Effect of Circuit Breaker Shunt Resistance on Chaotic Ferroresonance in Voltage Transformer

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***Abstract*— Ferroresonance or nonlinear resonance is a complex electrical phenomenon, which may cause over voltages and over currents in the electrical power system which endangers the system reliability and continuous safe operating. This paper studies the effect of circuit breaker shunt resistance on the control of chaotic ferroresonance in a voltage transformer. It is expected that this resistance generally can cause ferroresonance 'dropout'. For confirmation this aspect Simulation has been done on a one phase voltage transformer rated 100VA, 275kV. The magnetization characteristic of the transformer is modeled by a single-value two-term polynomial with q=7. The simulation results reveal that considering the shunt resistance on the circuit breaker, exhibits a great mitigating effect on ferroresonance over voltages.. Significant effect on the onset of chaos, the range of parameter values that may lead to chaos along with ferroresonance voltages has been obtained and presented.**

***Index Terms*— Circuit breakers Shunt Resistance, Chaos, Bifurcation, Ferroresonance, Voltage Transformers**

I. INTRODUCTION

Ferroresonance over voltage on electrical power systems were recognized and studied as early as 1930s. Kieny first suggested applying chaos to the study of ferroresonance in electric power circuits [1]. He studied the possibility of ferroresonance in power system, particularly in the presence of long capacitive lines as highlighted by occurrences in France in 1982, and produced a bifurcation diagram indicating stable and unstable areas of operation. Then the combination of nonlinear iron core inductor with series capacitor has been investigated and shown that this core is the most possible case for occurring ferroresonance in the power system. These capacitances can be due to number of elements, such as the line-to-line capacitance, parallel lines, conductor to earth capacitance and circuit breaker grading capacitance. A Special Ferroresonance Phenomena on 3-phase66kV VT-generation of 20Hz zero sequence continuous voltage is given in [2]. Typical cases of ferroresonance are reported in [3], [4], in these papers power transformer and VTs has been investigated due to ferroresonance over voltages. Digital simulation of transient in power system has been done in [5]. Application of nonlinear dynamics and chaos to ferroresonance in the distribution systems can be found in [6]. The susceptibility of a ferroresonance circuit to a quasi periodic and frequency locked oscillations has been presented in [7], in this case, investigation of ferroresonance has been done upon the new branch of chaos theory that is quasi periodic oscillation in the power system and finally ferroresonance appears by this route. Modeling iron core nonlinearities has been illustrated in [8]. Mozaffari has been investigated the ferroresonance in power transformer and effect of initial condition on this phenomena, he analyzed condition of occurring chaos in the transformer and suggested the reduced equivalent circuit for power system including power switch and trans [9],[10].

The mitigating effect of transformer connected in parallel to a MOV arrester has been illustrated in [11]. Analysis of ferroresonance in voltage transformer has been investigated by Zahawi in [12] and [13]. Analysis of Ferroresonance Phenomena in the Power Transformers Including Neutral Resistance Effect has been reported in [14]. Ferroresonance Conditions Associated with a 13 kV Voltage Regulator During Back-feed Conditions is given in [15]. Performance of Various Magnetic Core Models in Comparison with the Laboratory Test Results of a Ferroresonance Test on a 33 kV Voltage Transformer investigated in [16]. Mitigating Ferroresonance in Voltage Transformers in Ungrounded MV Networks has been reported in [17]. An Approach for Determining the Subsystem Experiencing and Producing a Bifurcation in a Power System Dynamic Model has been reported in [18].

In all previous studies, possibility of occurring ferroresonance and nonlinear phenomena in power system had been studied and control of this unwanted phenomena has not been studied, also the effects of circuit breaker shunt resistance on VT ferroresonance in the deeper case has not been investigated. Current paper studies the effect of circuit breaker shunt resistance on the control of ferroresonance over voltages in VT. It is shown that by considering this resistance, the behavior of system has been changed and ferroresonance drop out.

II. SYSTEM DESCRIBTION WITHOUT C.B SHUNT RESISTANCE

During Voltage Transformer (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 voltage transformer 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 4p.u can theoretically gained in worst case conditions. The magnetizing characteristic of a typical 100VA VTs can be presented by 7 order polynomial [12].

These VTs fed through circuit breaker grading capacitance, and studied using nonlinear dynamics analysis and packages such as Rung Kutta Fehlberg algorithm and

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MATLAB Simulink. Fig.1 shows the single line diagram of the most commonly encountered system arrangement that can give rise to VT ferroresonance [13]. 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.

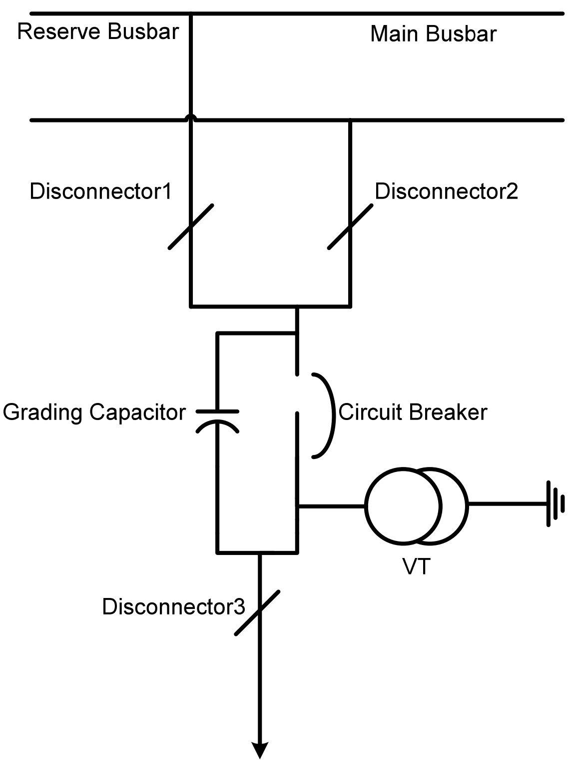

Fig.1.System one line diagram arrangement resulting to VT Ferroresonance

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

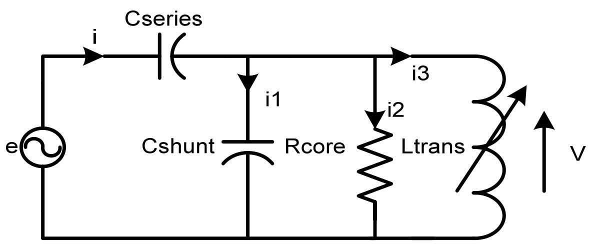

Fig.2. Basic reduced equivalent ferroresonance circuit [13]

In Fig. 2, E is the RMS supply phase voltage, Cseries is the circuit breaker grading capacitance and Cshunt 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 [9] by the polynomial

$$i = a\lambda + b\lambda^7 \qquad [1]$$

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

The polynomial of the order seven and the coefficient b of equation (1) are chosen for the best fit of the saturation region that was obtained by the comparison between different approximations of the saturation regions against the true magnetization characteristic that was obtain by dick and watson[5]. It was found that for adequate representation of the saturation characteristics of a voltage transformer core, the exponent q may acquire value 7 [10]. Fig.3 shows simulation of these iron core characteristic for q=5, 7, 11. The basic voltage transformer ferroresonance circuit of Fig.2 can be presented by a differential equation. 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.

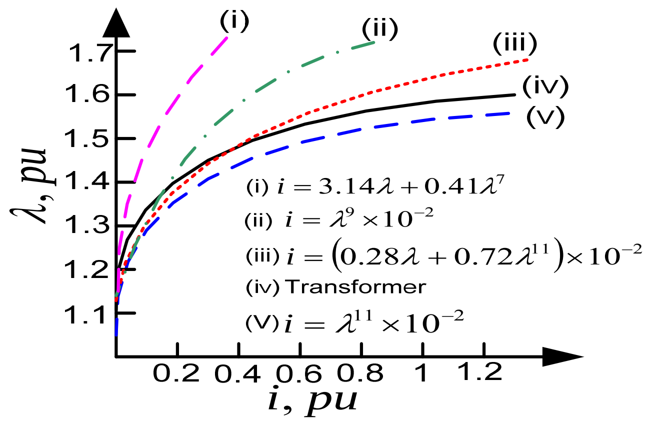

Fig.3. Nonlinear characteristics of transformer core with different values of q

III. SYSTEM DYNAMIC AND EQUATION

Mathematical analysis of equivalent circuit by applying KVL and KCL laws has been done and Equations of system can be presented as below:

$$\lambda_{peak} = \sqrt{2}\frac{v_{RMS}}{\omega} \qquad [2]$$

$$v_L = \frac{d\lambda}{dt} \qquad [3]$$

$$v_{C_{ser}} = e - v_l \qquad [4]$$

$$e = \sqrt{2}E\sin\omega t \qquad [5]$$

$$i = C_{ser}\frac{d(e - v_L)}{dt} = C_{ser}\left(\dot{e} - \frac{d^2\lambda}{dt^2}\right) \qquad [6]$$

$$i_1 = C_{sh}\frac{dv_L}{dt} = C_{sh}\frac{d^2\lambda}{dt^2} \quad [7]$$

$$i_2 = \frac{v_L}{R} = \frac{1}{R}\frac{d\lambda}{dt} \quad [8]$$

$$i_3 = a\lambda + b\lambda^7 \quad [9]$$

$$i = i_1 + i_2 + i_3 \Rightarrow C_{ser}(\sqrt{2}E\omega\cos\omega t - \frac{d^2\lambda}{dt^2}) =$$

$$C_{sh}\frac{d^2\lambda}{dt^2} + \frac{1}{R}\frac{d\lambda}{dt} + \left(a\lambda + b\lambda^7\right)$$

$$\sqrt{2}C_{ser}E\omega\cos\omega t = \left(C_{ser} + C_{sh}\right)\frac{d^2\lambda}{dt^2} + \frac{1}{R}\frac{d\lambda}{dt} + \quad [10]$$

$$\left(a\lambda + b\lambda^7\right) \Rightarrow \frac{C_{sh}}{\left(C_{ser} + C_{sh}\right)}\left(\sqrt{2}E\cos\omega t\right) = \frac{1}{\omega}\frac{d^2\lambda}{dt^2}$$

$$+ \frac{1}{R\omega\left(C_{ser} + C_{sh}\right)}\frac{d\lambda}{dt} + \frac{1}{\omega\left(C_{ser} + C_{sh}\right)}\left(a\lambda + b\lambda^7\right)$$

Where ω is supply frequency, and E is the rms supply phase voltage, Cseries is the circuit breaker grading capacitance and Cshunt is the total phase-to-earth capacitance of the arrangement and in equation (1) a=3.4 and b=0.41 are the seven order polynomial sufficient[13].

IV. SYSTEM DESCRIBTION WITH C.B SHUNT RESISTANCE

In this case, system under study is similar with the case above, but the model of circuit breaker has been changed. Equivalent Thevenin circuit of this case has been illustrated in fig.4.

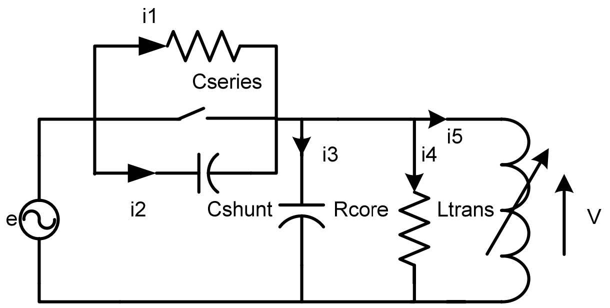

Fig.4. Basic reduced equivalent ferroresonance circuit

Nonlinear Equation of this circuit is as below:

$$i_1 = \frac{e - v_L}{R_{C.B}} \quad [11]$$

$$i_2 = C_{ser}\frac{d}{dt}\left(e - v_L\right) \quad [12]$$

$$i_3 = C_{sh}\frac{dv_L}{dt} = C_{sh}\frac{d^2\lambda}{dt^2} \quad [13]$$

$$i_4 = \frac{v_L}{R} = \frac{1}{R}\frac{d\lambda}{dt} \quad [14]$$

$$i_5 = a\lambda + b\lambda^7 \quad [15]$$

$$i_1 + i_2 = i_3 + i_4 + i_5 \quad [16]$$

$$\left(\frac{C_{ser}}{C_{ser} + C_{sh}}\right)\sqrt{2}\omega ECos(\omega t) + \left(\frac{1}{R_{C.B}\left(C_{ser} + C_{sh}\right)}\right)$$

$$\sqrt{2}ESin(\omega t) = \frac{d\lambda}{dt}\left(\frac{R + R_{C.B}}{R.R_{C.B}\left(C_{ser} + C_{sh}\right)}\right) + \frac{d^2\lambda}{dt^2} \quad [17]$$

$$+ \frac{1}{C_{ser} + C_{sh}}\left(a\lambda + b\lambda^7\right)$$

In this model of circuit, R_1 is paralleled with the Cseries and its value is $R_1 = 0.34$ p.u. Other parameters of system are similar with the case 1.

In the following analysis, instead of using actual values of circuit parameters $E, \omega, C_{series}, C_{Shunt}$ etc., system equations are made dimensionless by using per unit values, equation (10) may be written as

$$\frac{1}{\omega}\frac{dV}{dt} + \frac{1}{q}V + \frac{1}{\omega(C_{series} + C_{shunt})}(a\lambda + b\lambda^7) \quad [18]$$

$$= g\cos\theta$$

Where g and q are the driving force amplitude and damping parameter, respectively, given by

$$g = \frac{C_{series}}{(C_{series} + C_{shunt})}\sqrt{2}E \quad [19]$$

$$\frac{1}{q} = \frac{1}{R\omega(C_{series} + C_{shunt})} \quad [20]$$

And equation (17) can be written as:

$$\omega g\cos\omega t + \frac{g}{C_{ser}.R_{C.B}}\sin\omega t =$$

$$\frac{d\lambda}{dt}\left(\frac{R + R_{C.B}}{q.R_{C.B}}\right) + \frac{d^2\lambda}{dt^2} \quad [21]$$

$$+ \left(\frac{1}{C_{ser} + C_{sh}}\right)(a\lambda + b\lambda^7)$$

V. SIMULATION RESUILTS

Eq. (18) contains a nonlinear term and does 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 at 1p.u, corresponding to AC supply voltage and frequency. C series is the C.B grading capacitance and its value obviously depends on the type of circuit breaker. In this analysis C series is fixed at 0.5nF and C shunt vary between 0.1nF and 3nF.solutions are obtained for initial values of $V(t) = \sqrt{2}, \lambda(t) = 0$ at t=0, representing circuit breaker operation at maximum voltage. This corresponds to a lightly damped, lightly driven system in which q=47.24 and g=0.02. In this state, system for both cases, with and without circuit breaker shunt resistance has been simulated for E=1, 3p.u. it shows that the system under study has a periodic behavior for E=1p.u and chaotic behavior for E=3p.u while in the case of applying shunt resistance, system behavior remain periodic for E=1,3p.u Corresponding phase plan diagrams has been shown the clearance effect of applying the shunt resistance to the system and it is shown in figs.9, 10 for E=1p.u and figs.11 and 12 for E=3p.u.

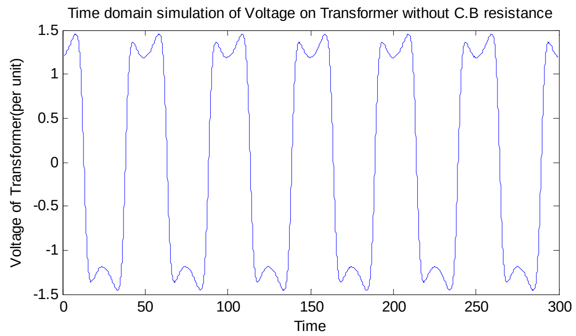

Figure 5. Time domain simulation for periodic motion without C.B shunt resistance shunt resistance, E=1p.u

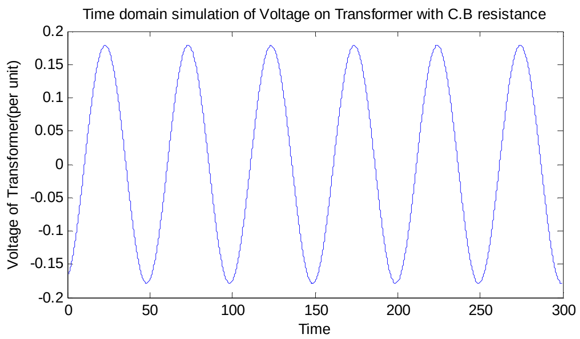

Figure 6. Time domain simulation for periodic motion with C.B shunt resistance, E=1p.u

Fig. 5 and Fig. 6 show Time domain simulation for these two cases that represent the sinusoidal wave with a frequency equal to the system frequency, i.e. 50 cycles per second for E=1p.u, but comparing the simulation result for E=3p.u in the case of considering shunt resistance it has been shown the effect of shunt resistance on system behavior this is presented in figs.7 and 8.

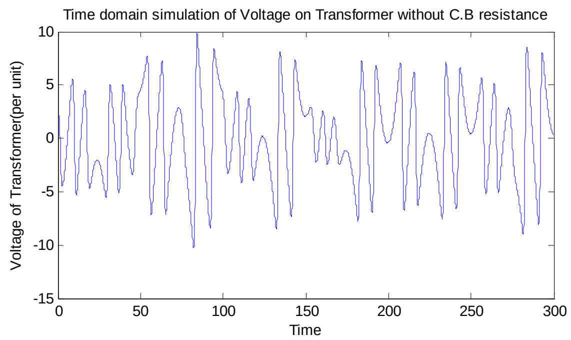

Figure 7. Time domain simulation for chaotic motion without C.B shunt resistance, E=4p.u

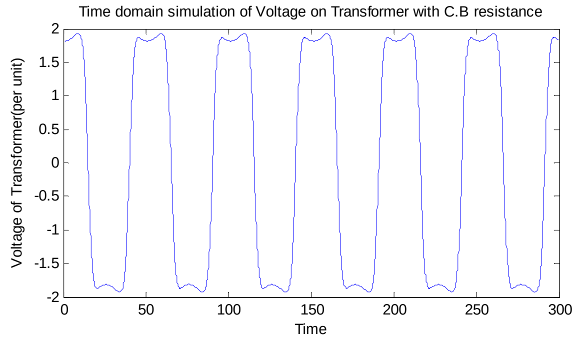

Figure 8. Time domain simulation for clamping the chaotic motion with C.B shunt resistance, E=4p.u

In Fig. 7 System behavior has been simulated without considering shunt resistance, time domain simulation is completely chaotic and ferroresonance over voltages reaches up to 10 p.u., in the equal condition, by applying shunt resistance, this over voltages has been damped and behavior of system goes to linear region, according to the Fig. 8 system frequency is equal the periodic condition and voltage of transformer has been fixed to 1.8 p.u.

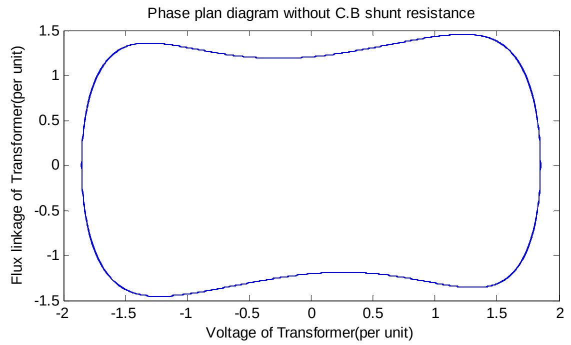

Figure 9. Phase plan diagram for periodic motion without C.B shunt resistance, E=1p.u

Fig. 9 shows the corresponding phase plan diagram when there is no shunt resistance effect and voltage of system is 1p.u. in this plot, flux linkage has been simulated versus voltage of transformer, it is shown that in the case of normal condition system behavior is periodic and there is no Ferroresonance phenomenon in it.

In the next state, by considering the shunt resistance effect, it is shown that the voltage of transformer reach to 0.16 p.u. with the frequency equal with the input frequency that has been shown in Fig. 10.

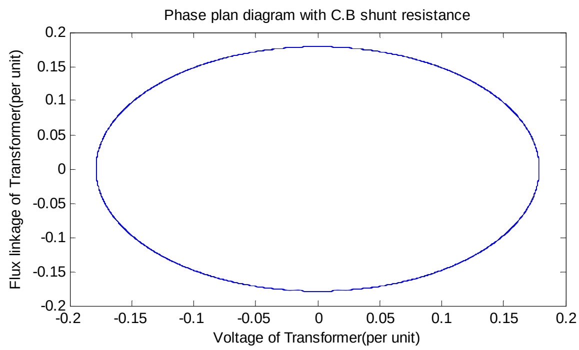

Figure 10. Phase plan diagram for periodic motion with C.B shunt resistance, E=1p.u

Due to the abnormal condition such as switching action or other cases that may cause transient phenomena, When input voltage of power system goes up to 3p.u, in the case of without considering shunt resistance effect, ferroresonance over voltage on voltage transformer reach up to 9p.u, this state has been shown by phase plan diagram in fig 11.

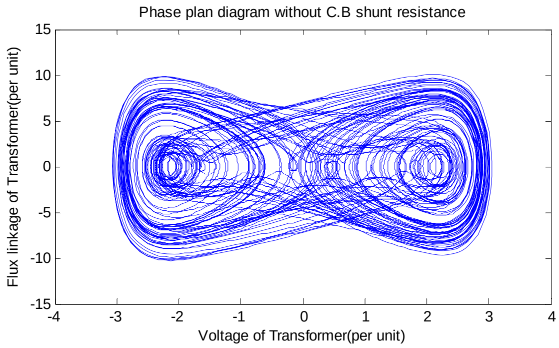

Figure 11. Phase plan diagram for chaotic motion without C.B shunt resistance, E=4p.u

By applying shunt resistance effect to the system while the input voltage is 3p.u, it is shown in fig 12 that ferroresonance over voltages clamp to 1.6p.u and it is presented in fig12.

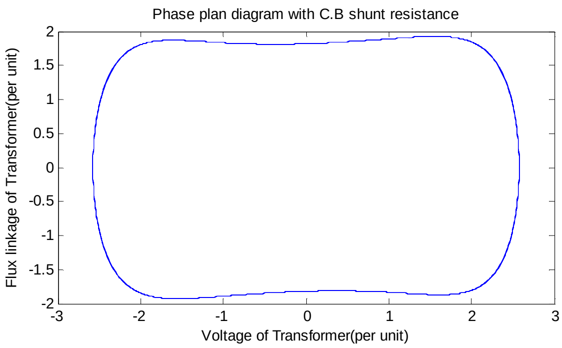

Figure 12. Phase plan diagram for clamping the chaotic motion with C.B shunt resistance, E=4p.u

It obviously shows that circuit breaker shunt resistance clamps the ferroresonance overvoltage and keeps it in E=2p.u. System parameters that considering for these case of simulation are as below:

$$C_{series} = 0.5\,nf\ , C_{shunt} = 1.25\,nf\ , R = 225\,M\Omega\,,$$

E=1,3p.

Another tool that was used for solving the nonlinear equation of studied system is bifurcation diagram. In this paper, it is shown the effect of variation in the voltage of system on the Ferroresonance overvoltage in the VT, and finally the effect of applying circuit breaker shunt resistance on this overvoltage by the bifurcation diagrams.

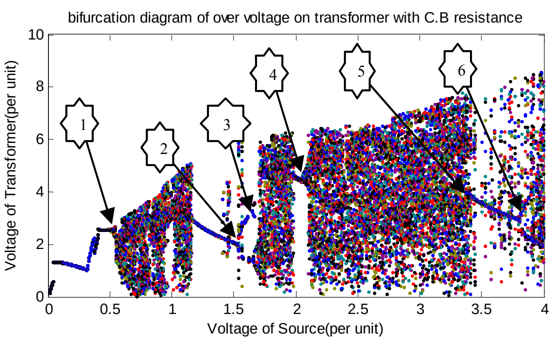

Figure 13. Bifurcation diagram for voltage of transformer versus voltage of system, without C.B shunt resistance

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Fig.13. clearly shows the ferroresonance over voltages on VT when the voltage of system increases up to 4p.u. Parameters value of the system in this case are as below:

$$E = 1 - 4\ p.u, \omega = 1\ p.u, C_{Shunt} = 0.5nf, C_{Series} = 0.1nf$$
$$R = 225M\Omega,$$

In fig.13 when E=0.25p.u, voltage of VT has a period1 behavior and system works under normal condition, in E=0.57p.u that has been shown by point1, its behavior is still period1 and after this voltage, suddenly crisis takes place and system behavior goes to the chaotic region, after that, when the input voltage reach to 1.2p.u, system comes out of chaotic region, again in the point2 and 3, bifurcation takes place, by this route system behavior goes to chaos, finally between point4 and 5, system remains in ferroresonance oscillation. After point5, system comes out of chaos again and then behaves linearly. It is shown that system behavior has period doubling bifurcation logic and there are many resonances in the system behavior. Bifurcation diagram with the same parameter in the case of applying C.B shunt resistance parallel to the VT is shown in fig.14.

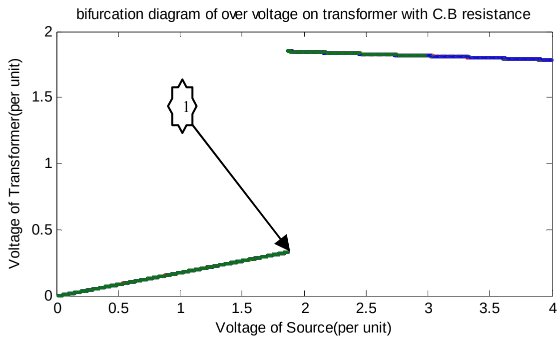

Figure 14. Bifurcation diagram for voltage of transformer versus voltage of system, corresponded by fig.13 with applying C.B shunt resistance

It is shown that by applying this resistance, system behaviors coming out of chaotic region and C.B shunt resistance can clamp over voltages from 8p.u to 1.8p.u, in this case there is a jump in the voltage of transformer when the input voltage reaches up to 1.8p.u which is indicated by point1. In the real systems, maximum over voltage that VT can stand is 4p.u. If over voltage increases more, it can exactly cause VT failure. By repeating simulation for wide range of parameter value, table (1) and (2) has been obtained and is shown in the appendix part.

VII. CONCLUTION

Low capacity Voltage Transformers fed through circuit breaker grading capacitance have been shown to exhibit fundamental frequency and chaotic ferroresonance conditions similar to high capacity power transformers fed via capacitive coupling from neighboring sources. Repeated simulation of the system's nonlinear differential equation has shown that a change in the value of the equivalent circuit capacitance to earth, possibly as a result of a change in system configuration, can give rise to different types of ferroresonance overvoltage. It has also been shown that chaotic ferroresonance states are not likely to occur under practical site conditions. C.B shunt resistance successfully can cause ferroresonance drop out and can control it, in the case of applying C.B shunt resistance system shows less sensitivity to initial condition and variation in system parameters. A comprehensive understanding of the possibilities that exist for ferroresonance is very desirable for engineers so that they can operate their systems outside dangerous regions and can plan the expansion of systems without enhancing the possibility of ferroresonance.

APPENDIX A

TABLE 1: SYSTEM WITHOUT CONSIDERING C.B SHUNT RESISTANCE

Elements	Periodic state		Fundamental Frequency Ferroresonance		Sub harmonic Frequency Ferroresonance		Chaotic Ferroresonance	
	Actual value	Per unit value	Actual value	Per unit value	Actual value	Per unit value	Actual value	Per unit value
C_{series}	0.5nf	39.585p.u	0.5nf	39.585p.u	0.5nf	39.585p.u	3nf	237.51p.u
C_{shunt}	3nf	237.51p.u	1.25nf	98.962p.u	0.19nf	15.042p.u	0.1nf	7.917p.u
R	225MΩ	.89p.u	225MΩ	.89p.u	225MΩ	0.89p.u	1900MΩ	7.392p.u
G	0.2		0.4		1.02		1.37	
Q	247.4		123.7		48.8		1850	
W	314rad/s	1p.u	314rad/s	1p.u	314rad/s	1p.u	314rad/sec	1p.u
E	275kv	1p.u	275kv	1p.u	275kv	1p.u	275kv	1p.u
RC.B	90MΩ	0.357p.u	90 MΩ	0.35p.u	90 MΩ	0.35p.u	90 MΩ	0.35p.u

APPENDIX B

TABLE2: SYSTEM WITH CONSIDERING C.B SHUNT RESISTANCE

Elements	Periodic state		Fundamental Frequency Ferroresonance		Sub harmonic Frequency Ferroresonance		Chaotic Ferroresonance	
	Actual value	Per unit value	Actual value	Per unit value	Actual value	Per unit value	Actual value	Per unit value
C_{series}	0.5nf	39.585p.u	0.5nf	39.585 p.u	0.5nf	39.585 p.u	3nf	237.51 p.u
C_{shunt}	3nf	237.51p.u	1.25nf	98.962 p.u	0.19nf	15.042 p.u	0.1nf	7.917 p.u
R	225MΩ	.89 p.u	225MΩ	.89 p.u	225MΩ	0.89 p.u	1900MΩ	7.392 p.u
G	0.2		0.4		1.02		1.37	
Q	247.4		123.7		48.8		1850	
W	314 rad/s	1 p.u	314 rad/s	1 p.u	314 rad/s	1 p.u	314 rad/sec	1 p.u
E	275 kv	1 p.u	275 kv	1 p.u	275 kv	1 p.u	275 kv	1 p.u

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