on Stability Domain of Ferroresonance Modes," *Power Delivery, IEEE Transactions on* , vol.24, no.1, pp.177-186, Jan. 2009

[10] Khorasani, P.G.; [14] Deihimi, A.; , "A new modeling of Matlab transformer for accurate simulation of ferroresonance," *Power Engineering, Energy and Electrical Drives, 2009, International Conference on POWERENG '09*, vol., no., pp.529-534, 18-20 March 2009

[11] H. Radmanesh, M. Rostami, "Effect of circuit breaker shunt resistance on chaotic ferroresonance in voltage transformer," Advances in Electrical and Computer Engineering, Vol. 10, No. 3, pp. 71-77, 2010.

[12] H. Radmanesh, “Controlling Chaotic Ferroresonance oscillations in Autotransformers Including Linear and Nonlinear Core Losses Effect,” *International Review of Electrical Engineering*, Vol. 5, No. 6, 2010, pp. 2644-2652.