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Ferroresonance Elimination in 275kV Substation

Hamid Radmanesh

Electrical Engineering Department, Islamic Azad University, Takestan Branch, Takestan, Ghazvin, Iran
hamid.radmanesh@aut.ac.ir

Abstract This work studies the non-conventional ferroresonance oscillation in the 275kV substation. Voltage transformer (VT) which is used in this substation has a 100VA capacity and magnetization characteristic of it was modeled by single-value two-term polynomial with q=7. In this study, at first ferroresonance oscillation in VT has been introduced, then effect of Metal Oxide Varistor (MOV) on limiting these nonlinear overvoltages is investigated. It has been shown for some parameters values, MOV cannot control the ferroresonance. So, by connecting the neutral earth resistance (NR) to the system grounding, non-conventional oscillation has been controlled for all value of system parameters. Simulation results show that considering neutral earth resistance exhibit great controlling of ferroresonance overvoltages. It is also shows by using this resistance, system exhibit less sensitivity to the changing the parameters value of the power system.

Keywords Ferroresonance Oscillation, Stabilizing, Chaos Control, Voltage Transformer, MOV, Neutral Earth Resistance

1. Introduction

Ferroresonance is a complex nonlinear electrical phenomenon which can cause dielectric and thermal problems to the power system components. 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]. In linear resonance, 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 voltage magnitude, initial magnetic flux condition of the transformer iron core, total loss in the ferroresonant circuit and moment of switching[2].VT ferroresonance from an energy transfer standpoint is given in[3]. In this paper, a new approach to determine whether ferroresonance can occur is developed, based on the energy transferred from the system to the voltage transformer during the switching transient. Discussion of modeling and analysis guidelines for slow transients has been given in[4]. Fast ferroresonance suppression of coupling capacitor voltage transformers (CCVT) was done in[5]. This paper describes a procedure for fast suppression of the phenomenon of ferroresonance in CCVT without major change in the design. It will be shown that it is possible to adjust parameters of the secondary overvoltage protection and the filter circuit so that the ferroresonance can be cleared in a very short time interval. 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, in to the PT's wye secondary circuit. Sensitivity studies on power transformer ferroresonance of a 400 kV double circuit are given in[7]. Novel analytical solution to fundamental ferroresonance in[8] investigated a major problem with the traditional excitation characteristic (TEC) of nonlinear inductors, in that the TEC contains harmonic voltages and/or currents, and has been used the way as if it were made up of pure fundamental voltage and current. Stability domain calculations of period-1 ferroresonance in a nonlinear resonant circuit have been investigated in[9]. Application of wavelet transform and MLP neural network for ferroresonance identification was done in[10]. In this paper an efficient method for detection of ferroresonance in distribution transformer based on wavelet transform is presented. Impacts of transformer core hysteresis formation on stability domain of ferroresonance modes were done in[11]. In this paper, impacts of various formations of hysteresis on the stability domain of ferroresonance modes of a VT have been studied. 2-D finite-element electromagnetic analysis of an autotransformer experiencing ferroresonance was given in[12]. Experimental and simulation analysis of ferroresonance in single-phase transformers considering magnetic hysteresis effects is investigated in[13]. A new modeling of MATLAB

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* Corresponding author:
hamid.nsa@gmail.com (Hamid Radmanesh)

transformer for accurate simulation of ferroresonance shows a new modeling of transformers in Simulink/MATLAB enabling to simulate slow transients more accurate than the existing models used in the software[14]. Effect of Magnetizing Curve Nonlinearity Index on the Occurring Chaotic Ferroresonance Oscillation in Autotransformers has been studied in[17]. In current paper, MOV and NR connected devices are used as a control method for stabilizing of unstable and high amplitude ferroresonance oscillation. Using of these methods result improving voltage waveform which leads to protection from insulation, fuses and switchgears. This paper organized as follow: At first the reasons of occurring ferroresonance in transformers is described. Then various types of ferroresonance in VT are explained. Then general introducing of controlling ferroresonance by considering neutral earth resistance and using it in current problem is shown.

2. Power System Modeling without Neutral Resistance

Ferroresonance can occur where VTs are connected to isolated sections of bus bars. Energy is coupled via the inter-circuit capacitance of the parallel lines or open circuit breaker grading capacitance. Specifically, the connection of VTs to isolated section of bus bar i.e. to a low capacitance should be avoided[15].

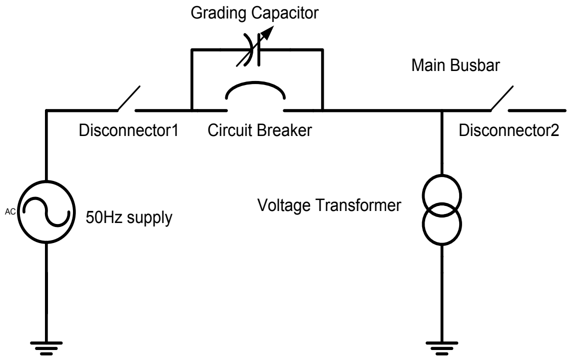

Figure 1. System one line diagram arrangement resulting to VT ferroresonance[15]

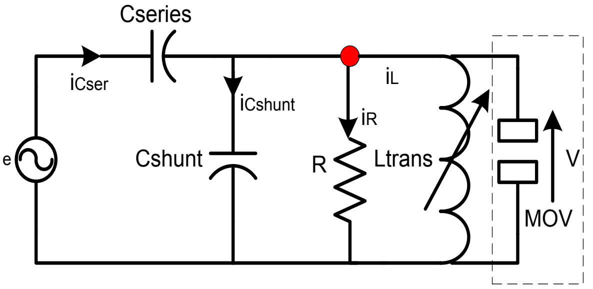

Figure 2. Basic reduced equivalent ferroresonance circuit connecting MOV

Fig. 1 shows the circuit diagram of system components at the 275 kV substations. VT is isolated from sections of bus bars via disconnector DS_2[15]. Ferroresonance conditions occurred upon closure of disconnector DS_1 with CB and DS_2 open, leading to a system fault caused by failure of the VT primary winding. Fig. 2 shows the basic ferroresonance equivalent circuit used in this analysis while MOV has been connected in parallel with the VT. The resistor R represents transformer core losses, in current paper the nonlinear transformer magnetization curve was modeled by a single valued seventh order polynomial obtained from the transformer magnetization curve[14],[15].

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 and MOV is a nonlinear resistance that has been added on the transformer. 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[15] by the polynomial

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

where, $a = 3.14, b = 0.41$

Fig. 3 shows simulation of these iron core characteristic ($\lambda - i$) for q=7.

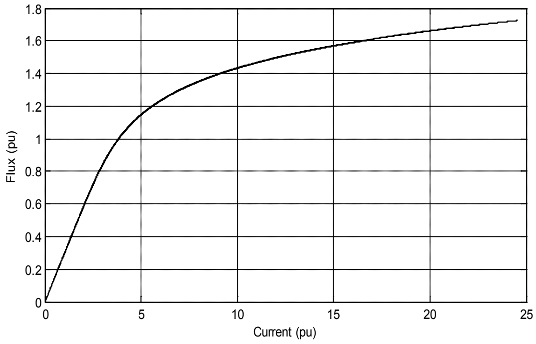

Figure 3. Flux- current characteristic of transformer core

The basic voltage transformer ferroresonance circuit of Fig. 2 can be presented by a differential equation[16]. Because of the nonlinear nature of the transformer magnetizing characteristics, the behavior of the system is extremely sensitive to change in system parameter and initial conditions. A small change in the value of system voltage, capacitance or losses may lead to dramatic change in the behavior of it. A more suitable mathematical language for studying ferroresonance and other nonlinear systems is provided by nonlinear dynamic methods. Mathematical tools that are used in this analysis are phase plan diagram, time domain simulation and bifurcation diagram.

3. Metal Oxide Varistor Model

MOV is highly nonlinear resistor used to protect power equipment against overvoltages. The nonlinear *V-I* characteristic of each column of the MOV is modeled by combination of the exponential functions which is shown in (2).

$$\frac{V}{V_{ref}} = K_i \left(\frac{I}{I_{ref}} \right)^{1/\alpha_i} \tag{2}$$

where, V represents resistive voltage drop, I represents arrester current, K is constant and α is nonlinearity constant. Fig. 4 shows *V-I* characteristic of MOV that has been simulated by the given parameters in this paper. The surge arrester block is modeled as a current source driven by the voltage appearing across its terminals. Therefore, it cannot be connected in series with an inductor or another current source. Recognition and study of chaotic ferroresonance has fostered a whole new technology of dynamical systems in power system. The technology collectively includes many new and better techniques and tools in nonlinear dynamics, time-series analysis, short and long-range prediction and numerically characterizing non-Euclidean objects.

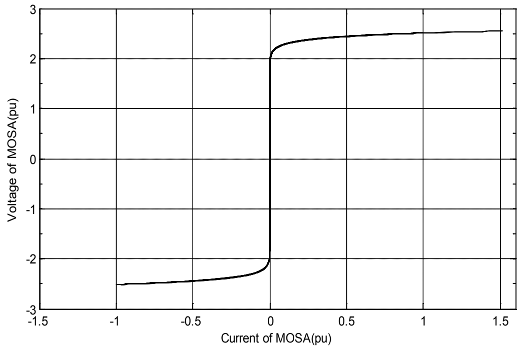

Figure 4. V-I characteristic of MOV

So mathematical analyses of equivalent circuit by have been done and equations of system can be presented here. Arrester can be expressed by"alpha" equation:

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

The differential equation for the circuit in Fig. 2 can be modified as follows:

$$e = \sqrt{2}E\sin(\omega t) \tag{4}$$

$$i_L = a\lambda + b\lambda^7 \tag{5}$$

$$v_L = \frac{d\lambda}{dt} \tag{6}$$

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

where, ω is supply frequency. The time behavior of the basic ferroresonance circuit is described by (7). Results for one parameters set show two possible types of ferroresonance. Table (1) shows base values used in the analysis and different states parameters are given in table (2). It has been shown by applying neutral earth resistance to the system, these two cases have been changed to the better oscillation behavior and amplitude of overvoltages has been greatly decreased.

Table 1. Base values of the system used for simulation

Base value of input voltage	275/sqrt (3) kV
Base value of volt-amperes	100 VA
Base angular Frequency	2π50 rad/sec

Table 2. Parameters used for various states simulation

Power system parameters	C_{series} *(nf)*	C_{shunt} *(nf)*	R_{core} *(MΩ)*	R_n *(kΩ)*	ω *(rad/sec)*	*E* *(KV)*	α	*k*
value	0.5	3	225	50	314	275	25	2.5101

4. System Descriptions Connecting Neutral Earth Resistance

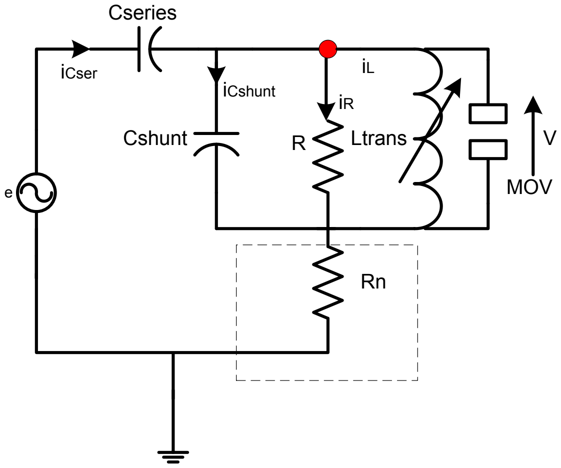

Figure 5. Basic reduced equivalent ferroresonance circuit including MOV and neutral earth resistance

The primary purpose of inserting impedance between the star point of a transformer and earth is to limit ferroresonance current. By comparison low voltage transformers tend to be directly earthed with this in mind the impedance that is inserted can be characterized as being of a high or low type. Low impedance earthing is conventionally defined as impedance that limits the prospective ferroresonance current to the full load current of the transformer. The value of impedance required is easily calculated to a reasonable approximation by dividing the rated phase voltage by the rated phase current of the transformer. Neutral resistance is conventionally achieved using resistors rather than inductors so as to limit the tendency for the fault arc to persist due to inductive energy storage[18]. These resistors will dissipate considerable heat when ferroresonance current flows and are usually only short term rated (typically 30secs) so as to achieve an economic design[18]. Due to the explanation above, In Fig. 5, R_n is the neutral earth resistance. Typical values for various system parameters has been considered for simulation were kept the same by the case 1, while neutral earth resistance has been added to the system and its value is given below:

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

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

$$\begin{aligned}&C_{ser}C_{sh}R_n\frac{d^2v_L}{dt^2} = C_{ser}\sqrt{2}E\omega\cos\omega t - \\ &\left(C_{ser} + C_{ser}\frac{R_n}{R_1} + C_{sh} + \left(\frac{1}{k}\right)^{\alpha}\alpha(v_L)^{\alpha-1}\right)\frac{d^2\lambda}{dt^2} - \\ &\left(C_{ser}R_n a + C_{ser}R_n bq\lambda^6\right)\frac{d\lambda}{dt} \\ &-\frac{v_L}{R_1} - \left(\frac{v_L}{k}\right)^{\alpha} - \left(a\lambda + b\lambda^q\right)\end{aligned} \tag{8}$$

5. Simulation Results

In this section of simulation, three state of ferroresonance have been studied in two cases, without considering neutral earth resistance and considering neutral resistance.

A. Simulation results without considering neutral earth resistance

Phase space and waveform of voltage for subharmonic response were shown in Figs. 6.a and 6.b. The phase plane diagram clearly shows the effect of MOV on the system behavior, MOV clamps the ferroresonance overvoltages on 2.3p.u and doesn't allow to overvoltages that across from this point. According to the Fig.3, *V-I* characteristic of MOV has been shown when voltage of transformer has been crossed from 2.2p.u, MOV causes across high current from its terminal and overvoltages has been damped by this nonlinear varistor. It is shown that overvoltages clamps by considering MOV in parallel to the transformer.

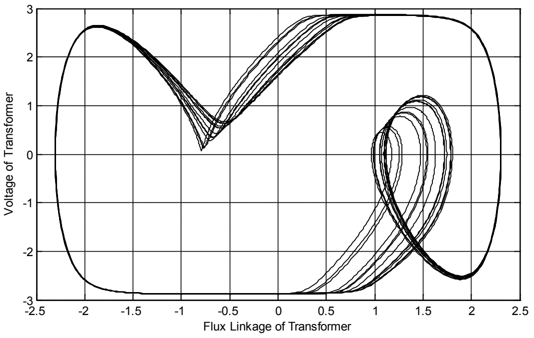

Figure 6. a) Phase plan diagram for fundamental resonance motion without neutral earth resistance effect

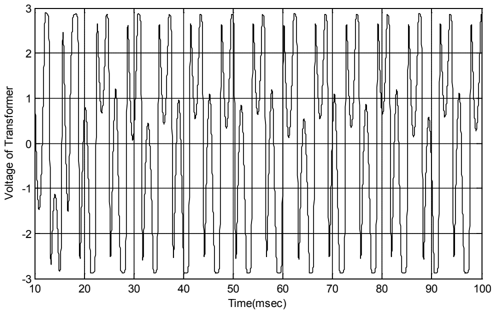

Figure 6. b) Time domain simulation for fundamental resonance motion without neutral earth resistance effect

B. Simulation results considering neutral earth resistance effect

In this case, effect of neutral earth resistance on the system behavior is investigated. Phase space and waveform of voltage for quasiperiodic response were shown in Figs. 7.a and 7.b show the effect of neutral resistance on the ferroresonance overvoltages. The phase plane diagram clearly shows the torus trajectory characteristic of the quasiperiodic waveform.

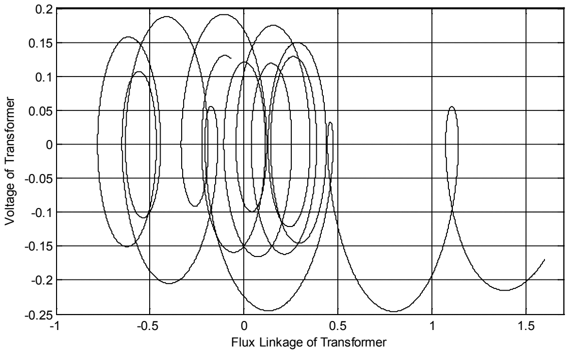

Figure 7. a) Phase plan diagram for quasiperiodic motion considering neutral earth resistance effect

By comparing this case with the previous case, it clearly shows that amplitude of subharmonic resonance decreases to 0.15p.u and subharmonic resonance has been changed to quasiperiodic resonance. The neutral earth resistance causes to increase the order of the nonlinear equation. This increasing in the nonlinear deferential equation changed type of the previous equation to the doffing equations, so behavior of this case has been shown as a torus behavior. Also, effect of neutral earth resistance is clearly obvious, because amplitude of ferroresonance overvoltages has been decreased from 2.2p.u to 0.15 p.u.

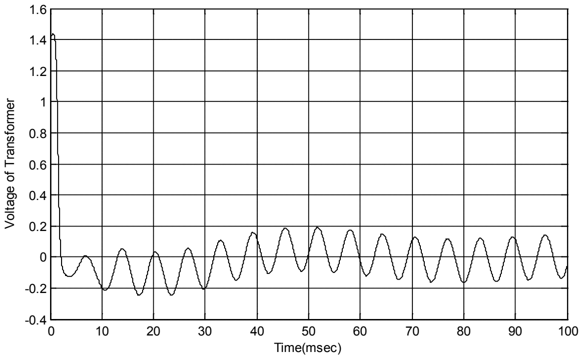

Figure 7. b) Time domain simulation for quasi-periodic motion considering neutral earth resistance effect

5. Bifurcation Diagram Analysis

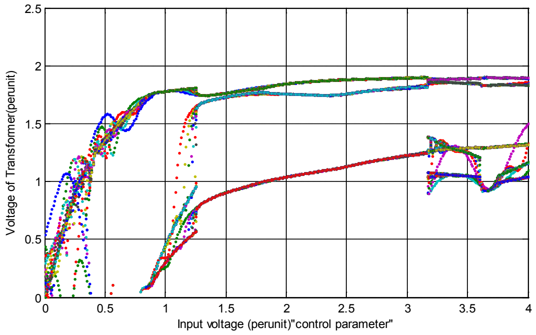

Figure 8. a) Bifurcation diagram considering MOV effect

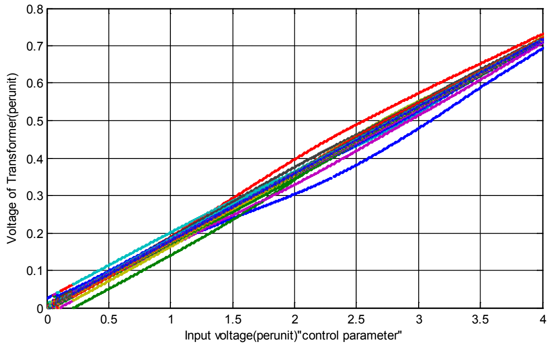

Figure 8. b) Bifurcation diagram considering neutral earth resistance and MOV

In this paper, it is shown the effect of variation in the voltage of the system on the ferroresonance overvoltage in the VT, and finally the effect of applying neutral resistance on this overvoltage by the bifurcation diagrams. Figs. 8.a and 8.b clearly shows the ferroresonance overvoltage in VT when voltage of system increase to 5p.u. In the bifurcation diagram of Fig. 8.a, system behavior has been shown in the case of considering MOV, as previously described, MOV clamps ferroresonance overvoltages to 2.2p.u. When input voltage has been increased up to 5p.u, ferroresonance appears for some value of the input voltages, MOV can control these overvoltages and keeps its amplitude under 2.2p.u. In this plot, before 1p.u ferroresonance appears, after that between 1p.u to 3p.u period-3 occurs, after that until 4p.u, period-3 oscillation has been changed to subharmonic resonance but MOV doesn't allow ferroresonance overvoltages goes up more than 2.2p.u. By applying neutral earth resistance to the system configuration, bifurcation diagram of Fig. 8.a has been changed to Fig. 8.b. Important effect of neutral earth resistance is that ferroresonance overvoltages has been controlled and quasiperiodic route to chaos has been take placed for bifurcation diagram. The neutral earth resistance successfully can control these overvoltages.

6. Conclusions

In this paper, ferroresonance overvoltages have been studied in the VTs. At first, effect of MOV on controlling these phenomena is studied. It is shown MOV can clamp the ferroresonance oscillation but it cannot control these nonlinear overvoltages for all parameters values. Then, it has been shown that system is greatly affected by neutral earth resistance. The presence of the neutral resistance results in clamping the ferroresonance oscillations. Neutral resistance successfully, suppresses or eliminates the chaotic oscillation in the power system. Finally, the system shows less sensitivity to changing in the system parameters.

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