Ferroresonance Phenomena in Unloaded Transformers Applying MOV

Hamid Radmanesh, Matin Nademi, and Maryam Nademi

***Abstract*—This Paper studies the effect of a parallel Metal Oxide Varistor (MOV) on the ferroresonance oscillations of the transformer including nonlinear core losses. It is expected that the arresters generally cause ferroresonance 'dropout'. Time-domain simulation has been carried out using MATLAB SIMULINK to study this effect. Simulation has been done on a three phase unloaded transformer with one open phase. Effect of varying input voltage has been studied. The simulation results reveal that connecting the arrester to the transformer poles, exhibits a great mitigating effect on ferroresonant overvoltages. Phase plan 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 has been obtained, showed and tabulated.**

***Index Terms*—Power transformer, nonlinear core losses effect, chaos, ferroresonance, Metal Oxide Varistor (MOV)**

I. Introduction

In simple terms, ferroresonance is a series of resonance involving nonlinear inductance and capacitances. It typically involves the saturable magnetizing inductance of a transformer and a capacitive distribution cable or transmission line connected to the transformer. Its occurrence is more likely to happen in the absence of adequate damping. Research involving ferroresonance in transformers has been conducted over the last 80 years. The word ferroresonance first appeared in the literature in 1920 [1], although papers on resonance in transformers appeared as early as 1907 [2]. Practical interest was generated in the 1930's when it was shown use of series capacitors for voltage regulation caused ferroresonance in distribution systems [3], resulting in damaging overvoltages. The first analytical work was done by Rudenberg in the 1940's [4]. More precise and detailed work was done later by Hayashi in the 1950's [5]. Subsequent research has been divided into two main areas: improving the transformer models and studying ferroresonance at the system level. An understanding of the nonlinear parameters describing a transformer core is prerequisite to dealing with ferroresonance. Swift [6] and Jiles [7] provide insights into transformer core behaviour and the separation of hysteresis and eddy current losses. Frame [8] and others have developed piecewise-linear methods of modelling the nonlinearities in saturable inductances. Hopkinson [9] performed system tests and simulations on the effect of different switching strategies on the initiation of ferroresonance in three-phase systems. Smith [10] categorized the modes of ferroresonance in one type of three-phase distribution transformer based on the magnitude and appearance of the voltage waveforms. Abrupt transition or jump from one 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 [11], [12]. The theory of nonlinear dynamics has been introduced to provide deeper insight into the phenomenon [13]. Fundamental theory of nonlinear dynamics and chaos can be found in [12], [14]. The susceptibility of a ferroresonance circuit to a quasi periodic and frequency locked oscillations are presented in [15], [16]. Paper in [17] investigated the effect of transformer modeling on the predicted ferroresonance oscillations. Using a linear model, [18] have brought the effect of core loss in damping ferroresonance oscillations. In [19] emphasizes treating core loss as a nonlinear function of voltage on transformer. An algorithm for calculating core losses based on no-load characteristics of transformer is given in [20]. The mitigating effect of transformer connected in parallel to a MOV is illustrated in [21]. Analyze chaotic ferroresonance phenomena in power transformers including neutral resistance effect have been given in [22]. Effect of circuit breaker shunt resistance on chaotic ferroresonance in voltage transformer has been studied in [23]. In all previous studies, the effects of MOV on power transformer including nonlinear core losses are neglected. In previous works, it has been shown that nonlinear core loss can decrease ferroresonance phenomena in power transformer [24]. This paper studies the effect of MOV on the global behaviour of a ferroresonance circuit with nonlinear core loss.

II. System Modeling

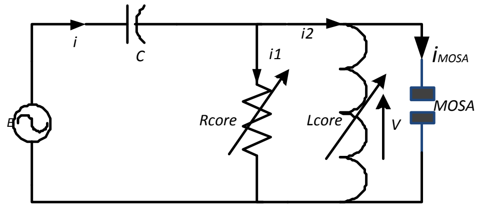

Fig. 1. Basic ferroresonance circuit

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

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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 [21]. The MOV 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 (1):

$$i_L = a\lambda \tag{1}$$

However, for very high currents, the iron core might be saturated where the flux-current characteristic becomes highly nonlinear. The λ-I characteristic of the transformer can be demonstrated by the polynomial which is given in (2) [24]:

$$i_L = a\lambda + b\lambda^q \tag{2}$$

Arrester can be expressed by the so-called alpha equation [21]:

$$V = KI^{1/\alpha} \tag{3}$$

where, V represents resistive voltage drop, I represents arrester current and K is constant and α is nonlinearity constant. In this paper, the core loss model adopted is described by a third order power series which coefficients are fitted to match the hysteresis and eddy current nonlinear characteristics given in [11]:

$$i_{Rm} = h_0 + h_1 V_m + h_2 V_m^{\ 2} + h_3 V_m^{\ 3} \tag{4}$$

Per unit value of i_{Rm} is given in (5)

$$i_{Rm} = -0.000001 + 0.0047V_m - 0.0073V_m^{\ 2} + 0.0039V_m^{\ 3} \tag{5}$$

The differential equation for the circuit in Fig. 1 can be derived as follows:

$$\frac{dv_l}{dt} = \frac{dE}{dt} - \frac{1}{C}\left(h_0 + h_1 v_l + h_2 v_l^{\ 2} + h_3 v_l^{\ 3}\right) - \frac{1}{C}\left(a\lambda + b\lambda^q\right) - \frac{1}{C}\left(\frac{1}{k}\right)^{\alpha} .(v_l)^{\alpha} \tag{6}$$

$$\frac{dv_l}{dt} = \frac{d^2\lambda}{dt^2} \tag{7}$$

where, ω represents the power frequency and E is the peak value of the voltage source, shown in Fig. 1.

III. Simulation Results

TABLE I: Typical Values for Various System Parameters [21]

Power system parameters		Power system parameters	value
a	*0.0028*	*q*	*7, 9 and 11*
b	*0.0072*	*L*	*360μH*
C	*0.047*	*k*	*3.5*
E	*0-7pu*	*α*	*16.5, 25, 50*
ω	*1pu*	*R*	*50, 100*

Typical values for various system parameters considered for simulation are listed in Table I.

Initial conditions:

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

For the cases including arrester, it can be seen that ferroresonant drop out will be occurred. Figs. 2, 3 and 4 show the phase plan diagram of system states without arrester for E=3 pu. Figs. 4, 5 and 6 show the bifurcation diagram without arrester for E=1-6 pu which depicts chaotic behavior.

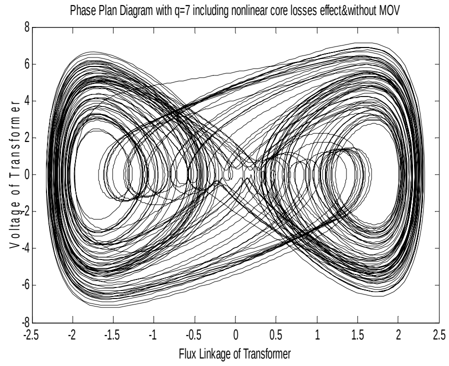

Fig. 2. Phase diagram of system including nonlinear core losses and without MOV, q=7

Figs. 5, 6 and 7 show the corresponding bifurcation diagrams of the system states without MOV and including nonlinear core losses for q=7, 9, 11 which depicts chaotic behavior. In Fig. 2 input voltage has been plotted against the flux of the power transformer. When the magnitude of the input voltage is 3pu, trajectory of the system has chaotic behavior and amplitude of the flux and ferroresonance overvoltage reaches up to 7pu. By increasing in the degree of core nonlinearity, q, the behavior of the system has being more chaotic as shown in Fig. 3. In this case q=9 and oscillation in the voltage of the transformer goes up.

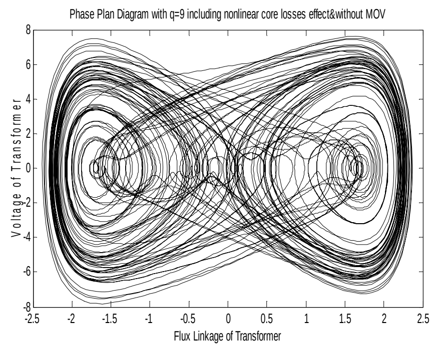

Fig. 3. Phase diagram of system including nonlinear core losses and without MOV, *q=9*

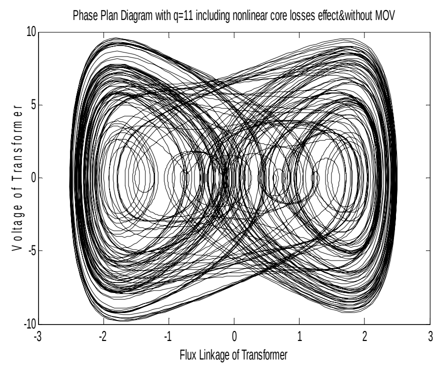

Fig. 4. Phase diagram of system including nonlinear core losses and without MOV, q=11

Fig. 4 shows the Phase plan diagram has been simulated by *q*=11. It shows that chaotic resonance is highly dependent on the transformer modeling.

Another tool that can show manner of the system in vast variation of parameters is bifurcation diagram. In Fig. 5, voltage of the system has been increased to 6pu and ferroresonance has been begun in 4pu, it is shown that if input voltage goes up due to the abnormal operation or switching action, ferroresonance occurs, because of the nonlinearity in core losses, ferroresonance began in the big value of the input voltage.

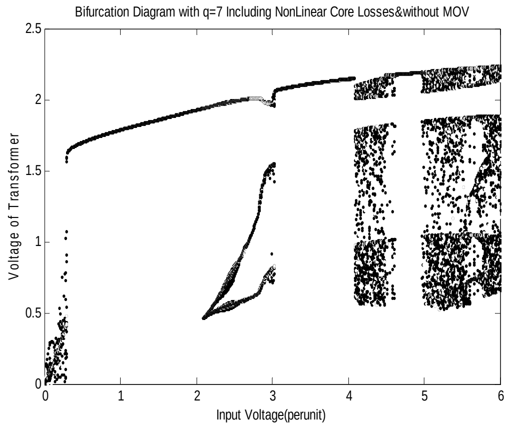

Fig. 5. Bifurcation diagram with *q*=7, without MOV

Fig. 5 shows the abnormal phenomena in the unloaded transformer with the core model nonlinearity q=7, it clearly shows when the *q* degree changes from 7 to 9; ferroresonance begins in 3.9 pu. By comparing Fig. 6 with Fig. 7, it is clear that margin of the beginning ferroresonance has been decreased.

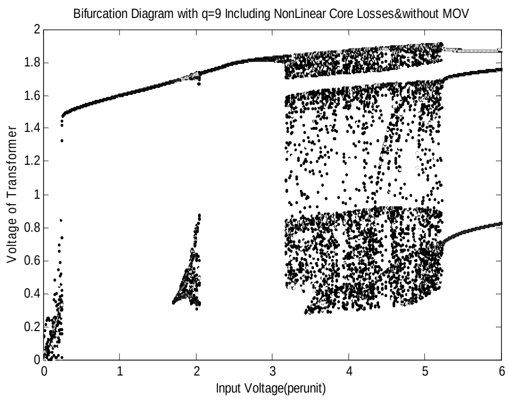

Fig. 6. Bifurcation diagram with q=9, without MOV

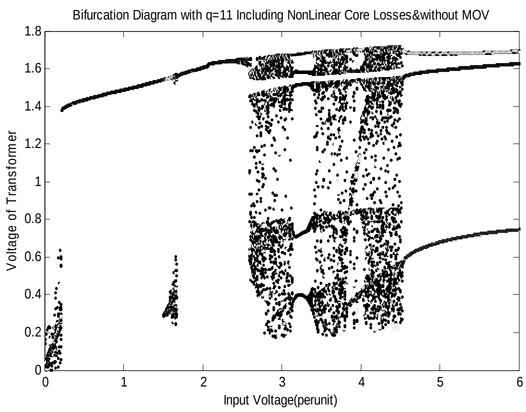

Fig. 7. Bifurcation diagram with q=11, without MOV

Fig. 7 shows the bifurcation diagram of the overvoltage with q=11. It shows that with *q*=11, system behavior reaches to 1.6 pu.

Figs. 8, 9 and 10 show the corresponding phase diagram for the system in Fig. 1. Also, Figs. 11, 12 and 13 show the bifurcation diagrams for corresponding system including MOV. It is shown that chaotic region mitigates by applying MOV.

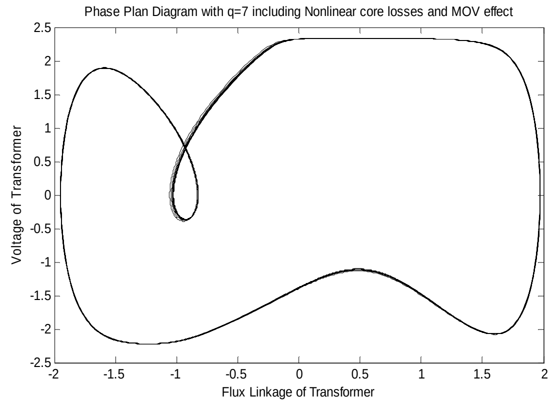

Fig. 8. Phase plan diagram of system with q=7, applying MOV

The use of geometric graphical methods like phase plan projections and bifurcation can be applied to obtain a better understanding of ferroresonance. Figs. 11, 12 and 13 show the bifurcation diagrams for corresponding system including MOV. It is shown that chaotic region mitigates by applying MOV. This occurs more typically for very large values of *q*.

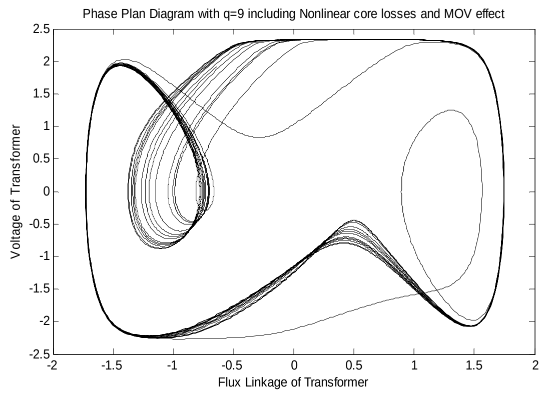

Fig. 9. Phase plan diagram of system with q=9, applying MOV

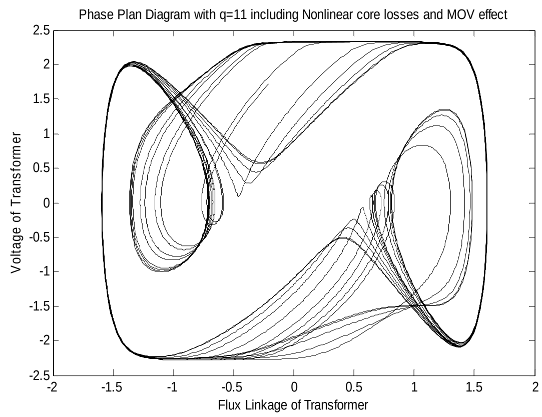

Fig. 10. Phase plan diagram of system with q=11, including MOV

In Fig. 11, the degree of transformer core is q=7, in this figure, one jump has occurred in the trajectory of the system and voltage of the transformer has period-3 oscillation.

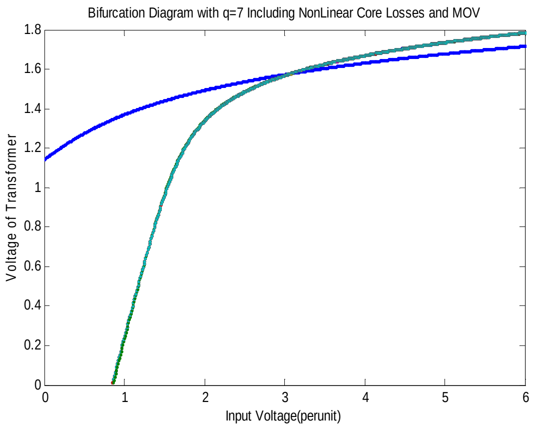

Fig. 11. Bifurcation diagram with q=7, applying MOV

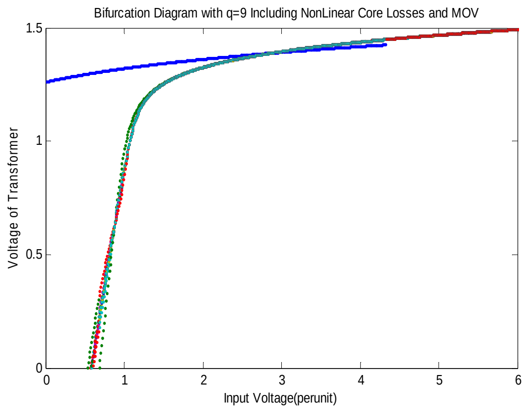

Fig. 12. Bifurcation diagram with q=9, applying MOV

In Fig. 12, q=9 and by considering MOV in the system, there is no nonlinear phenomena and voltage of the transformer has a period-3 oscillation. By increasing the core nonlinearity, behavior remains in periodic oscillation and MOV can cause ferroresonance drop out.

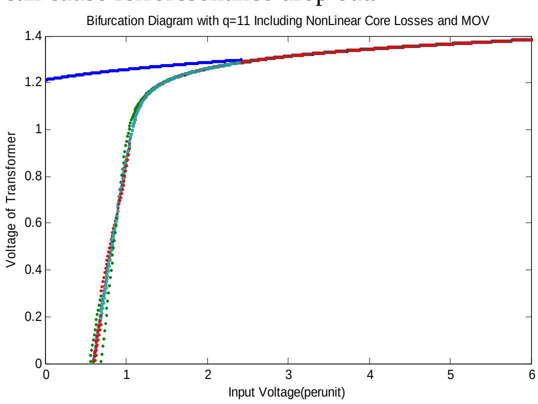

Fig. 13. Bifurcation diagram with q=11, applying MOV

A bifurcation is essentially a jump from one mode of ferroresonance to another. A simulation technique was developed to very slowly ramp the capacitance and record jumps from one mode to another. Due to nonlinearities, it is important to ramp the capacitance both upward and downward, to ensure that as many ferroresonance modes are discovered as possible. “Period 3” simply means that the waveform takes three periods of the forcing function to repeat, it contains 1/3 harmonics. The model correctly predicts the existence of all modes of ferroresonance at the correct values of capacitance. The actual waveforms simulated are very close for the period’s one, two, and three. Period five is generally correct, with slightly lower than actual peak amplitudes predicted. The chaotic response predicted is slightly higher than the actual one. The model used a simplistic linear resistance to represent the core losses of each core. The system has been greatly affected by arrester parameter. Maintaining same parameters, except transformer losses, simulations repeated, which showed that the tendency to fall in chaotic regions increases while, core losses decreases.

IV. Conclusion

The dynamic behaviour of a transformer can be characterized by multiple solutions. Inclusion of nonlinearity in the core loss reveals that bifurcation diagrams will be smoother when compared with linear models. It has been shown that system has been greatly affected by MOV. The presence of the MOV results in clamping the Ferroresonance over voltages in studied system. The MOV successfully, suppresses or eliminates the chaotic behaviour of proposed model. Consequently, the system shows less sensitivity to initial conditions in the presence of the MOV.

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