Novel Circuit Breaker Modeling in 275kV Substation

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ABSTRACT

Ferroresonance an electrical phenomenon may cause overvoltages in the electrical power system. In this paper, an overview of available papers is provided, at first ferroresonance is introduced and then various type of ferroresonance in a voltage transformer (VT) is simulated. Then effect of new model of circuit breaker (CB) on damping ferroresonance oscillation is examined. Finally effect of earth resistance on the stabilizing these oscillations in the case of nonlinear core loss has been studied. Core loss is modelled by third order power series in terms of voltage and includes nonlinearities in core loss. For confirmation, the simulation is done on a one phase voltage transformer rated 100VA, 275kV. The simulation results reveal that novel modeling of circuit breaker exhibits a great controlling effect on ferroresonance overvoltages.

Keywords: Ferroresonance Oscillation, Stabilizing, Chaos Control, Voltage Transformer, Nonlinear Core Loss, Neutral Earth Resistance, Circuit Breaker.

1. INTRODUCTION

Ferroresonance is a nonlinear resonance, which has result in multiple periodic and non-periodic modes in the system behavior. Considering system parameters and the initial condition of the ferroresonant circuit, it may settle to one of the following behaviors such as fundamental, subharmonic, quasi-periodic or chaotic resonances. Usually, the ferroresonance contains a nonlinear inductance and capacitances. The nonlinear inductance typically is a saturate magnetizing inductance of a transformer and the capacitance is a capacitive distribution cable or transmission line connected to the transformer. Ferroresonance phenomenon has been recognized in many papers as early as 1907[1]. Isolated ferroresonant solutions in transmission lines have been investigated in [2-6], which presents the detailed analysis of the subharmonic mode of the ferroresonance and its sensitivity with respect to the length of the deenergised line. The study of the periodic ferroresonance in electrical power networks by bifurcation diagrams has been carried out in [7]. The analysis of the lightning-caused ferroresonance in capacitor voltage transformer (CVT) has been given in [8]. The S-domain model of three winding transformer for modal analysis has been given in [9]. The influence of non-differential components to the power system small signal stability region has been studied in [10]. Considering the importance of the initial condition in the nonlinear systems on the initiation of the ferroresonance in the model of a 275 kV magnetic voltage transformer has been investigated in [11]. The transient response of a practical ferroresonant circuit has been studied in detail in [12]. The iterative approximation technique has been used for the determination of the transient response due to sudden application of a sinusoidal voltage. The analysis of subharmonic oscillations in a ferroresonant circuit with the focuse on subharmonic (period-3) ferroresonant oscillations has been given in [13]. A novel analytical solution to the fundamental ferroresonance including power frequency excitation characteristic has been investigated in detail in [14]. A method of protecting the voltage transformer against ferroresonance overvoltages with a compact active load has been developed by [15]. The static VAR compensator (SVC) and the thyristor-controlled series capacitor (TCSC) analytical model, a systematical method for suppressing ferroresonance at neutral-grounded substations and the frequency response of the unified power flow controller (UPFC) has been simultaneously studied in [16]. A sensitivity study on power transformer ferroresonance in a 400 kV power system is presented in [17]. In that paper, the model of 1000 MV-400/275/13 kV power transformer has been described and the simulations have been compaired with field test results. The influence of supply, circuit and magnetic material parameters on the occurance of the fundamental ferroresonance mode in a series inductance-capacitance-resistance (LCR) circuit with a nonlinear inductor has been discussed in [18] and [19]. The effect of the circuit breaker shunt resistance on the chaotic ferroresonance in voltage transformers has been studied in [20]. The suppression technique of the ferroresonance phenomenon in the coupling capacitor of the voltage transformer has been given in [21]. The impact of hysteresis and magnetic couplings on the stability domain of ferroresonance in asymmetric three-phase three-leg transformers has been discussed in [22]. Mitigating the ferroresonance of 161

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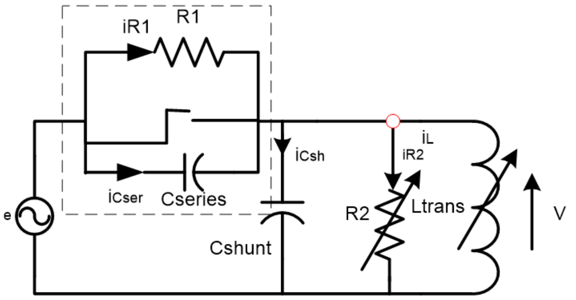

Fig.1: *Basic reduced equivalent ferroresonance circuit including nonlinear core loss and air gap resistance effect.*

kV electromagnetic potential transformer by damping reactors in gas-insulated switchgear has been presented in [23]. The frequency domain analysis of a power transformer ferroresonance has been studied in [24]. This paper organized as follow: At first the reason of occurrence ferroresonance in transformers is described. Then various types of ferroresonance in voltage transformer in the case of considering novel model of circuit breaker are explained. Then general introducing of controlling ferroresonance by considering neutral earth resistance in the case of modeling nonlinear core loss and using it in current problem is shown. Next section is devoted to simulation and showing usefulness of this method. Ultimately, the work will be concluded in last section.

2. SYSTEM MODELLING CONSIDERING PROPOSED CIRCUIT BREAKER MODEL

Circuit Breaker is a switching which can be operated for controlling and protection of electrical power system respectively. The power system deals with high currents, the special attention should be given during designing of circuit breaker to safe interruption of arc produced during the operation of circuit breaker. During short circuit or any other fault, this equipment suffers a high stress of fault current in them which may damage the equipment permanently. For saving this equipment the fault current should be cleared from the system as quickly as possible. Again after the fault is cleared, the system must back to its normal working condition as soon as possible for supplying reliable quality power to the loads. During interruption of high level current, there would be large arcing in between switching contacts, so care should be taken to quench these arcs in safe manner. The resistance of air between contacts of circuit breaker has been modeled in this paper as a limiter resistance. This resistance can successfully control the ferroresonance amplitude as shown in simulation results.

Fig.1 shows the basic ferroresonance equivalent circuit used in this analysis. The resistor R represents

Table 1: *Base values of the system used for simulation.*

Base value of input voltage	158.7713 kV
Base value of volt-amperes	100 VA
Base angular Frequency	$2\pi 50$ rad/sec

transformer core loss. In [2, 14] was shown that the probability of chaos increases as loss decrease. In [14] accurate model for magnetization curve of core considering hysteresis, was introduced but in current paper the nonlinear transformer magnetization curve was modeled by a single valued seventh order polynomial obtained from the transformer magnetization curve[15]. In Fig. 1, 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. In the peak current range for steady-state operation, the flux-current linkage can be approximated by a linear characteristic such as $i_L = \alpha\lambda$ where the coefficient of the linear term (α) corresponds closely to the reciprocal of the inductance ($\alpha = 1/L$). 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. A small change in the value of system voltage, capacitance or loss may lead to dramatic change in the behavior of it. Recognition and study of chaos has fostered a whole new technology of dynamical systems. The technology collectively includes many new and better techniques and tools in nonlinear dynamics, time-series analysis, and short- and long-range prediction, quantifying complex behavior, and numerically characterizing non-Euclidean objects. In other words, studying chaos has developed procedures that apply to many kinds of complex systems, not just chaotic ones. As a result, chaos theory lets us describe, analyze, and interpret temporal data (whether chaotic or not) in new, different, and often better ways. Due to the explanation above, mathematical analysis of equivalent circuit by applying KVL and KCL has been done and equations of system can be presented as below:

$$i_4 = h_0 + h_1 v_L + h_2 v_L^2 + h_3 v_L^3 \tag{2}$$

$$\begin{aligned} &\frac{1}{R_{C\cdot B}} \cdot \sqrt{2}E\sin(\omega t) - \frac{1}{R_{C\cdot B}}\frac{d\lambda}{dt} \\ &\quad + C_{ser}\sqrt{2}\omega E\cos(\omega t) \\ &= (C_{ser} + C_{sh})\frac{d^2\lambda}{dt^2} + (a\lambda + b\lambda^7) \\ &\quad + (h_0 + h_1 v_L + h_2 v_L^2 + h_3 v_L^3) \end{aligned} \tag{3}$$

Table 2: *Summary of protection constraints.*

System Behaviour	C_{series} (nf)	C_{shunt} (nf)	R_1 (MΩ)	R_{core} (MΩ)	R_n (MΩ)	ω (rad/sec)	E (kV)
Subharmonic Ferroresonance I	0.5	3	85	225	25	314	158.7713
Subharmonic frequency ferroresonance	0.1	0.5	85	225	25	314	158.7713
Subharmonic ferroresonance II	0.5	0.19	85	225	25	314	158.7713
Period9 oscillation	3	0.1	85	1900	25	314	158.7713

Table 3: *Parameters value of nonlinear core model [19].*

h_0	-0.000001
h_1	0.0047
h_2	-0.0073
h_3	0.0039

Table 4: *Initial conditions of propose system.*

λ	0	$\dot{\lambda}$	1.4144	$\ddot{\lambda}$	0.5

where, ω is supply frequency, 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. Table (1) shows power system base values used in the analysis and parameters of different states are given in table (2). In this paper various conditions has been simulated and its results are listed in table (2).

3. SYSTEM MODELLING CONNECTING NEUTRAL EARTH RESISTANCE

In this case, the system which was considered for simulation is shown in Fig.2.The value of impedance required for neutral earth connection is easily calculated to a reasonable approximation by dividing the rated phase voltage by the rated phase current of the transformer. Neutral earth impedance 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. Neutral resistance value is given below: $R = 25M\Omega$ The differential equation

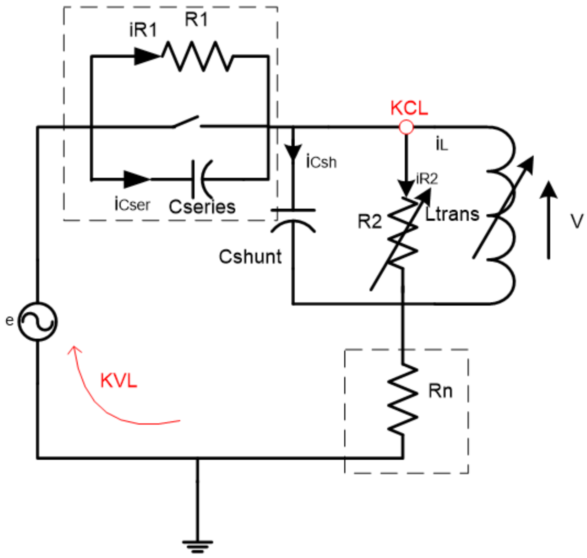

Fig.2: *Basic reduced equivalent ferroresonance circuit considering neutral earth resistance.*

for the circuit in Fig.2 can be presented as follows:

$$\begin{aligned} C_{series}C_{shunt}R_n\frac{d^2V_L}{dt^2} &= \\ C_{series}\sqrt{2}E\omega\cos(\omega t) + \frac{1}{R}\sqrt{2}E\sin(\omega t) - \\ \big(C_{series} + C_{shunt} + C_{series}R_nh_1 \\ +2C_{series}R_nh_2v_L + 3C_{series}R_nh_3v_L^2\big)\frac{dv_L}{dt} \\ -(C_{series}R_na + C_{series}R_nbq\lambda^6)\frac{d\lambda}{dt} \\ -(h_0 + h_1v_L + h_2v_L^2 + h_3v_L^3 + a\lambda + b\lambda^7) \\ -\frac{1}{R_1}\big(v_L + R_nC_{shunt}\frac{dv_L}{dt} + R_nh_0 + R_nh_1v_L \\ +R_nh_2v_L^2 + R_nh_3v_L^3 + R_n(a\lambda + b\lambda^7)\big) \end{aligned} \tag{4}$$

4. BENEFITS OF ANALYZING FOR CHAOS

Important reasons for analyzing a set of data for chaos are: Analyzing data for chaos can help indicate whether haphazard-looking fluctuations actually

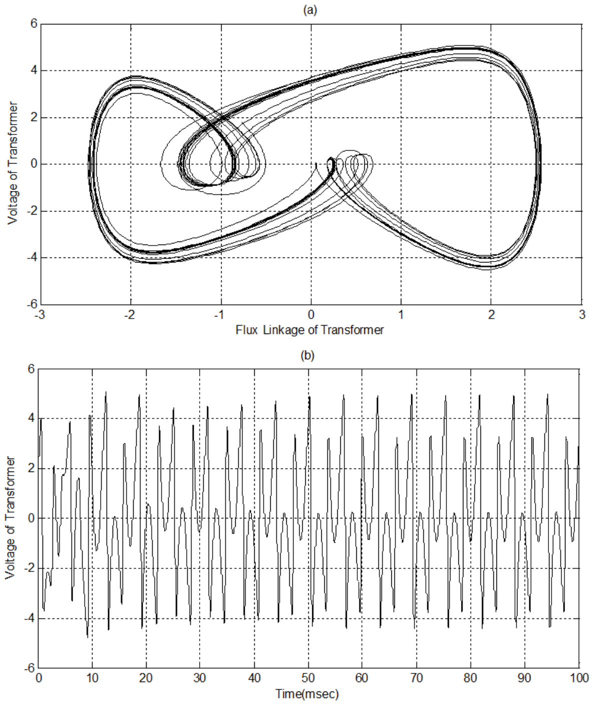

Fig.3: *Subharmonic oscillation without neutral earth resistance and CB effect a)Phase plane diagram b). Time domain simulation.*

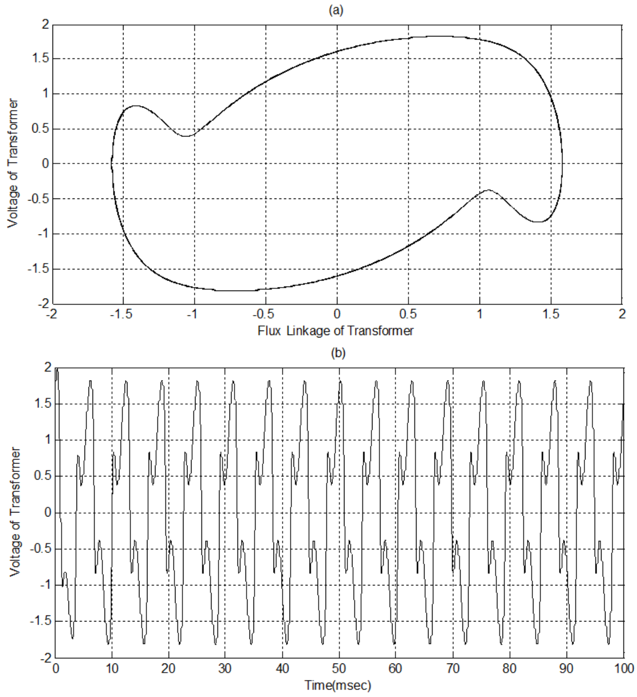

Fig.4: *Fundamental oscillation without neutral earth resistance considering CB effect a) Phase plane diagram b) Time domain simulation.*

represent an orderly system in disguise. If the sequence is chaotic, there's a discoverable law involved, and a promise of greater understanding. Identifying chaos can lead to greater accuracy in short-term predictions. Chaos analysis can reveal the time-limits of reliable predictions and can identify conditions where long term forecasting is largely meaningless. If something is chaotic, knowing when reliable predictability dies out is useful, because predictions for all later times are useless. Recognizing chaos makes modeling easier. A model is a simplified representation of some process or phenomenon. Mathematical or statistical models explain a process in terms of equations or statistics. Analog models simulate a process or system by using one-to-one "analogous" physical quantities of another system. Finally, conceptual models are qualitative sketches or mental images of how a process works [17].

5. SIMULATION RESULTS

Phase space and waveform of voltage for subharmonic oscillation were shown in Figs. 3 (a) and (b). The phase plane diagram clearly shows the closed trajectory characteristic of subharmonic waveform and amplitude of the overvoltages reaches to 5p.u. Figures 4 (a) and (b) show fundamental ferroresonance oscillation. The phase plane diagram again shows the characteristics of a fundamental waveform. Operation in the ferroresonance region is demonstrated by the high amplitude of the transformer voltage waveform, it shows the amplitude decreases and reaches to 1.5p.u, but behavior of the system is not periodic. Voltage waveform and phase plane diagram of quasi-periodic oscillation were shown in Figs. 5 (a) and (b). The resulting waveform will be periodic, but with a period of 40 ms or twice the period of the supply cycle. It is shows by this value of parameters, system can work with quasi-periodic oscillation and amplitude of overvoltage reaches to 0.8p.u in the worst case, this is the safe operation of system. The phase plane diagram clearly shows the closed torus trajectory characteristic of a quasiperiodic waveform. In this case of simulation, effect of neutral earth resistance has been considered on the results, parameter values kept constant with the previous case, but value of neutral earth resistance has been added to table (2). Some other cases for ferroresonance elimination in the case of connecting two limiter circuits (neutral earth resistance and proposed CB) has been studied and its results are listed in table (5).

6. HARMONIC ANALYSIS

For confirmation of proposed model, harmonic analysis has been done. In this section occurrence of ferroresonance and the resulting harmonics in a voltage transformer are simulated. Fundamental ferroresonance oscillation is shown in Fig. 6. This FFT shows existence of harmonics in the system behavior in which 3^{rd} and 5^{th} harmonics are included. Also, as shown here some quasiperiodic oscillations have

Table 5: *Initial conditions of propose system.*

Parameters / System behaviour	R_n ($M\Omega$)	R_1 ($M\Omega$)	ω (rad/sec)
Quasiperiodic oscillation I	25	85	314
Quasiperiodic oscillation II	25	85	314
Quasiperiodic oscillation III	25	85	314
Quasiperiodic oscillation V	25	85	314

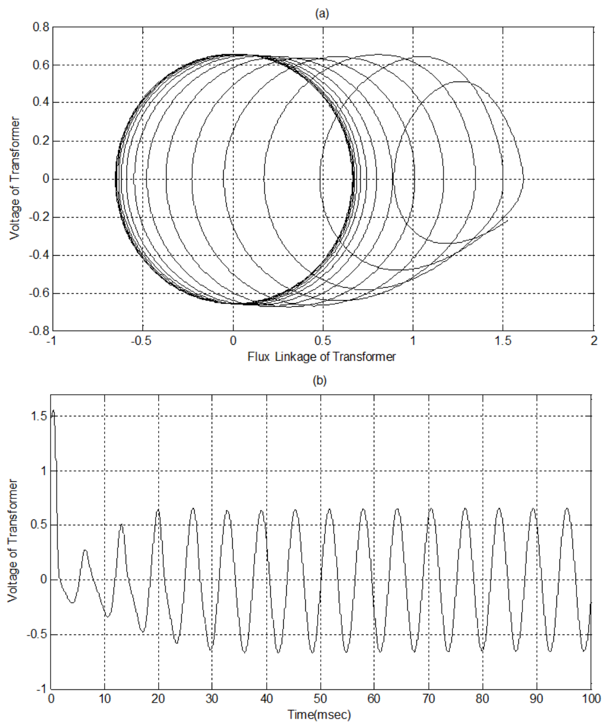

Fig.5: *Quasi-periodic oscillation considering neutral earth resistance and CB effect a) Phase plane diagram b) Time domain simulation.*

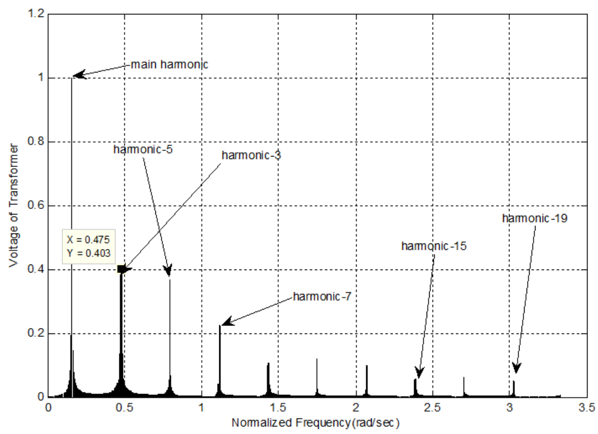

Fig.6: *Single sided amplitude spectrum of voltage on transformer which shows fundamental ferroresonance oscillation.*

occurred in this case which are middle range harmonics. Single sided amplitude spectrum of voltage on the transformer for subharmonic ferroresonance is shown in Fig. 7. The resulting FFT has subharmonic behavior which includes fundamental frequency and harmonic orders of 3, 5, 7 and 9. Also, in this case there are some middle harmonics that are known as quasiperiodic oscillation in the power system. According to the power spectrum density it is seen that magnitude of the subharmonics are relatively high, residing around the main frequency. Ferroresonance oscillation in this case has 4p.u amplitude, which is very dangerous for the power system equipment and may cause voltage transformer failure.

7. CONCLUSION

Chaos occurs only in deterministic, nonlinear, dynamical systems. A dynamical system can evolve in either of two ways. One is on separate, distinct occasions (discrete intervals). The other is continuously. If it changes continuously, we can measure it discretely or continuously. Equations based on discrete observations are called difference equations, whereas those based on continuous observations are called differential equations. In this work it has been shown that system has been greatly affected by neutral resistance. For some parameters value that circuit breaker cannot controlled the ferroresonance overvoltages. Presence of the neutral resistance results in clamping the ferroresonance overvoltages for all parameters value in studied system. The neutral resistance successfully, suppresses or eliminates the chaotic behaviour of proposed model. Consequently, the system shows less sensitivity to initial conditions in the presence of the neutral resistance.

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