Analysis of Effect of MOV on Chaotic Ferroresonant Oscillations in unloaded Transformers by Chaos Theory

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Abstract

In this paper the effect of a parallel metal oxide surge arrester on the ferroresonance oscillations of transformers is studied. It is proved that ferroresonance phenomenon in transforemer can be classified in chaotic dynamics systems. In this contribution chaos occurs in system from a sequence of period doubling bifurcation (PDB). Analysis of dynamics of ferroresonant circuit is carried out using bifurcation theory. It is expected that the arresters generally cause ferroresonance drop out. Simulation has been done on a three phase power transformer with one open phase. Effect of varying input voltage is studied. The simulation results reveal that connecting the arrester to transformers poles, exhibits a great mitigating effect on ferroresonant over voltages. Phase plane along with bifurcation diagrams are also presented. Significant effect on the onset of chaos, the range of parameter values that may lead to chaos and magnitude of ferroresonant voltages is obtained, shown and tabulated.

***Index terms*—** component; Power Transformer, Phase Plane Diagram, Bifurcation Diagram, Chaotic Ferroresonance, Chaos Theory, Nonlinear Core loss Model, Metal Oxide A

1 Analysis of Effect of MOV on Chaotic Ferroresonant Oscillations in unloaded

Transformers by Chaos Theory erroresonance is a complex nonlinear electrical phenomenon that can cause dielectric & thermal problems to components power system. Electrical systems exhibiting ferroresonant behaviour are categorized as nonlinear dynamical systems. Therefore conventional linear solutions cannot be applied to study ferroresonance. The prediction of ferroresonance is achieved by detailed modeling using a digital computer transient analysis program [1]. Ferroresonance should not be confused with linear resonance that occurs when inductive and capacitive reactance of circuit is equal. In linear resonance the current and voltage are linearly related and are frequency dependent. In the case of ferroresonance it is characterized by a sudden jump of voltage or current from one stable operating state to another one. The relationship between voltage and current is depends not only on frequency but also on other factors such as system voltage magnitude, initial magnetic flux condition of transformer iron core, total loss in the ferroresonant circuit and moment of switching [2].

Ferroresonance may be initiated by contingency switching operation, routine switching, or load shedding involving a high voltage transmission line. It can result in Unpredictable over voltages and high currents. The prerequisite for ferroresonance is a circuit containing iron core inductance and a capacitance. Such a circuit is characterized by simultaneous existence of several steady-state solutions for a given set of circuit parameters. 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. Typical cases of ferroresonance are reported in [1], [2], [3] and [4]. Although analyzing methods such as harmonics balance method can be use for analyzing nonlinear differential equations, but solving these equations lead to a set of complex algebraic equations [3]. Thus, scientists should use other methods to solve nonlinear dynamic equations. One of these methods is bifurcation theory which some articles use from this method [5,6,7]. Bifurcation theory enables us to describe and analyze qualitative properties of solutions (fixed points) when system parameters change. Studying ferroresonance by bifurcation theory has been carried out [8, **??**,10,11]. But there are some problems in these articles. For example method used in [15] is valid only in limited cases while creating a bifurcation diagram by a continuation method can be more systematic and save computational effort [3]. The samples of ferroresonace in power system have been described in [12,4,13]. Analyzing chaotic ferroresonant behavior in power transformer and dependence of this behavior on system parameters such as amplitude of voltage source, capacitance and resistance of system, core loss, initial conditions and e and effect of neutral resistance in damping ferroresosnant oscillations and change in system behavior from chaotic to multi frequency in [3,7,14,15,16,17] have been studied. Evaluation of route to chaos in transformer with modeling and solving equations in conditions that defined model for core loss is considered linear and effect of complexity of circuits breaker models in transmission and distribution lines with considering effect of damping in system and elimination of caused harmonics in [10,18] have been studied. Theory of nonlinear dynamics has been found to provide deeper insight into the phenomenon. [19], [11], [20] and [21] are among the early investigations in applying theory of bifurcation and chaosto ferroresonance. The susceptibility of a ferroresonant circuit to a quasi-periodic and frequency locked oscillations are presented in [22]. The effect of initial conditions is also investigated. The effect of transformer modeling on the predicted ferroresonance oscillations has been studied in [23]. Using a linear model, authors of [24] have indicated the effect of core loss in damping ferroresonance oscillations. The importance of treating core loss as a nonlinear function of voltage is highlighted in [22]. An algorithm for calculating core loss from no-load characteristics is given in [25]. Evaluation of chaos in transformer, effect of resistance of key on the chaotic behavior transformer and subharmonics that produced with ferroresonance in this type transformer and quantification of the chaotic behavior of ferroresonant transformer circuits are studied in [20], [25] and [26].

Transformer is assumed to be connected to the Power System while one of the three switches are open and only two phases of it are energized, which produces induced voltage in the open phase. This voltage, back feeds the distribution line. Ferroresonance will occur if the distribution line is highly capacitive. System involves the nonlinear magnetizing reactance of the transformer's open phase and resulted shunt and series capacitance of the distribution line.

Base system model is adopted from [3] with the MOV arrester connected across the transformer winding which is showed in Fig. **??** Linear approximation of the peak current of the magnetization reactance can be presented by Eq. (**??**):

However, for very high currents, the iron core might be saturated where the flux-current characteristic becomes highly nonlinear. The li characteristic of the transformer can be demonstrated by the polynomial in Eq. (**??**)

Arrester can be expressed by the Eq. (**??**):

(3) V represents resistive voltage drop, I represents arrester current and K is constant and is nonlinearity constant. The differential equation for the circuit in Fig. **??** can be derived as follows:

Presenting in the form of state space equations, and p will be state variables as follows:

Multiple Scales Method By using the multiple scales method one obtains a first order approximation for the solution of Eq. (**??**) as:

The parameters ?, a and k are of ?. Further, the frequency independent of system is such that Where ? is named external detuning. By using the multiple scales method, we seek of first order uniform expansion of Eq. (**??**) in the form: Where T 0 = t and T 1 = ?T 0 . In term of T 1 the time derivative becomes: Substituting Eq. (**??**0) and Eq. (**??**1) into Eq. (**??**6) and equating coefficient of like power of ?, we obtain:

The solution of Eq. (**??**2) can be expressed as: Substituting Eq. (**??**4) in Eq. (**??**3):

Where cc is complex conjugate of preceding terms and the prime indicates the derivation with respect to T 1 . Using Eq. (**??**) in eliminating the lead to secular terms in from Eq. (**??**2), we obtain:

If A is defined in the polar form , where ?, ? are functions of T with separating real and imaginary part in Eq. (**??**3):

1 From Eq. (**??**7), we obtain Eq. (**??**8) and Eq. (**??**9):

With multiplyingsin? in Eq. (**??**8) and cos? in Eq. (**??**9) we have: With multiplying cos? in Eq. (**??**8) and sin? in Eq. (**??**9) we have:

Setting ??= 0 and ??= 0 in Eq. (**??**0) and (**??**1) we find that their fixed points are given by: Squaring and adding Eq. (**??**2) and (**??**3 Bifurcation theory describes and studies behavior of system with change in one or more parameters of system and discusses in case of stability and instability of fixed points in the values of system parameters. Suppose system is defined as Eq. (32):

Where x is a state vector. In fact flux and voltage in terminal of transformer are state variables. ? is a parameter of system that can be value of series capacitance or amplitude of input voltage. for ? = ? c at which the vector field f losses its structural stability is called a bifurcation point and ?c the value of bifurcation. For analyzing and studying in bifurcation diagram we use of jacobian matrix, J = Df as the linearization of f at (x0, ?0) which points x0 are fixed points.

Saddle node bifurcation When J is nonhyperbolic, i.e. J has a zero eigenvalue and no other eigen value with zero real part, saddle node bifurcation (SNB) occurs. SNB is caused with changes in the number of fixed points. Indeed, one stable fixed point and unstable fixed point cause SNB. Necessary and enough conditions for SNB are: Necessary conditions:

2 Enough conditions:

If eigen values of jacobian matrix are considered as when real 0 jacobian matrix is hyperbolic and other wise nonhyperbolic.

The stability of the fixed points depends on the eigenvalues of the jacobian matrix (??2), (23); that is, the eigevalue of:

Determinant of [?I ? A yields eigenvalues:

Where ? is eigenvalue. Substituting the polar form of A into Eq. (??1) and substituting result into Eq. (??2), we find that, to first approximation x1is given by: For nontrivial solutions, ? ? 0 and it follows from Eq. (??8) that: Substituting Eq. (29) into Eq. (??7), we find that to the first approximation, the free oscillations of Eq. (??) are given by: Where ? is given by Eq. (??8), which has the normal form of a supercritical pitchfork bifurcation. Equation of eigenvalues introduce as the following equation:

We obtain first order approximation of Eq. (??) by multiple scale method and by using the chaos theory we discuss in case of stability.

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Pitch fork or transcritical bifurcation points appoint necessary conditions, too. For more detail see ??30]. Hopf bifurcation If J has a pair of complex conjugate on the imaginary axis and other eigenvalues lying off the imaginary axis, hopf bifurcation (HB) occurs. if periodic solutions are unstable, bifurcation is said to be subcritical and supercritical if stable. Thus, connects fixed points to periodic solutions. SNB and HB are stationary point. Periodic solutions that are caused by a HB can increase bifurcations and complexity of system behavior, themselves. Limit cycles which are caused by a HB can involve system into chaotic region and global bifurcation occurs. Suppose x be a small perturbation to the periodic solution to Eq. (30) and 1. We obtain: Thus, periodic in T, A (t) is periodic, too. Thus: be equal with A (t) Because is Stability of periodic solutions is determined by its characteristic.

Now, we define the mondoromy matrix M to be ? (t). Eigenvalues of M are multipliers, denoted by Mi , i = 1, n. If all eigenvalues of M lie in the unit circle, we find out, For a periodic solution one of multipliers is equal to +1, with corresponding eigenvector tangential to the periodic orbit at x.

Stability of a limit cycle is determined by its multipliers and depending on the way in which multipliers venter or leave the unit circle.

4 C Cyclic fold bifurcation

If one of multipliers enters or leaves the unit circle along the positive real axis cyclic fold bifurcation (CFB) occurs. In Fig. ?? (a) is example of this bifurcation.

5 Fig. 2. Multiplier crossings of the unit circle

If one of the multipliers leaves unit circle along the negative real axis bifurcation is said to be a period doubling bifurcation (PDB) (b in Fig. ??). This bifurcation causes new solutions with period 2T. If this behavior continues, causes solutions with infinitive period. These solutions are aperiodic which are called chaotic solutions. If one of the lyapunov exponents be positive for systems of ODEs, is representing of chaotic behavior in system.

6 Torus bifurcation

7 Period doubling

If a complex conjugate pair of multipliers with Re{mi } ? 0 leaves the unit circle, causes quasi-periodic solution.

C indicates this behavior. Quasi periodic solutions have period that is equal to in commensurate of main period T. In phase plane diagram these solutions create figures in form of torus.

8 Routes to chaos

Chaotic solutions are aperiodic and unstable solutions. These solutions depend on initial conditions. In this section we imply 4 routes to chaos: PDB Crises Intermittency Torus bifurcation Intermittency is a route to chaos. In this route oscillation in regular mode occasionally interrupted by turbulent burst of aperiodic oscillations at irregular intervals and chaos emerges in system. In case of torus bifurcation if stable periodic solution undergoes to a supercritical secondary hopf bifurcation with changes in parameter of system. This causes two quasi periodic solutions with two in commensurate frequencies.

When parameter increases torus is destroyed and system becomes chaotic. Sudden changes in parameter of system cause crises and system becomes chaotic. When crises occur chaotic attractor enters unstable periodic solutions or saddle points.

Crises have different types. Some of these types are:

Fundamental matrix for Eq. (??5) is (T) , such as: If lyapunov exponent be positive, routes will repel other routes and other wise will attract other route. In case of stability of fixed points, when all lyapunov exponents are

8 ROUTES TO CHAOS

negative, these points are stable and in limit cycle lyapunov exponent is zero. Necessary and enough condition for chaotic behavior system are one or more positive lyapunov exponents. For more details, see [28].If

exponent:

Typical values for various system parameters considered for simulation are as given below [5]: Time domain simulations were performed using the MATLAB programs which are similar to EMTP simulation [3]. For cases including arrester, it can be seen that ferroresonant drop out will be occurred.Fig. **??** show the phase plane plot of system states without arrester for E=1 p.u.

Figure **??** 3 Phase plane diagram for E=1, q=11 without MOV When Vin increases system is entered into saturation section of magnetization curve and ferroresonance occurs. In Figs. 4,5,6,7 this phenomenon is shown. Behavior of system is single frequency but PDB has occurred. Magnetization curve in Fig. **??** and phase plane diagram in Fig. **??** and voltage and flux waveforms are shown in Figs. **??** and 7. These figures are gained whenVin = 3.5, q = 7. Phase plane diagram shows this reality that behavior of system is a single frequency behavior. But voltage and flux waveforms show that behavior of system has an undesirable effect on system insulation and maybe damage it. With consideration to Fig. **??**3, Fig. **??**4 and Fig. **??**5 MOV makes a mitigation in ferroresonance chaotic behavior in transformer that in down value of q the chaotic region are removed and the behavior will be periodic, for greater value of q for example for q=11 independent chaotic regions which can be created under MOV nominal voltage have survived so chaotic behavior has been eliminated. Figs. 16,17 show that chaotic region mitigates by applying MOA surge arrester. The system shows a greater tendency for chaos for saturation characteristics with lower knee Considering to Fig. **??**7 MOA makes a mitigation in ferroresonance chaotic behavior in the transformer that in down value of q the chaotic region are removed and the behavior will be periodic, for greater value of q such as q=11 independent chaotic regions which can be created under MOA nominal voltage have survived so chaotic behavior has been eliminated. Tendency to chaos exhibited by the system increases while q increases too.

Chaotic ferroresonant oscillations of unloaded transformer nonlinear core loss model have been described. The presence of the arrester results in clamping the Ferroresonant over voltages in the studied system. The arrester successfully suppresses or eliminates the chaotic behaviour of proposed model. Consequently, the system shows less sensitivity to initial conditions in the presence of the arrester. It is seen from the bifurcation diagram that chaotic ferroresonant behavior depends on parameter q. MOV makes a mitigation in ferroresonance chaotic behavior in transformer that in down value of q the chaotic region are removed and the behavior will be periodic. System stability increased with decreasing q and chaotic regions are eliminiated. It is found when q=11 at vin=4 p.u. beahavior of system is chaotic while for q=7 in the same value of vin system is in subharmonic mode and its stability is more than case that q=11. It was shown that chaos occurs in transformer from a sequence of PDB. It was found that nonlinear magnetization curve has a great influence on bifurcation diagrams and domains of ferroresonance occurrence. nonlinear core loss model has been used in dynamics equations. It was found that the nonlinear core loss model causes the mitigation and delay in chaotic ferroresonant oscillations. Also presence of nonlinear term in core loss function causes PDBs become more regular. [1] [2]

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Figure 2: F

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Figure 3: Figure. 1 2) (1)

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Figure 5:

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Figure 6: Fig. 4 : 4 Fig. 5 : 7 Fig. 6 : 7 Fig. 7 :Fig. 8 :

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Figure 7: Figure 8 :

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Figure 8: Figure10:Figure 11 Figure 12 :Fig. 13 ,

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Figure 9: Figure 13 :Figure 14 :Figure 15 :

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Figure 10: Fig. 16 :Fig. 17 :

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Figure 11: Global

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	(B) behaviour of system with mov for e= 4, 5, 6
2011 November 26	Initial conditions:
Volume XI Issue VIII Version I F) (	Table 1. (A) Behaviour of System Without Mov For E= 1, 2, 3
Researches in Engineering Journal of Global	(B) Behaviour of System without Mov For E= 4, 5, 6
	Table 2. (A) Behaviour of System with Mov for E= 1, 2, 3

Figure 12: Table (1

[Zare et al. (2007)] 'Analysis of Ferroresonance Modes in Power Transformers using Preisach-Type Hysteretic Magnetizing Inductance'. Rezaei Zare , A Sanaye Pasand , M Mohseni , H Farhangi , S Iravani , R . *IEEE Transactions on Power Delivery* April 2007. 22 (2) .

[Anbari et al. (2001)] 'Analysis of nonlinear phenomena in MOV connected transformer'. K Anbari , R Ramanjam , T Keerthiga , K Kuppusamy . *Gen., Trans and Dist* Nov. 2001. 148 p. . (IEE proc.)

[Kavasseri ()] *Analysis of subharmonic oscillations in a ferroresonant circuit*, G Kavasseri . 2005. Elsevier journal. p. . Electrical Power and Energy Systems

[Rajesh and Kavasseri (2006)] *Analysis of subharmonics oscillations in a ferroresonant circuit*, G Rajesh , Kavasseri . March. 2006. Elsevier journal. 28 p. . Electrical Power and Energy Systems

[Sakarung and Chatratana (2005)] 'Application of PSCAD/EMTDC and Chaos Theory to Power System Ferroresonance Analysis'. P Sakarung , S Chatratana . *International Conference on Power Systems Transients (IPST)*, June. 2005. p. .

[Ben-Tal et al. (2001)] 'Banded Chaos in Power Systems'. A Ben-Tal , V Kirk , G Wake . *IEEE Transactions on Power Delivery* Jan. 2001. 16 (1) .

[Escudero et al. (2007)] *Characterization of ferroresonant modes in HV substation with CB grading capacitors*, M V Escudero , I Dudurych , M A Redfern . Jan. 2007. Elsevier Electric Power Systems Research. p. .

[Mozaffari et al. ()] 'Effect of initial conditions on chaotic ferroresonance in power transformers'. S Mozaffari , M Sameti , A C Soudack . *IEE Proceedings/Generation, Transmission and Distribution*, 1997. p. .

[Al-Anbarri et al. ()] *Effect of iron core loss nonlinearity on chaotic ferroresonance in power transformers*, K Al-Anbarri , R Ramanujam , R Saravanaselvan , K Kuppusamy . 2003. p. . Electric Power Systems Research Elsevier journal

[Al-Anbarri et al. ()] *Effect of iron core loss nonlinearity on chaotic ferroresonance in power transformers*, K Al-Anbarri , R Ramanujam , R Saravanaselvan , K Kuppusamy . 2003. p. . Electric Power Systems Research Elsevier journal

[Abbasi et al. (2010)] 'Effect of Metal Oxide Arrester o Chaotic Behavior of Power Transformers'. A Abbasi , M Rostami , S H Fathi , H R Abbasi , H Abdollahi . *Energy and Power Engineering(EPE journal)* Nov. 2010. 2 p. .

[Abbasi et al. ()] *Elimination of Chaotic Ferroresonance in power transformers including Nonlinear Core Losses applying of Neutral Resistance*, A Abbasi , H Radmanesh , M Rostami , H Abbasi ; Eeeic09 . 2009. Poland.

[Abbasi et al. ()] *Evaluation of Chaotic Ferroresonance in power transformers including Nonlinear Core Losses*, A Abbasi , M Rostami , H Radmanesh , H R Abbasi , ; Eeeic09 . 2009. Poland.

[Pattanapakdee and Banmongkol (2007)] 'Failure of Riser Pole Arrester due to Station Service Transforme Ferroresonance'. K Pattanapakdee , C Banmongkol . *International Conference on Power Systems Transients (IPST)*, (France) June. 2007.

[Pattanapakdee and Banmongkol (2007)] 'Failure of Riser Pole Arrester due to Station Service Transformer Ferroresonance'. K Pattanapakdee , C Banmongkol . *International Conference on Power Systems Transients (IPST)*, June. 2007.

[Emin and Tong ()] 'Ferroresonance experience in UK: simulations and measurements'. Z Emin , K Y Tong . *International Conference on Power Systems Transients (IPST)*, 2001.

[Araujo et al. (1993)] 'Ferroresonance in power systems: chaotic behaviour'. A E A Araujo , A C Soudack , J R Marti . *IEE Proc.-C* May. 1993. 140 (3) p. .

[Mork ()] 'Five-legged wound/core transformer model: derivation, parameters, implementation, and evaluation'. B A Mork . *IEEE Transactions on Power Delivery* 1999. 14 p. .

[Chkravarthy and Nayar ()] 'Frequency locked and quasi periodic (QP) oscillations in power systems'. S K Chkravarthy , C V Nayar . *IEEE Transactions on Power Delivery* 1997. 13 p. .

[Mukerjee et al. ()] 'Indices for ferroresonance performance assessment in power distribution network'. R N Mukerjee , B Tanggawelu , E A Ariffin , M Balakrishnan . *International Conference on Power System Transients (IPST)*, 2003.

[Abbasi et al. ()] 'Investigation and Control of Unstable Chaotic Behavior Using of Chaos Theory in Electrical Power Systems'. H R Abbasi , A Gholami , M Rostami , A Abbasi . *Series ferroresonance in power systems*, S K Chakravarthy, C V Nayar (ed.) March 2011. 1995. 7 p. . (Electr. Power Energy Sys)

[Neves and Dommel ()] 'On modeling iron core nonlinearities'. W L A Neves , H Dommel . *IEEE Transactions on Power Systems* 1993. 8 p. .

[Zare et al. ()] *Performance of various magnetic core models in comparison with the laboratory test results of a ferroresonance test on a 33 kV voltage transformer*, Rezaei Zare , A Mohseni , H Sanaye Pasand , M Farhangi , S Iravani , R . 2006. IEEE.

[Emin et al. (2001)] ‘Quantification of the chaotic behavior of ferroresonant voltage transformer circuits’. Z Emin , B A T Zahawi , Y K Tong , M Ugur . *A. H. Nayfeh, APPLIED NONLINEAR DYNAMICS Analytical, Computational and Experimental Methods* June. 2001. 27. 2004. WILEY-VCH Verlag GmbH & Co. KGaA. 48 (6) . (IEEE Transactions on Circuits and Systems, Fundamental Theory and Applications)

[Ben-Tal et al. ()] ‘Studying ferroresonance in actual power systems by bifurcation diagram’. A Ben-Tal , D Shein , S Zissu . *Electric Power Systems Research*, 1999. 49 p. .

[Thompson and Stewart ()] J M T Thompson , H B Stewart . *Nonlinear dynamic and chaos*, (Ltd, England) 2002. John Wiley & Sons.