Ferroresonance Study in Voltage Transformers Connecting Metal Oxide Varistor

Hamid Radmanesh, Mahdi Jafari, Matin Nademi, and Maryam Nademi

Abstract—**This paper studies the effect on Metal Oxide Varistor (MOV) on ferroresonance phenomenon in iron core voltage transformer (VT). It is expected that MOV generally cause ferroresonance 'dropout'. Time-domain study has been carried out to study this effect. Simulation has been done on a voltage transformer rated 100VA, 275 kV. The magnetization characteristic of the transformer is modeled by a single-value two-term polynomial with order seven. The core loss is modeled by linear resistance. The simulation results reveal that connecting the MOV in parallel to VT, exhibits a great mitigating effect on ferroresonance overvoltages. Phase plan, voltage waveforms, along with bifurcation diagrams are also derived. Significant effect on the onset of chaos, the range of parameter values that may lead to chaos along with ferroresonance overvoltages has been obtained and presented.**

Index Terms—**Metal oxide varistot, chaos, bifurcation, ferroresonance, voltage transformers**

I. Introduction

Ferroresonance is a complicated nonlinear electrical phenomenon, which can lead to dangerous transformer overvoltages many times the normal equipment ratings. Ferroresonance occurs when a nonlinear inductor, usually a transformer with a saturable magnetic core, is excited through a linear capacitor from a sinusoidal source, particularly in the presence of long lines or capacitive power cables. It is usually initiated by a system disturbance of some form, for example, the disconnection of transformer feeder lines or the opening of a circuit breaker in series with a voltage transformer. Also, it can produce unpredictable overvoltages and abnormal currents. The prerequisite for ferroresonance is a circuit containing nonlinear iron core inductance and some existed capacitance. The 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. The first analytical work was done by Rudenberg in the 1940's [1]. More exacting and detailed work was done later by Hayashi in the 1950's [2]. Subsequent research has been divided into two main areas: improving the transformer models and studying ferroresonance at the system level. Typical cases of ferroresonance are reported in [3]. One of the most possible cases which may happen is nonlinear iron core inductor that is fed by a series capacitor. These capacitances can be originated from several things, such as line-to-line capacitance, parallel lines, conductor to earth capacitance and circuit breaker grading capacitance [3]. Arturi [4] and Mork [5] have demonstrated the use of duality transformations to obtain transformer equivalent circuits. In [6], the chaotic behavior of the simple power system is investigated for a range of loading conditions through computer simulations. The analysis of the severe over voltages caused by neutral shift and ferroresonance due to the disconnection of one phase of an ungrounded-ye delta transformer bank from the source is presented in [7]. The implications of applying MOV in the distribution environment are described in [8], [9]. In [10], the performances of metal oxide arresters exposed to ferroresonance conditions in pad mount transformers are analyzed. In [10], it has been pointed out that the arresters have a mitigating effect on the chaotic ferroresonance. An improved algorithm for generating the bifurcation diagrams of steady-state solutions to analyses chaotic ferroresonance in the presence of multiple nonlinearities has been reported in [11] Evolving Poincare maps is a new tool and it provides better visualization of the dynamics [12]. The effect of a connected MOV in parallel to the power transformer is illustrated in [13]. Evaluation of chaotic ferroresonance in power transformers including nonlinear core losses is investigated in [14]. Analysis of ferroresonance phenomena in power transformers including neutral resistance effect is investigated in [28]. Analysis of chaotic ferroresonance in transmission systems in the same right-of-way' has been done in [16], and finally effect of circuit breaker shunt resistance on chaotic ferroresonance in voltage transformer has shown in [17], in this work ferroresonance has been controlled by considering C.B resistance effect. In all previous studies, the effect of MOV on ferroresonance phenomena in voltage transformer has been neglected. Current paper studies the effect of MOV on the global behavior of a VT ferroresonance circuit in voltage transformer.

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II. System Modelling Without MOV

During VT ferroresonance an oscillation occurs between the nonlinear iron core inductance of the VT and existing capacitances of network. In this case, energy is coupled to the nonlinear core of the VT via the open circuit breaker grading capacitance or system capacitance to sustain the resonance. The result may be saturation in the VT core and very high voltage up to 4pu can theoretically gained in worst case conditions. The magnetizing characteristic of a typical 100VA VTs can be presented by 7 order polynomial [17]. These VTs fed through circuit breaker grading capacitance, and studied using nonlinear dynamics analysis and packages such as Rung kutta Fehlberg algorithm and MATLAB SIMULINK. Fig. 1 shows the single line diagram of the most commonly encountered system arrangement that can give rise to VT ferroresonance [17]. Ferroresonance can occur upon opening of disconnector *3* with circuit breaker open and either disconnector *1* or *2* closed. Alternatively it can also occur upon closure of both disconnector *1* or *2* with circuit breaker and disconnector *3* open.

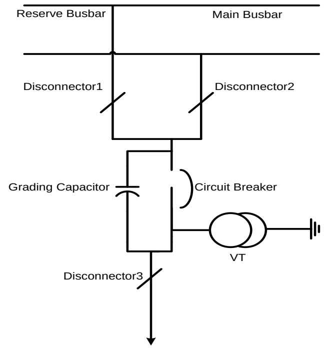

Fig. 1. System one line diagram arrangement resulting to VT ferroresonance

The system arrangement shown in Fig. 1 can effectively be reduced to an equivalent circuit as shown in Fig. 2.

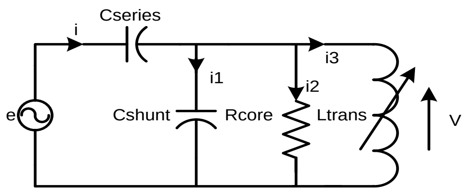

Fig. 2. Basic reduced equivalent ferroresonance circuit [30]

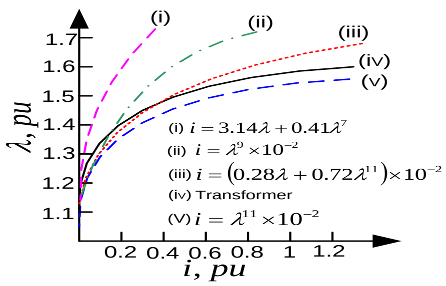

Fig. 3. Nonlinear characteristics of transformer core with different values of *q*

In Fig. 2, *E* is the RMS supply phase voltage, C_{series} is the circuit breaker grading capacitance and C_{shunt} is the total phase-to-earth capacitance of the arrangement. The resistor *R* represents a voltage transformer core loss that has been found to be an important factor in the initiation of 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 voltage transformer is modeled as in [8] by the polynomial

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

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

The polynomial of order seven and the coefficient *b* of 1 are chosen for the best fit of the saturation region.

Fig. 3 shows the comparison between different approximations of saturation region against the true magnetization characteristic that was obtained from field measurement by dick and Watson [18].

III. System Dynamic and Equation

Mathematical analysis of equivalent circuit by applying KVL and KCL has been done and equations of system can be presented. Where, ω is supply frequency, and *E* is the rms supply phase voltage, C_{series} is the circuit breaker grading capacitance and C_{shunt} is the total phase-to-earth capacitance of the arrangement and in (1) *a=3.4* and *b=0.41* are the seven order polynomial sufficient [17].

$$\lambda_{peak} = \sqrt{2}\,\frac{v_{RMS}}{\omega} \tag{2}$$

$$v_L = \frac{d\lambda}{dt} \tag{3}$$

$$i = C_{ser}\frac{d(e - v_L)}{dt} = C_{ser}\left(\dot{e} - \frac{d^2\lambda}{dt^2}\right)$$

$$i = i_1 + i_2 + i_3 \Rightarrow \frac{C_{ser}(4)}{(C_{ser} + C_{sh})}\left(\sqrt{2}E\cos\omega t\right) = \frac{1}{\omega}\frac{d^2\lambda}{dt^2} + \frac{1}{R\omega(C_{ser} + C_{sh})}\frac{d\lambda}{dt} + \frac{1}{\omega(C_{ser} + C_{sh})}\left(a\lambda + b\lambda^7\right) \tag{5}$$

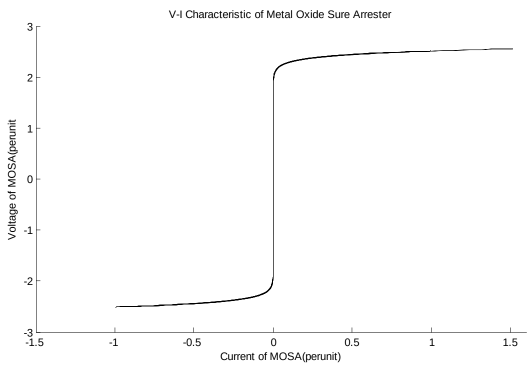

Fig. 4. V-I characteristic of MOV

IV. Metal Oxide Varistor Model

Surge arrester is highly nonlinear resistor used to protect power equipment against overvoltages. The nonlinear V-I characteristic of each column of the surge arrester is modelled by combination of the exponential functions of the form:

$$\frac{V}{V_{ref}} = K_i \left(\frac{I}{I_{ref}} \right)^{1/\alpha_i} \tag{6}$$

where V represents resistive voltage drop, I represents arrester current and K is constant and α is nonlinearity constant. This V-I characteristic is graphically represented as follows:

V. System Modelling With MOV

Connecting MOV to the system in Fig. 2, circuit can be driven in Fig. 5.

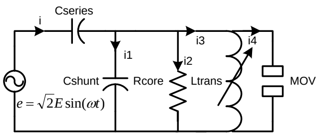

Fig. 5. Basic reduced equivalent ferroresonance circuit connecting MOV

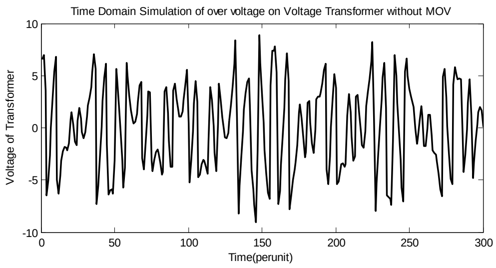

Fig. 6. Time domain simulation for chaotic motion without MOV

The differential equation for the circuit in Fig. 5 can be modified as follows:

$$\omega E \cos\omega t - \frac{1}{R_{core}}\frac{d\lambda}{dt} - \frac{1}{C_{series}}\left(\frac{d\lambda}{kdt}\right)^{\alpha} - \frac{1}{C_{series}}(a\lambda + b\lambda^7) = \frac{(C_{series}+C_{shunt})}{C_{series}}\left(\frac{d^2\lambda}{dt^2}\right) \tag{7}$$

VI. Simulation Results

Multipliers Equations (10) and (14) contain a nonlinear term and do not have simple analytical solution. So the equations were solved numerically using an embedded Runge-Kutta-Fehlberg algorithm with adaptive step size control. Values of E and ω were fixed by 1 pu, corresponding to AC supply voltage and frequency. C_{series} is the CB grading capacitance and its value obviously depends on the type of circuit breaker which is used. In this analysis C_{series} is assumed 0.5nF and C_{shunt} vary between 0.1nF to 3nF. Initial condition are $V(t)=\sqrt{2},\ \lambda(t)=0$ at t=0, representing circuit breaker operation at maximum voltage. In this state, system for both cases, with and without MOV has been simulated for E=4 pu. The studied system has a chaotic behaviour for E=4 pu while by applying MOV, system behaviour remains periodic for E=1 pu and E=4 pu. Figs. 6 and 7 show time domain simulation for these two cases which represented the chaotic voltage wave form some subharmonic resonance, Figs. 8 and 9 show the simulation result for E=4 pu including of MOV by phase plan diagram.

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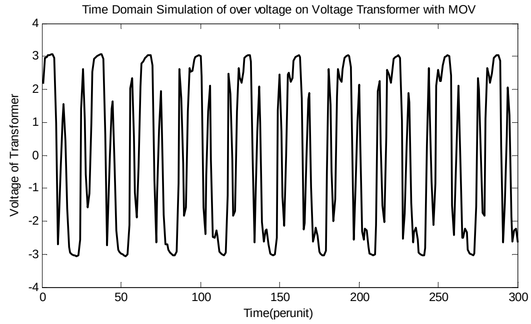

Fig. 7. Time domain simulation for chaotic motion with MOV

Corresponding phase plan diagrams has been shown the effect of the MOV to damp the overvoltages and it is shown in Figs. 8, 9 for E=4 pu. it obviously shows that MOV clamp the ferroresonance overvoltage and keep it in E=2.5 pu. Phase plan diagrams has been shown the apparent the MOV effect. It is obviously shows that MOV clamp the ferroresonance overvoltage and keeps it in E=2.5pu. Table (1) shows the system parameters that have been considered for this case of simulation.

TABLE I: Parameter Value for Simulation

Parameter	Actual value	Per unit value
E	*275kv*	*1 pu*
ω	*377 rad/sec*	*1 pu*
C_{series}	*0.5 nf*	*39.959 pu*
C_{shunt}	*1.25nf*	*99 pu*
Rcore	*225 MΩ*	*0.89 pu*

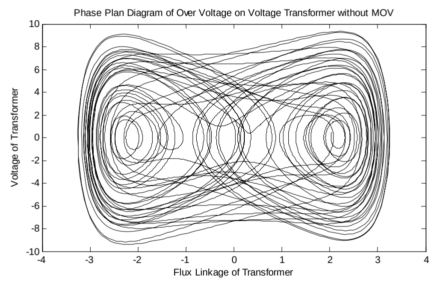

Fig. 8. Phase plan diagram for chaotic motion without MOV

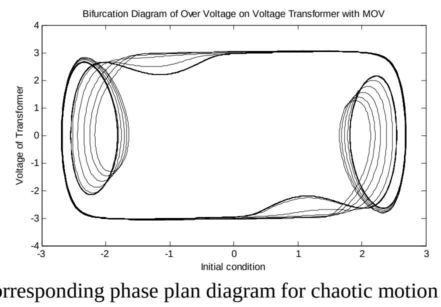

Fig. 9. Corresponding phase plan diagram for chaotic motion with MOV

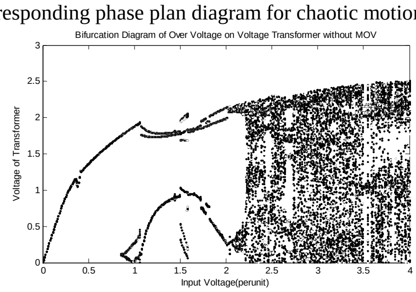

Fig. 10. Bifurcation diagram for voltage of transformer versus voltage of system, without MOV

By using bifurcation diagrams, Fig. 10 clearly shows the ferroresonance overvoltage in VT when voltage of system increase to 3 pu.

System parameters are listed in Table II.

TABLE II: PARAMETER VALUE FOR SIMULATION

Parameter	Actual value	Per unit value
E	*275kv*	*1 pu*
ω	*377 rad/sec*	*1 pu*
C_{series}	*0.5 nf*	*39.959 pu*
C_{shunt}	*0.1nf*	*7.92 pu*
Rcore	*225 MΩ*	*0.89 pu*

In Fig. 10, when E=0.25 pu, voltage of VT has a period-1 behaviour. In E=1 pu, period-3 appears and in E=2.5 pu crisis take place and suddenly system goes to the chaotic region. It has been shown that system behaviour is period doubling bifurcation and there are many resonances, because system is continuous then it is look like doffing equation. Corresponding bifurcation diagram with the same parameter in the case of applying MOV parallel to the VT has been shown in Fig. 11.

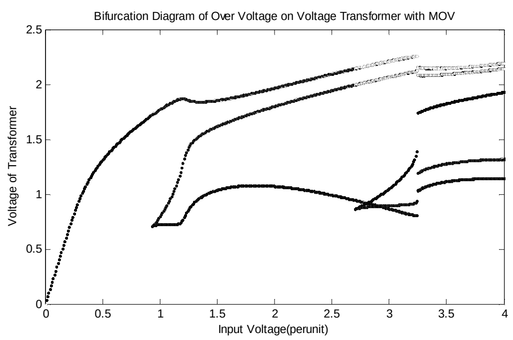

Fig. 11 Bifurcation diagram for voltage of transformer versus voltage of system, considering MOV effect

By applying MOV, system behaviours coming out from chaotic region, the MOV clamps the overvoltage from 3pu to 1.8pu. In the real systems, maximum overvoltage that VT can withstand is 4pu, and if over voltages cross it, VT failure follows.

VII. CONCLUSION

Voltage Transformers fed through circuit breaker grading capacitance have been shown exhibiting fundamental frequency and chaotic ferroresonance conditions similar to high capacity power transformers fed via capacitive coupling from nearby sources like parallel transmission lines. Simulations have shown that a change in the value of the equivalent line to ground capacitance, may originate different types of ferroresonance over voltages. MOV successfully can cause ferroresonance drop out. In the case of applying MOV, system shows less sensitivity to initial conditions and variation in system parameters. To continue this study, one may include nonlinear core model and enhance extracted results.

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