Application of PSCAD/EMTDC and Chaos Theory to Power System Ferroresonance Analysis

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Abstract-- Ferroresonance is a nonlinear dynamic electrical phenomenon, which frequently occurs in a power system that comprises no-load saturable transformers, transmission lines (or cables) and single-phase switching with three-phase supply. Common characteristics of a nonlinear system are multiple equilibrium points, limit cycles, jump resonance and subharmonic generation.

This paper presents an extension of PSCAD/EMTDC to analyze ferroresonance in the power system. Field tests were performed on two networks to identify the crucial factors in ferroresonance. EMTDC was then used to simulate the ferroresonance for the same network configurations and parameters. The accuracy of the modeling was verified with the results from the field tests. Analytical methods for nonlinear dynamic systems and MATLAB are used to obtain characteristic curves such as a time-domain waveform, phase-plane, and Poincaré section. Four modes of ferroresonance are shown for four different initial conditions. The brute-force calculation was employed to generate a bifurcation diagram. Sensitivity of resonance to voltage supply and load can be determined from the bifurcation diagram.

The performance of MOV arresters exposed to ferroresonance in pad-mounted transformers is briefly discussed.

Keywords: Ferroresonance, Chaos, Bifurcation diagram, PSCAD/EMTDC

I. INTRODUCTION

THE energization and deenergization by manual single-phase fuse cutout switching operation or by abnormal situation (unbalanced faults) in three-phase distribution systems, consisting of a series/parallel combination of an unloaded or very light loaded transformer with saturation characteristic and capacitor in the form of distribution-line capacitive coupling, present high potential for the occurrence of ferroresonance.

Ferroresonance is a jump resonance, which can suddenly jump from one normal steady-state response (sinusoidal line frequency) to another ferroresonance steady-state response. It is characterized by a high overvoltage and random time duration, which can cause dielectric and thermal problems to the transmission and distribution systems and switchgear.

Due to the nonlinearity of the saturable inductance, ferroresonance possesses many properties associated with a nonlinear system, such as:

1. Several steady-state responses can exist for a given configuration and given set of parameters. The different solutions can occur, depending on the time of switching performed in the circuit (initial conditions). Ferroresonance is highly sensitive to the change of initial conditions and operating conditions.
2. Ferroresonance may exhibit different modes of operation which are not experienced in linear system.
3. The frequency of the voltage and current waveforms may be different from the sinusoidal voltage source.
4. Ferroresonance possesses a jump resonance, whereas the voltage may jump to an abnormally high level.

This type of phenomenon is not predictable by linear theory because the unusual solutions cannot be obtained by linear methods. A more suitable mathematical tool for studying ferroresonance and other nonlinear systems is provided by nonlinear dynamic methods.

II. NONLINEAR DYNAMIC METHODS

Some common behaviors of a nonlinear system are multiple equilibrium points (the point that the system operates without change), limit cycle, jump resonance and subharmonic generation. If the system output is extremely sensitive to initial conditions, this phenomenon is called chaos. Chaos frequently occurs in a highly nonlinear system. For such a system, the change in initial condition causes the system to move into a nonlinear region, which increases the possibility of chaos. Because a nonlinear system has much more complex behaviors, analyzing it is much more difficult. The major analytical tools [1]-[7] that can be used to study a nonlinear system are as follows:

A. Bifurcation diagram

As the operating condition (for example the magnitude of the supply voltage) of a nonlinear system changes, the equilibrium point can change along the number of equilibrium points. The values of these parameters, which start to produce different steady-state conditions, are known as critical or bifurcation values. A bifurcation diagram is a plot that displays single or multiple solutions (bifurcations) as the value of the control parameter is increased.

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B. Phase Plane

The phase plane analysis is a graphical method, in which the time behavior of a system is represented by the movement of a point representing the state variables of the system with time. As time evolves, the initial point follows a trajectory. If a trajectory closes on itself, then the system produces a periodic solution. In the chaotic system, the trajectory will never close to become cycles.

C. Poincaré Section

The phase plane can be displayed as a sequence of discrete points, which are sampling at constant time intervals (i.e. the time period of the supply). The plot of these points is called a Poincaré Section. The Poincaré Section gives information about the ratio of the frequency of the supply to the output response of the system [6]. The Poincaré Section can provide useful information about the ratio of the frequency of the forcing function to the actual frequency of the system. For example, if the period of ferroresonance voltage waveform is 2*20 ms, Poincaré Section shows two points (for 50 Hz supply). If the distance from origin to the point is more than 1 unit for 1 pu. of power supply, it implies overvoltage. Four modes of ferroresonance can be observed from Poincaré Section.

1. Fundamental mode. A Poincaré Section will produce only one point.
2. Subharmonic mode. For n subharmonics or 1/n harmonics output, n points occur on the Poincaré Section.
3. Quasi-periodic mode. A closed curve appears on the Poincaré Section.
4. Chaotic mode. The plot produces completely separated points occupying an area , which is sometimes called the strange attractor in the Poincaré Section.

III. Field Test

Two field tests were carried out in the Provincial Electricity Authority (PEA) distribution network to demonstrate the physical phenomena associated with ferroresonance. The first test was carried out at Phuthamonthon, Nakorn Pathom on 30 October 1999 and the second test was carried out at Sanpatong, Chiang Mai on 29 and 30 March 2000 [8].

A. First Test

The first field test was carried out on a transformer connected with an overhead line as shown in Fig. 1. The switching was performed at a single phase fused cutouts (SW1). The switching events consisted of sequential energization and deenergization at the switching location SW1 (A-B-C and C-B-A, respectively). Three units of gapless metal oxide surge arresters were installed at the primary windings of the transformer. The transformer was a 3-phase type, 160 kVA, 22/0.4 kV, with delta connection in primary winding and wye-ground connection in secondary winding (Dyn11). A capacitor bank of 40 kVAR rating with delta connection (power-factor regulation) was installed at the secondary windings of the transformer. The results of the first field test are listed in Table I.

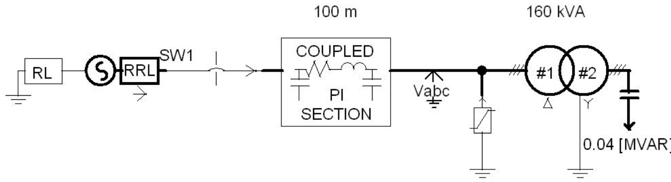

Fig. 1. Single line diagram of first field test

TABLE I
RESULTS OF THE FIRST FIELD TEST

Case	Condition	Arrester	C_{bank}	Max.V_{l-n} (p.u.)	Phase Location
1.1	Energize	Yes	Yes	1.00	C
	De-Energize	Yes	Yes	1.70	C
2.1	Energize	Yes	No	1.00	C
	De-Energize	Yes	No	1.26	B
3.1	Energize	No	Yes	1.00	C
	De-Energize	No	Yes	2.26	C
4.1	Energize	No	No	1.00	C
	De-Energize	No	No	1.37	B

Note: Yes – with specified device; No – without specified device

B. Second Test

The second field test was carried out on a network with four transformers of different sizes, 500 kVA, 100 kVA, and two transformers with the same rating of 50 kVA. All transformer windings were connected in Dyn11 configuration, There was no capacitor bank, and the transformers were operating at no load. The single line diagram is shown in Fig. 2. The switching was performed at the single phase fused cutouts (SW1). The sequences of switching events were the same as in the first field test. The results from the second field test are listed in Table II.

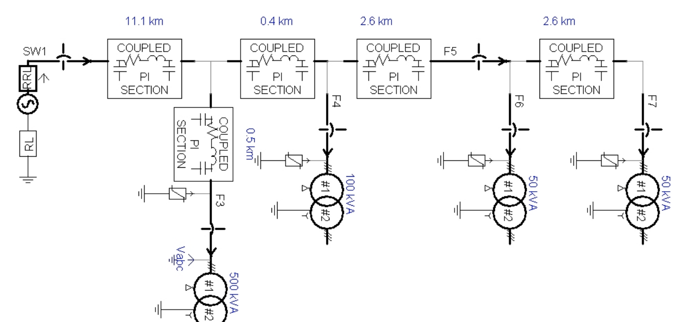

Fig. 2. Single line diagram of second field test.

From both tests, it can be observed that:

1. In the first test, ferroresonance is more likely to occur during deenergization (the maximum voltage is higher than 1.0) rather than during energization. The power-factor regulation capacitor has very little effect on ferroresonance due to already existing coupling capacitors of the lines.

2. In the second test, ferroresonance occurs at nearly all cases. This is perhaps due to the increasing number of units of saturable transformers, which would increase the nonlinearity of the system

TABLE II
RESULTS OF THE SECOND FIELD TEST

Case	Trans. Size (kVA)	Condition	Max.V_{l-n} (p.u.)	Phase Location	Note
2.1	500	Energize	1.0	B,C	--
		De-Energize	2.1	C	Hum
2.2	100	Energize	2.22	C	Hum
		De-Energize	2.2	B,C	Hum
2.3	50	Energize	1	B,C	--
		De-Energize	2.11	B,C	Hum
2.4	500 and 100	Energize	2.2	B,C	Hum
		De-Energize	2.2	B,C	Hum
2.5	500, 100, 50 and 50	Energize	2.1	B,C	Hum
		De-Energize	2.2	B,C	Hum

Note: Hum – audible noise from transformer

IV. EMTDC MODEL VERIFICATION

EMTDC simulation tool can simulate the time response of the transient phenomena in the power system with a very high degree of accuracy. In the simulation of ferroresonance, the model of the saturation characteristic of the transformer is very important. Two models of three phase transformer are offered by the EMTDC program. The first model, which includes the magnetic and capacitive coupling effect requires a lot more information on the construction of the transformer. This model must be used if the accuracy of the transient state is required. The second model is based on three single-phase transformers, which include the saturation effect but does not include coupling inductances between the windings. This model compromises the accuracy of the transient simulation with the ease of calculation and less information on transformers is required. In this study, the second model is used which may be a disadvantage in the transient simulation but should not affect the steady state solutions very much. The steady state solutions are used for the nonlinear dynamic methods.

In order to verify the accuracy of EMTDC, many simulations were carried out for the same conditions associated with the field tests reported in Table I and Table II. One case simulated, with the circuit in Fig. 1 and operating condition of case 1.1 of Table I, is shown in Fig. 3. The recorded voltage waveforms of the same event are shown in Fig. 4. It can be observed that even though the simplified model (three single phase transformers) was used in the simulation, the steady state results were good enough for further study. The steady state magnitudes of the voltage in phase C determined by measurement was 1.7 pu. The simulated waveform of phase C also approaches the magnitude of 1.7 pu. in the steady state. Notable discrepancies between recorded waveforms and simulated waveforms can be clearly seen during the transient.

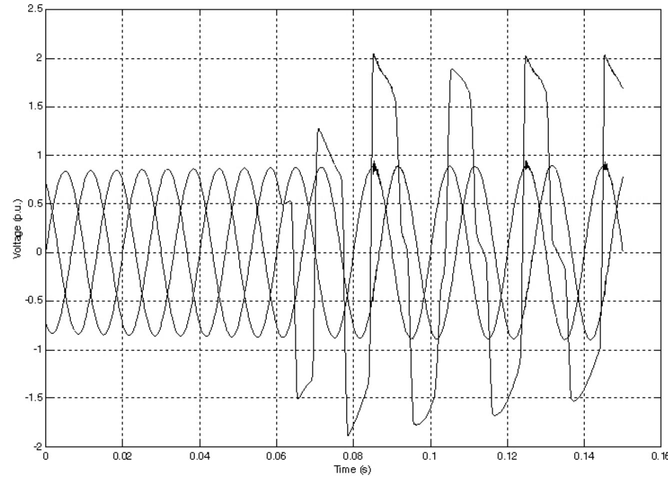

Fig. 3. PSCAD/EMTDC simulations of Case 1.1 (deenergization)

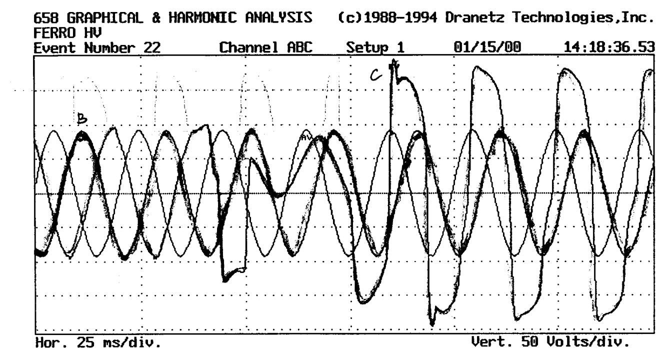

Fig. 4. Recorded voltage waveforms of Case 1.1 in the first field test (deenergization)

V. FOUR MODES OF FERRORESONANCE

The study on the sensitivity of the nonlinear power system due to initial conditions was made by simulation on the network with four transformers (Fig. 2). The condition of Case 2.5 in the Table II was chosen. By carefully choosing the switching angles of the voltage at the deenergization instant, four modes of ferroresonance can be obtained for the same configuration [9]. The time step of 10 microseconds and Poincaré Section of 50 Hz were used in the simulations. The results are shown in the form of time-domain waveform in A, Phase Plane in B, and Poincaré Section in C.

A. Fundamental Ferroresonance

At the deenergization angle of 36 degrees and without the connection of arresters, the fundamental mode of ferroresonance occurred. This can be seen in Fig. 5 as a single-frequency-distorted waveform in the time domain, together with the closed-cycle trajectory in the phase plane. Only one point appears on the Poincaré Section for this mode.

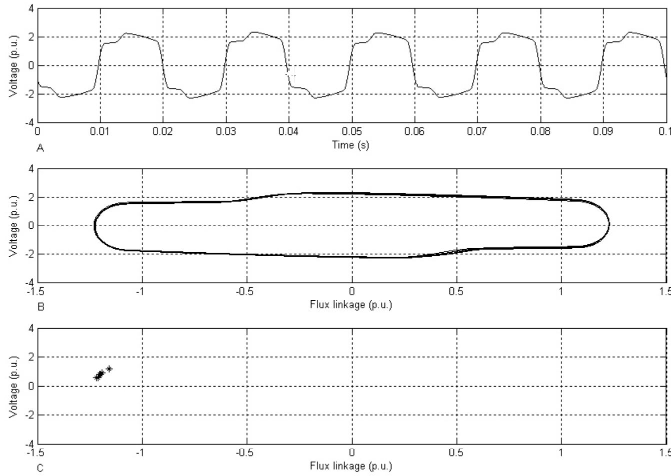

Fig. 5. Fundamental ferroresonance corresponding to case 2.5 for deenergization at 36 degrees without arrester

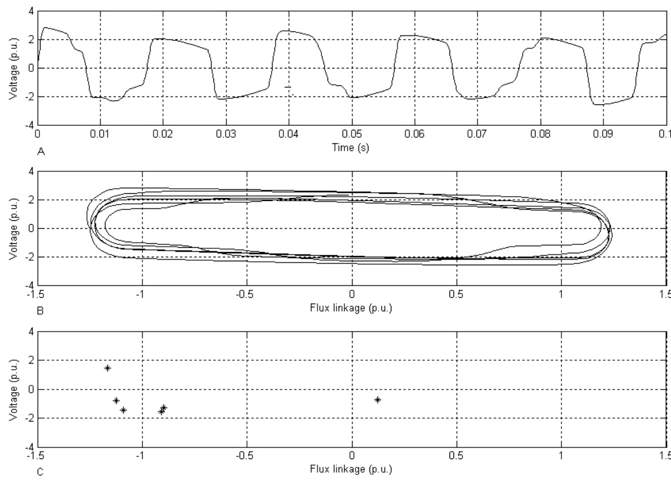

Fig. 6. Subharmonic ferroresonance corresponding to case 2.5 for deenergization at 52 degrees without arrester.

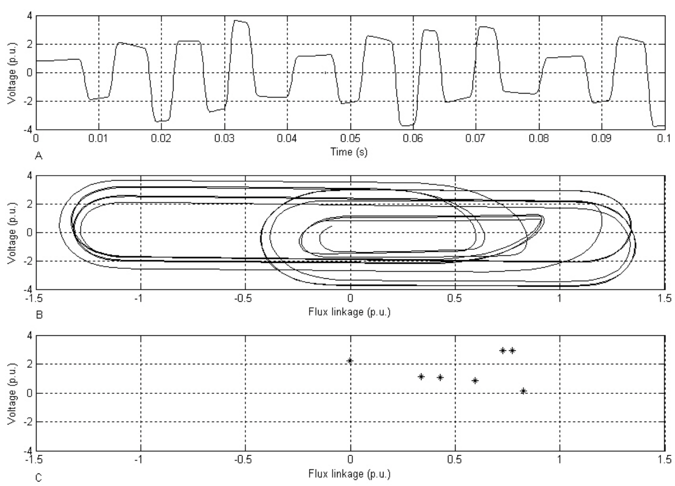

Fig. 7. Quasiperiodic ferroresonance corresponding to case 2.5 for deenergization at 178 degrees without arrester.

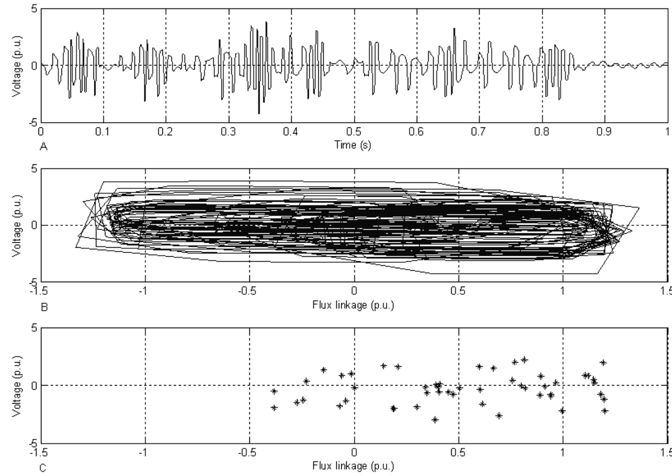

Fig. 8. Chaotic ferroresonance corresponding to case 2.5 by deenergization at 150 degrees without arrester.

B. Subharmonic Ferroresonance

If the switching angle was changed from 36 degrees to 52 degrees, the ferroresonance changed from fundamental mode to subharmonic mode. The results in Fig. 6 show a periodic time domain waveform with a period nT where T is the period of the voltage source. The phase plane plot is a closed trajectory with varying sizes in Fig. 6B. The Poincaré Section in Fig. 6C shows subharmonic ferroresonance with six points.

C. Quasi-periodic Ferroresonance

When the switching instant was changed to 178 degrees, the ferroresonance changed to quasi-periodic mode. Fig. 7A shows a non-periodic time domain waveform, and the phase plane in Fig 7B is in the form of changing cycles. The Poincaré Section should appear as a closed curve, but due to low number of samples the closed curve did not form here. This mode of ferroresonance is conditionally stable. As the time evolves, it will change to another mode which is either fundamental or chaotic mode.

D. Chaotic Ferroresonance

The switching instant of 150 degrees produced chaotic mode of ferroresonance. The time domain waveform in Fig. 8A shows an irregular and unpredictable time behaviour. The phase plane in Fig. 8B is in the form of a trajectory that never closes on itself. The Poincaré Section in Fig. 8C reveals a random set of points confined to a particular region.

VI. Bifurcation Diagram

The sensitivity of the power system with saturable transformer to voltage levels and loads was investigated by a bifurcation diagram. The study was made on the circuit with four transformers as shown in Fig. 2. The magnitude of the source voltage and load of the transformers were assigned as bifurcation parameters.

The steady-state responses were calculated by brute-force method, in which several (five to eight) thousand time-domain simulations were made [10].The initial conditions of the worst case for deenergization were applied to all simulations. Bifurcation diagrams were plotted with the MATLAB software and corresponding data files, which were recorded with the PSCAD.

A. Bifurcation with changing source voltage

Fig. 9 shows the bifurcation diagram for different values of voltage source in the absence of the arrester. The regions, with many scattered points appearing for the same value of voltage, indicate the chaotic mode of ferroresonance. These regions are between the source voltage of 0.7 - 0.8 pu and more than 0.85 pu. The tendency of chaos increases with higher magnitude of voltage source. The overvoltage can be as high as 3 to 4 pu., for the source voltage between 0.9 and 1.0 pu. Between the source voltages of 0.80 and 0.85 pu., only one solution occurred for one value of source voltage. This indicates the constant amplitude bus voltage without ferroresonance.

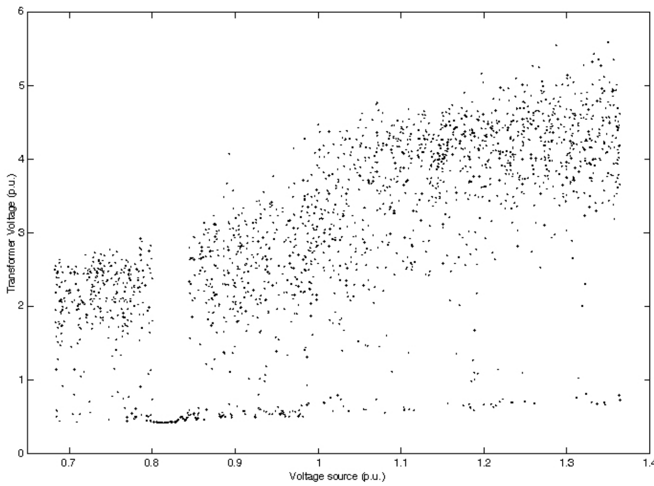

Fig. 9. Bifurcation diagram with changing source voltage in the absence of the arrester

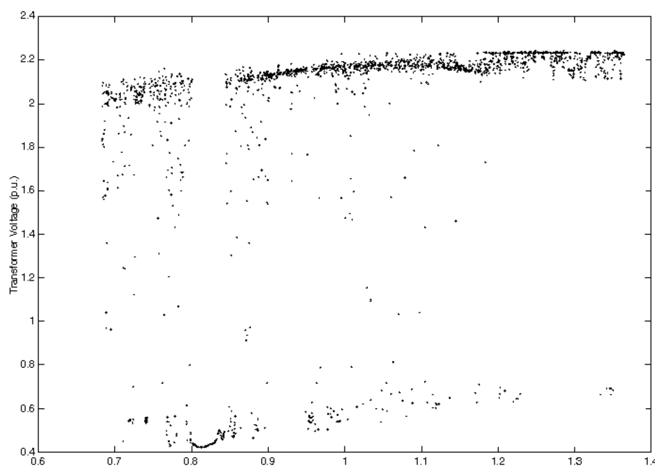

Fig. 10. Bifurcation diagram with chnaging source voltage in the presence of the arrester

The bifurcation diagram for the same conditions of Fig. 9, but with the presence of the arrester is shown in Fig. 10. The tendency for ferroresonance was the same as in Fig. 9, but the overvoltages were clamped at 2.2 pu. by the arrester. In the simulation, the mode of ferroresonance which frequently occurs, is chaotic ferroresonance. The chaotic mode combines the characteristics of various modes of ferroresonance.

B. Bifurcation with chnaging load of transformer

The sensitivity of the system to load is shown by the bifurcation diagram in Fig. 11. The initial conditions were the same as in the Fig. 9, with the circuit configuration in Fig. 2. The loads of different percentages of the rating of each transformer were added to the transformer. The chaotic ferroresonance can be seen at no load and light load from the areas with scattering points of different transformer voltages. The overvoltages can be as high as 2.5 to 3.5 pu. No ferroresonance can be seen if the transformer was loaded more than 5 % of its rating.

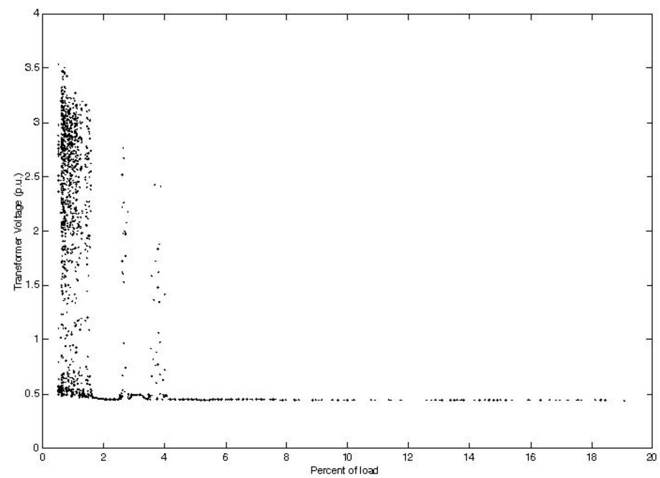

Fig. 11. Bifurcation diagram with changing load of transformer

VII. Arrester Damage

When ferroresonance occurs in the lines, the overvoltage will be clamped by the arrester and the current will flow through the arrester. The heat caused by this current has to be transferred from the arrester to the environment. If the rate of heat dissipation is less than the rate of heat production, the temperature of the arrester will rise continuously. If the temperature rises above the temperature limit, the arresrter will be permanently damaged. The damage can be seen as cracks in the MOV at the middle part of the arrester. This is because heat dissipation at the middle part of the arrester is less effective than at the two end parts of the arrester.

In some cases of ferroresonance, the damage does not occur but the current-voltage characteristic of the MOV will change. This defective MOV will lose its ability to block the current at the operating voltage level. Therefore when the energization is completed and ferroresonance disappears, large current will flow through the defective arrester which can cause rapid overheating. Melting of the metal terminals, arc and explosion will follow.

Therefore, if the lightning arresters at some points are damaged during single phase switching operation, it is safe to assume that ferroresonance occurs during switching. However, if the single phase switching operation is completed without any incidents but the arresters damage at few seconds later. It is very likely that the arresters are defective (from the ferroresonace during switching) and are destroyed by large current at the operating voltage level.

VIII. Conclusions

The commercial time domain simulation packages (PSCAD/EMTDC) are modified to generate phase plane and Poincaré Section to explain different modes of ferroresonance according to nonlinear dynamic methods. The brute-force calculation based on time-domain simulation is used to generate bifurcation diagram. The bifurcation diagram is used to display different ferroresonance states as a function of different parameters. However, the number of calculations of such a diagram is extensive and long computation time is required.

The results of this study confirm that the ferroresonance phenomenon is very sensitive to initial conditions and operating conditions. This extremely nonlinear system possesses chaotic behavior. Hence, it is very hard to determine the ranges of the parameters which ferroresonance will occur. The application of commercial time-domain simulation packages (PSCAD/EMTDC) has many advantages over the conventional mathematical analytic methods, in terms of:

1. There being no need to develop a complex nonlinear differential equation for the system;
2. The ferroresonance being easily modeled with modules of lines, transformers, loads and protection equipment from the library;
3. Despite brute force calculation having to be used to generate a bifurcation diagram, the process is not cumbersome;
4. Nonlinear dynamics methods for system analysis being applied.

The results from field tests confirm that during single phase energization or deenergization, where one (two) phase(s) of the unloaded ferroresonance was disconnected, and one (two) phase was left connected to the power source, a sustained overvoltage can be generated due to ferroresonance. Therefore, it is recommended to avoid this type of operation. In addition, ferroresonance overvoltage suppression by an arrester at the transformer terminal is also recommended.

IX. Appendix

Parameters of the transformer: 22/0.4 kV 50 Hz, Dyn1 [8]

Tran. rated power (kVA)	50	100	160	500
Leakage reactance (p.u.)	0.0425	0.0415	0.0425	0.0679
No load loss (p.u.)	0.0029	0.0025	0.0019	0.00134
Air core reactance (p.u.)	0.08066	0.08002	0.085	0.2888
Knee voltage (p.u.)	1.1613	1.1503	1.1491	1.0161

X. Acknowledgment

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XI. References

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XII. Biographies

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