Global Journal of researches in engineering
Electronic and electronics Engineering
Volume 11 Issue 8 Version 1.0 December 2011
Type: Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals Inc. (USA)
Online ISSN: 2249-4588 & Print ISSN: 0975-5861

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

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GJRE-F Classification : FOR Code: 090607

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I. Introduction

Ferroresonance 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, 9, 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

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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].

II. System Modeling for Transformer

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.

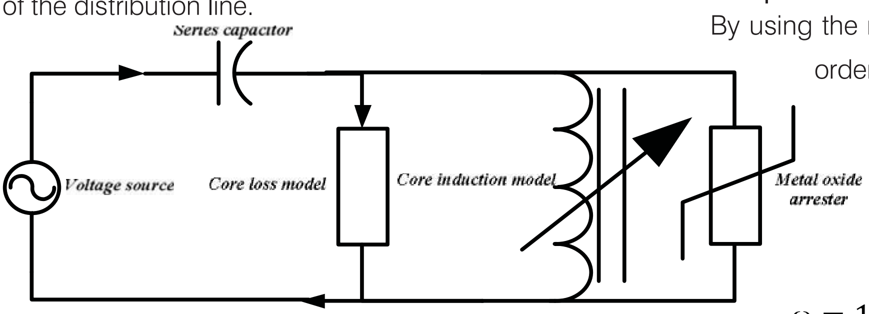

Figure. 1 Circuit of system

Base system model is adopted from [3] with the MOV arrester connected across the transformer winding which is showed in Fig. 1 Linear approximation of the peak current of the magnetization reactance can be presented by Eq. (1):

$$i_l = a\lambda \quad (1)$$

However, for very high currents, the iron core might be saturated where the flux-current characteristic becomes highly nonlinear. The li $\lambda - i_l$ characteristic of the transformer can be demonstrated by the polynomial in Eq. (2)

$$i_l = a\lambda + b\lambda^q \quad (2)$$

Arrester can be expressed by the Eq. (3):

$$V = K\,I^{\alpha} \quad (3)$$

V represents resistive voltage drop, I represents arrester current and K is constant and α is nonlinearity constant. The differential equation for the circuit in Fig. 1 can be derived as follows:

$$\omega E\cos\omega t = p^2\lambda + \frac{p\lambda}{RC} + \left(\frac{1}{C}\right)\left(a\lambda + b\lambda^q\right) + \left(\frac{1}{C}\right)\left(\frac{|p\lambda|}{K}\right)^{\alpha} sign(p\lambda) \quad (4)$$

Where dt d$p = \frac{d}{dt}$ and ω represents the power frequency and E is the peak value of the voltage source, shown in Fig. 1.

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

$$\lambda = x_1,\; p\lambda = x_2 \quad (5)$$

$$x_1 = x_2 \quad (6)$$

$$\dot{x}_2 = \omega E\cos\omega t - \frac{x_2}{RC} - \left(\frac{1}{C}\right)\left(ax_1 + bx_1^{\,q}\right) - \left(\frac{1}{C}\right)\left(\frac{|x_2|}{K}\right)^{\alpha} sign\; x_2 \quad)7($$

Multiple Scales Method

By using the multiple scales method one obtains a first order approximation for the solution of Eq. (7) as:

$$x_1 = h\cos(\omega t - \gamma) + O(\varepsilon) \quad (8)$$

The parameters μ, a and k are independent of ε. Further, the frequency of system is such that

$$\omega = 1 + \varepsilon\delta \quad (9)$$

Where δ is named external detuning. By using the multiple scales method, we seek of first order uniform expansion of Eq. (7) in the form:

$$x_1(t;\varepsilon) = x_{1,0}(T_0, T_1) + \varepsilon x_{1,1}(T_0, T_1) + \cdots \quad (10)$$

Where $T_0 = t$ and $T_1 = \varepsilon T_0$. In term of T_1 the time derivative becomes:

$$\frac{d}{dt} = D_0 + \varepsilon D_1 + \varepsilon^2 D_2 + \cdots \tag{11}$$

Substituting Eq. (10) and Eq. (11) into Eq. (36) and equating coefficient of like power of ε, we obtain:

$$O(\varepsilon^0): \quad {D_0}^2 x_{1,0} = 0 \tag{12}$$

$$O(\varepsilon): \quad {D_0}^2 x_{1,1} + a x_{1,1} + 2 D_0 D_1 x_{1,0} + \mu D_0 x_{1,0} + b {x_{1,1}}^q = k\cos\omega_0 t \tag{13}$$

The solution of Eq. (12) can be expressed as:

$$x_{1,0} = A(T_1) T_0 + A_0 \tag{14}$$

Substituting Eq. (14) in Eq. (13):

$${D_0}^2 x_{1,1} + a x_{1,1} + b {x_{1,1}}^q = -2A' - \mu A + \frac{k}{2} e^{i\delta T_1} + cc \tag{15}$$

Where cc is complex conjugate of preceding terms and the prime indicates the derivation with respect to T_1. Using Eq. (7) in eliminating the lead to secular terms in $x_{1,1}$ from Eq. (12), we obtain:

$$2A' - \mu A + \frac{k}{2} e^{i\delta T_1} = 0 \tag{16}$$

If A is defined in the polar form $A = \frac{1}{2} \alpha e^{i(\beta + \delta T_1)}$, where α, β are functions of T_1 with separating real and imaginary part in Eq. (13):

$$\alpha' e^{i(\beta+\delta T_1)} + \alpha i(\beta' + \delta) e^{i(\beta+\delta T_1)} + \frac{1}{2} \alpha e^{i(\beta+\delta T_1)} - \frac{k}{2} e^{i\delta T_1} = 0 \tag{17}$$

From Eq. (17), we obtain Eq. (18) and Eq. (19):

$$\alpha' \cos\beta - \alpha \beta' \sin\beta - \alpha\, \delta \sin\beta + \frac{1}{2} \alpha \cos\beta = 0 \tag{18}$$

$$\alpha' \sin\beta + \alpha\beta' \cos\beta + \alpha\delta\cos\beta + \frac{1}{2} \alpha \sin\beta = 0 \tag{19}$$

With multiplying – $\sin\beta$ in Eq. (18) and $\cos\beta$ in Eq. (19) we have:

$$\alpha\beta' + \alpha\delta + \frac{k}{2}\sin\beta = 0 \tag{20}$$

With multiplying $\cos\beta$ in Eq. (18) and $\sin\beta$ in Eq. (19) we have:

$$\alpha' + \frac{1}{2}\alpha - \frac{k}{2}\cos\beta = 0 \tag{21}$$

Setting $\alpha' = 0$ and $\beta' = 0$ in Eq. (20) and (21) we find that their fixed points are given by:

$$\alpha_0 \delta + \frac{k}{2} \sin\beta_0 = 0 \tag{22}$$

$$\frac{1}{2}\alpha_0 - \frac{k}{2}\cos\beta_0 = 0 \tag{23}$$

Squaring and adding Eq. (22) and (23) yield the frequency response equations:

$${\alpha_0}^2 \delta^2 + \frac{1}{4} {\alpha_0}^2 = \frac{1}{4} k^2 \tag{24}$$

The stability of the fixed points depends on the eigenvalues of the jacobian matrix (22), (23); that is, the eigevalue of:

$$A = \begin{bmatrix} 1/2 & \frac{k}{2}\sin\beta \\ \frac{k}{2\alpha^2}\sin\beta & -\frac{k}{2}\cos\beta \end{bmatrix} \tag{25}$$

Determinant of [λI − A yields eigenvalues:

$$\lambda^2 + \left(\frac{k}{2\alpha}\cos\beta\right)\lambda - \frac{k}{4\alpha}\cos\beta - \frac{k^2}{4\alpha^2}\sin^2\beta = 0 \tag{26}$$

Where λ is eigenvalue. Substituting the polar form of A into Eq. (11) and substituting result into Eq. (12), we find that, to first approximation x1is given by:

$$x_1 = \alpha\cos(\omega t + \beta) + \cdots \tag{27}$$

$$\text{If } k = 0 \xrightarrow{\text{yields}} \begin{cases} \alpha\beta' = -\alpha\delta \\ \alpha' = -\frac{1}{2}\alpha \end{cases} \tag{28}$$

For nontrivial solutions, α ≠ 0 and it follows from Eq. (28) that:

$$\beta = -\delta T_1 + \beta_0,\ T_1 = \varepsilon t \xrightarrow{\text{yields}} \beta = -\varepsilon\delta t + \beta_0 \tag{29}$$

Substituting Eq. (29) into Eq. (27), we find that to the first approximation, the free oscillations of Eq. (7) are given by:

$$x_1 = \alpha\cos(\omega_0 t + \beta_0) + \cdots \tag{30}$$

Where α is given by Eq. (28), which has the normal form of a supercritical pitchfork bifurcation. Equation of eigenvalues introduce as the following equation:

$$\lambda^2 + \left(\frac{1}{2}\alpha_0 - \frac{1}{2}\right)\lambda - \frac{1}{4} - \delta^2 = 0 \tag{31}$$

We obtain first order approximation of Eq. (8) by multiple scale method and by using the chaos theory we discuss in case of stability.

Bifurcation and chaos theory

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):

$$\dot{X} = f(x,\gamma) \tag{32}$$

Where x is a state vector. In fact flux and voltage in terminal of transformer are state variables. γ is a parameter of system that can be value of series capacitance or amplitude of input voltage. for γ = γc at which the vector field f losses its structural stability is called a bifurcation point and γc 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, γ0) which points x0 are fixed points.

If eigen values of jacobian matrix are considered as λ_i when real$\{\lambda_i\} \neq 0$ jacobian matrix is hyperbolic and other wise nonhyperbolic.

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:

$$f(x_0,\gamma_0) = 0,\ \det\left(J(x_0,\gamma_0)\right) = 0 \tag{33}$$

Enough conditions:

$$\left.\frac{\partial f}{\partial x}\right|_{(x_0,\gamma_0)} = 0 \tag{34}$$

$$\left.\frac{\partial f}{\partial \gamma}\right|_{(x_0,\gamma_0)} \neq 0 \tag{35}$$

$$\left.\frac{\partial^2 f}{\partial x^2}\right|_{(x_0,\gamma_0)} \neq 0 \tag{36}$$

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.

Stability of periodic solutions is determined by its characteristic.

Suppose $x = \varphi(x_0, t) + \vartheta(t)$ be a small perturbation to the periodic solution to Eq. (30) and $\vartheta(0) \ll 1$. We obtain:

$$\dot{x} = f(x) = f(\varphi\ x_0, t\ + \vartheta(t)) \quad (37)$$

$$= f(\varphi(x_0, t) + \frac{d}{dt} f(\varphi(x_0, t) \times \vartheta + O(\vartheta^2) \quad (38)$$

$$\dot{x} = \dot{\varphi}(x_0, t) + \dot{\vartheta}(t) = f(\varphi(x_0, t) + \vartheta_0 \quad (39)$$

Thus,

$$\dot{\vartheta} = f(\varphi(x_0, t) + O(\vartheta^2) \quad (40)$$

If $\frac{d}{dt} f(\varphi(x_0, t)$ be equal with A (t) Because (x_0, t) is periodic in T, A (t) is periodic, too. Thus:

$$\dot{\vartheta} = A(t)\vartheta, A(t) = A(t + T) \quad (41)$$

Fundamental matrix for Eq. (75) is Ψ (T) , such as:

$$\dot{\Psi}(t) = A(t)\Psi(t), \Psi(0) = I \quad (42)$$

$$\vartheta(t) = \Psi(t)\vartheta(0) \quad (43)$$

Now, we define the mondoromy matrix M to be Ψ (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,

$$\lim_{n\to\infty} |\vartheta(nt)| = 0 \quad (44)$$

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.

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. 2 (a) is example of this bifurcation.

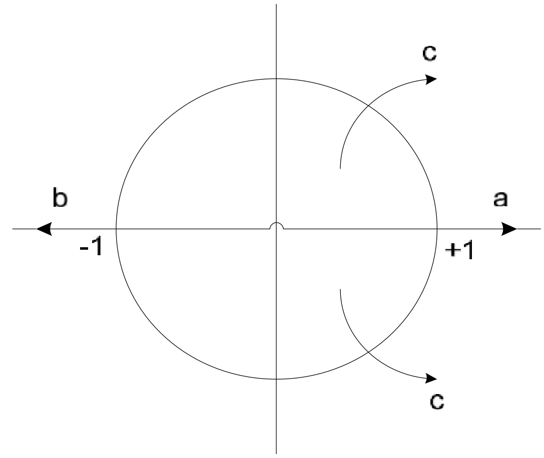

Fig. 2. Multiplier crossings of the unit circle

Period doubling

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. 2).
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.

Torus bifurcation

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.

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:

Exterior crisis, blucsky catastrophe or dangerous bifurcation, interior crisis and attractor merging crisis. For more detail, see [27].

For recognizing chaotic oscillations, we use from lyapu exponent. If eigen values of system are λilyapunov exponent:

$$L_i = \lim_{t\to\infty} \frac{1}{t}\ln(\lambda_i(t)), i = 1, n \quad (45)$$

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 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].

III. Simulation results

Typical values for various system parameters considered for simulation are as given below [5]:

$$q = 5 \rightarrow \begin{cases} b = 0.0005 \\ a = 0 \end{cases}$$

$$q = 7 \rightarrow \begin{cases} b = 0.001 \\ a = 0 \end{cases}$$

$$q = 11 \rightarrow \begin{cases} b = 0.0072 \\ a = 0.0028 \end{cases} ;$$

$$\omega = 1\ p.u., R = 100\ \ p.u., C = 0.047\ \ p.u.$$
$$E = 0 - 6\ p.u., K = 2.501\ , \alpha = 25\ .$$

Initial conditions:

$$\lambda(0) = 0, p\lambda(0) = 1.44\ p.u.$$

Table (1) shows different values of E, considered for analyzing the circuit in absence of surge arrester.

Table 1. (A) Behaviour of System Without Mov For E= 1,2, 3

q \ E	1	2	3
5	Priodic	Priodic	Priodic
7	Priodic	Priodic	Chaotic
11	Priodic	Priodic	Chaotic

(B) Behaviour of System without Mov For E= 4, 5, 6

q \ E	4	5	6
5	Chaotic	Chaotic	Chaotic
7	Chaotic	Chaotic	Chaotic
11	Chaotic	Chaotic	Chaotic

Table 2 includes the set of cases which are considered for analyzing the circuit including arrester:

Table 2. (A) Behaviour of System with Mov for E= 1, 2, 3

q \ E	1	2	3
5	Priodic	Priodic	Priodic
7	Priodic	Priodic	Priodic
11	Priodic	Chaotic	Priodic

(B) behaviour of system with mov for e= 4, 5, 6

E / q	4	5	6
5	Priodic	Priodic	Priodic
7	Priodic	Priodic	Chaotic
11	Chaotic	Chaotic	Chaotic

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. 3 show the phase plane plot of system states without arrester for E=1 p.u.

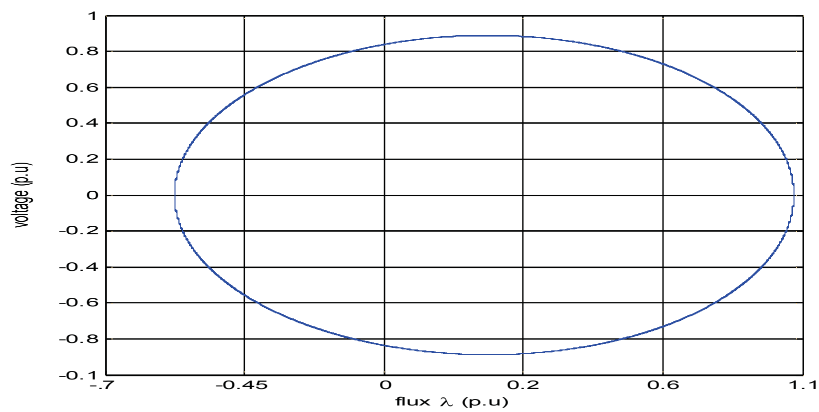

Figure. 3 Phase plane diagram for E=1, q=11 without MOV

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. 4 and phase plane diagram in Fig. 5 and voltage and flux waveforms are shown in Figs. 6 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.

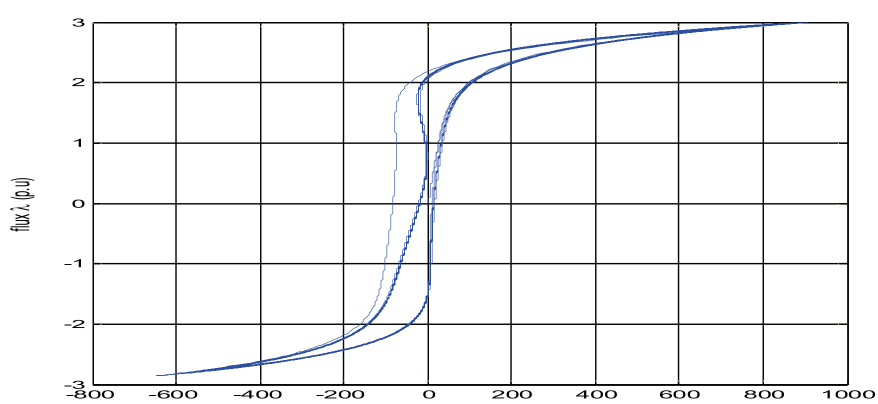

Fig. 4: Nonlinear transformer magnetization curve for second nonlinear core loss model forVin = 3.5, q = 7 4

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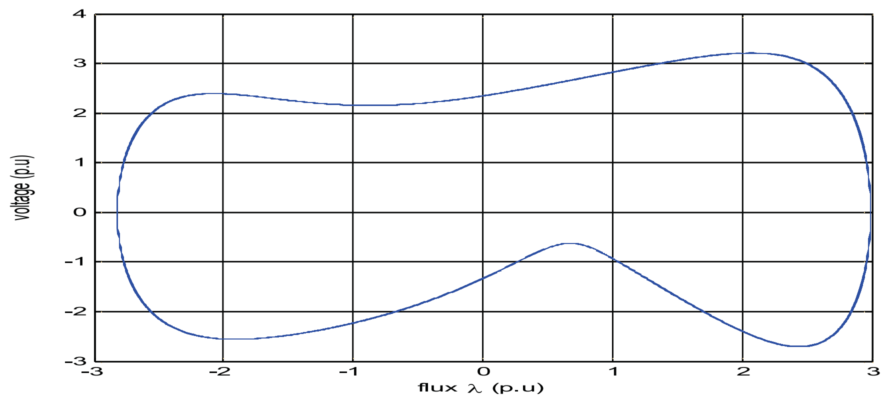

Fig. 5: phase plane diagram for Vin = 3.5, q = 7

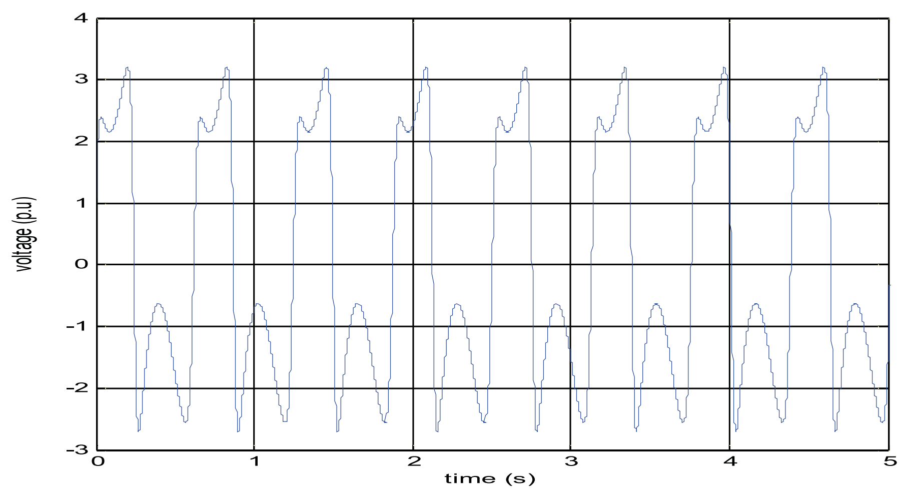

Fig. 6: Voltage waveform for V = 3.5, q = 7

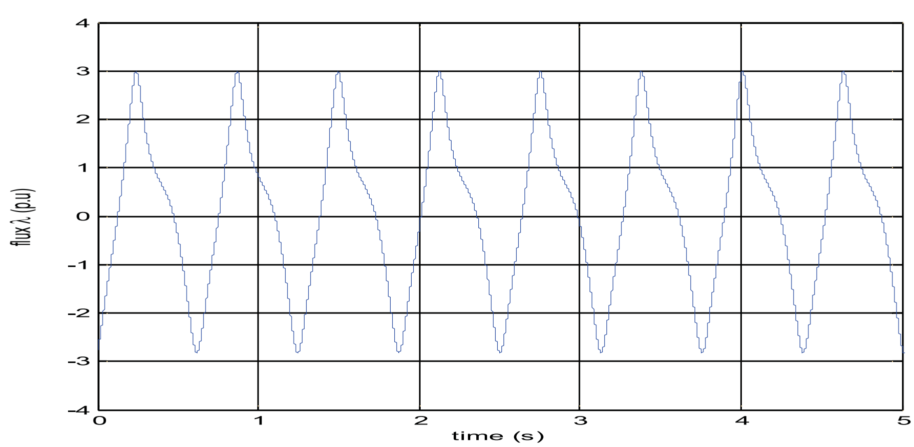

Fig. 7: Flux waveform forV_{in}=3.5,q=7

Fig. 8: shows the phase plane plot and time domain simulation of system states without arrester for E=4 p.u.which depicts chaotic behavior and Fig. 9 shows the corresponding time domain wave form.

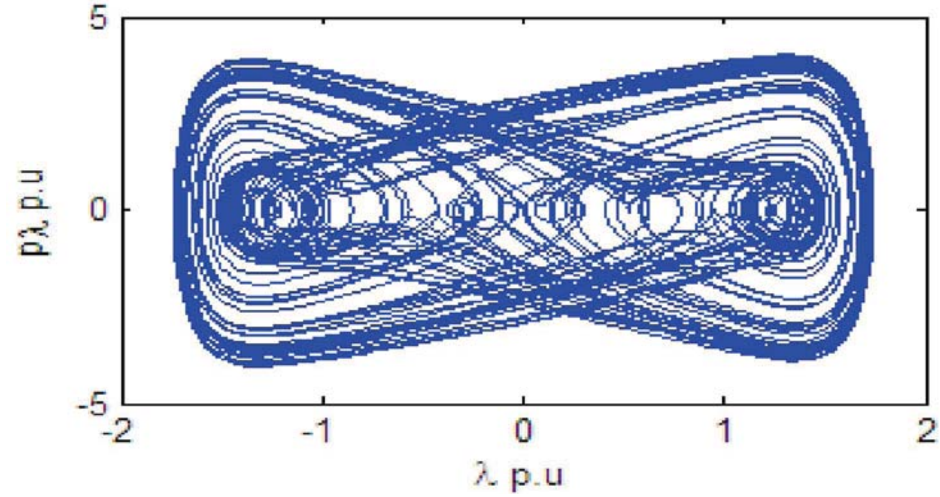

Figure 8: Phase plane diagram for E=4, q=11 without MOV

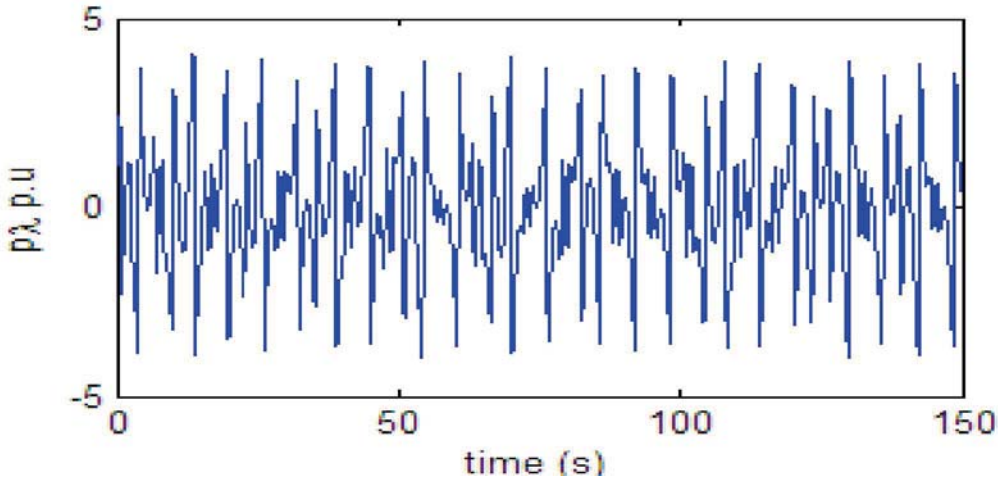

Figure.9 : time domain chaotic wave form for E=4, q=11 without MOV

Also figures 10-12 show the bifurcation diagram of chaotic behaviours for three of values of q. The system shows a greater tendency for chaos for saturation characteristics with lower knee points, which corresponds to higher values of exponent q.

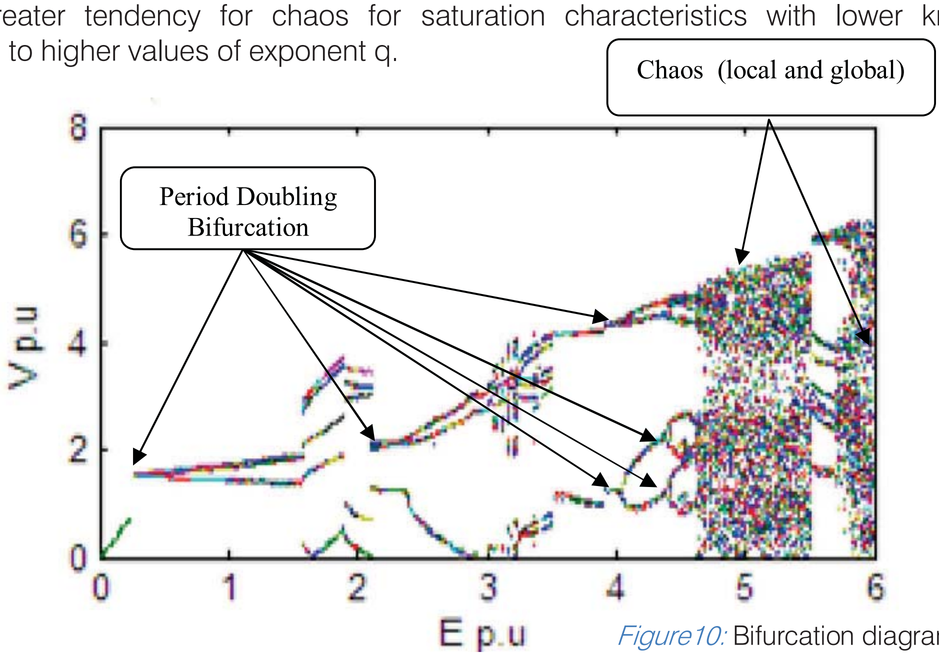

Figure10: Bifurcation diagram for q=5 without MOV

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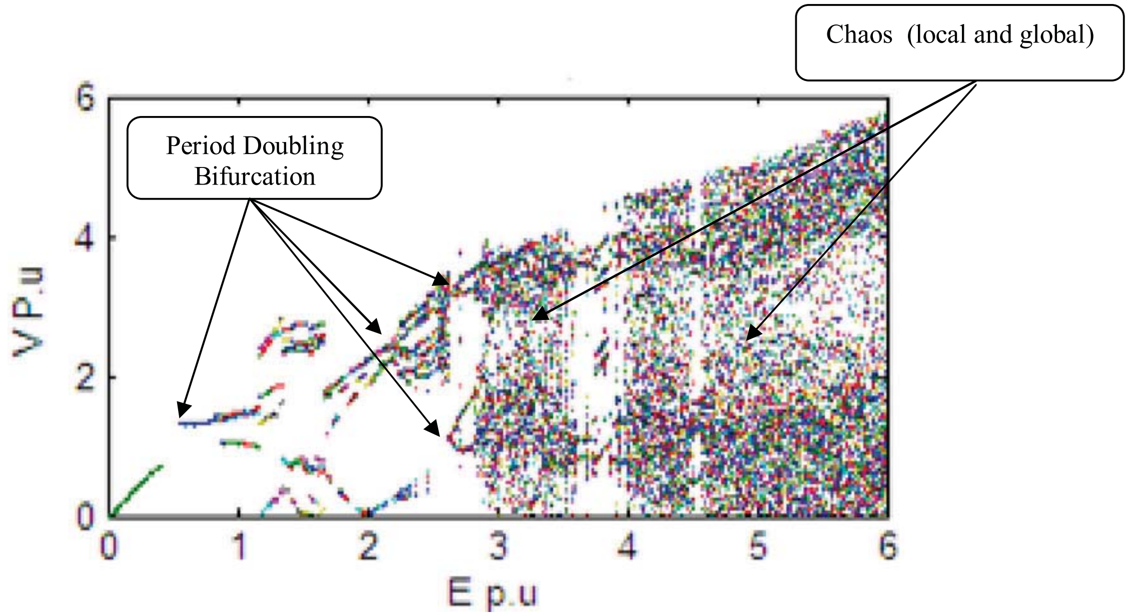

Figure 11 Bifurcation diagram for q=7 without MOV

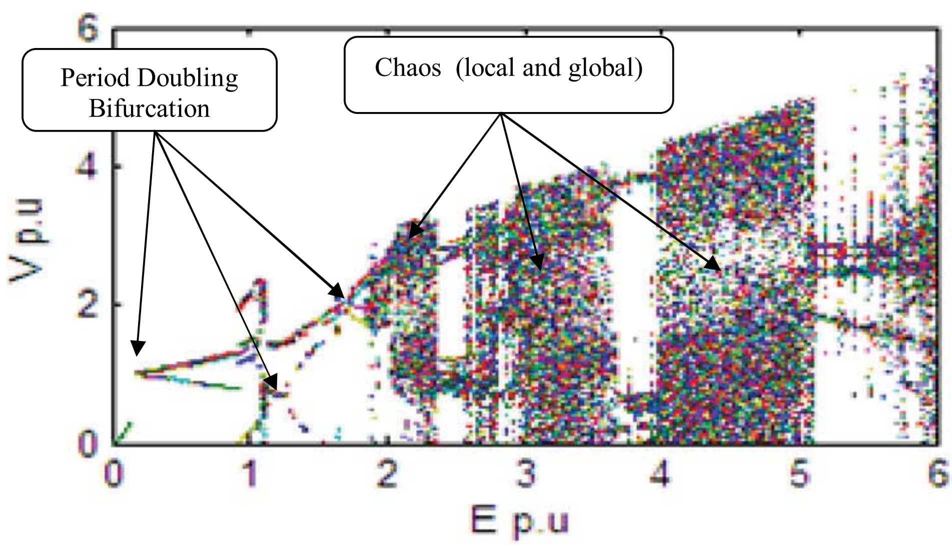

Figure 12: Bifurcation diagram for q=11without MOV

Fig. 13, Fig. 14 and Fig. 15 show that chaotic region mitigates by applying MOV surge arrester. Tendency to chaos exhibited by the system increases while q increases too.

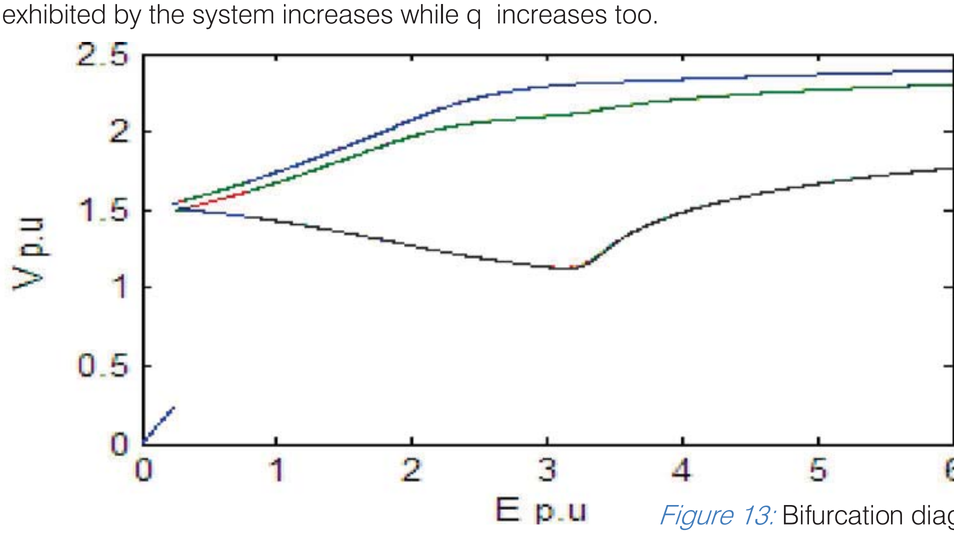

Figure 13: Bifurcation diagram for q=5 with MOV

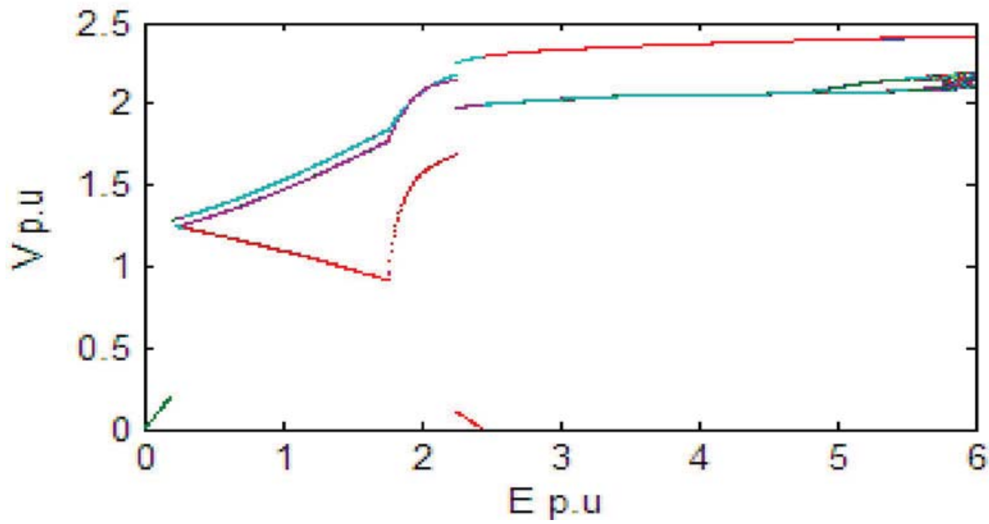

*Figure 14 :*Bifurcation diagram for q=7 with MOV

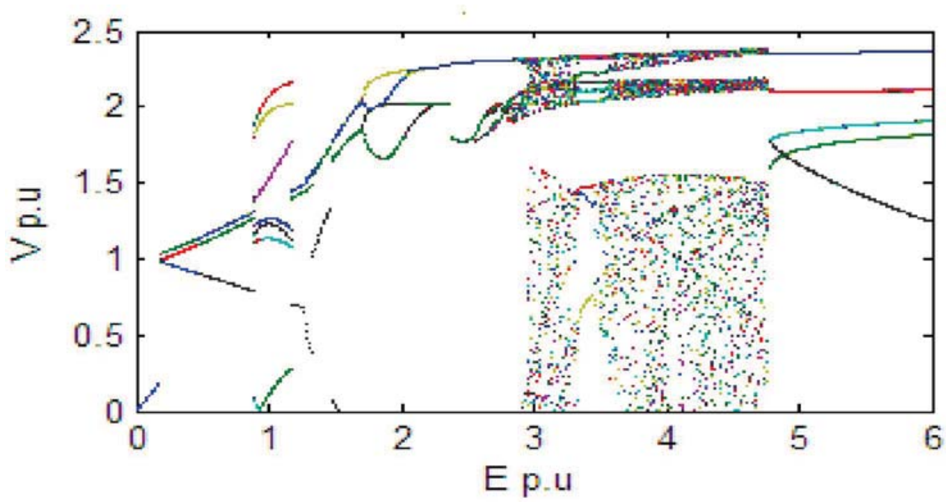

Figure 15: Bifurcation diagram for q=11 with MOV

With consideration to Fig. 13, Fig. 14 and Fig. 15 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

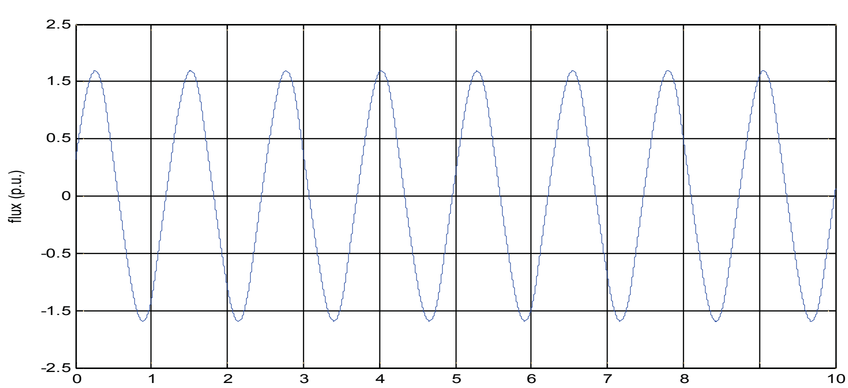

Fig. 16: Flux waveform with MOA at vin= 3.1p.u.

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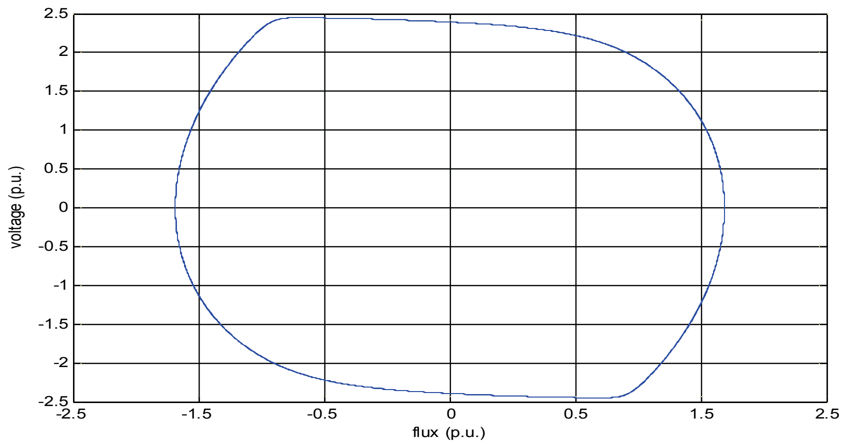

Fig. 17: Phase plane diagram with MOA at vin= 3.1p.u.

Considering to Fig. 17 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.

IV. Conclusion

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.

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