CHAPTER 1

INTRODUCTION

1.1 GENERAL

Ferroresonance phenomenon was observed early in the evolution of power systems, and has been extensively studied since the early 1920s (Philippe Ferracci 1998). It is a nonlinear phenomenon and is not well understood. A lightly loaded power transformer excited by a source through a cable is a potential configuration for ferroresonance. It is a result of energy transfer between magnetising impedance of open phase(s) of the transformer and the cable capacitance. It can also occur in a transformer subjected to normal switching such as de-energisation by opening of associated circuit breaker fitted with grading capacitors.

Ferroresonance is characterised by overvoltages and overcurrents at frequencies that are equal to or different from that of the exciting source. It is often neglected in the routine power system studies carried out for design, planning and operation. The likelihood of occurrence of ferroresonance is expected to increase due to: (i) widespread use of amorphous metal as magnetic core of distribution transformer (ii) the environmental restriction in transmission and distribution expansion which forces the utilities to modify the existing configuration. Catastrophic equipment failures that continue to occur have stimulated renewed interest in the subject.

The distinctive features of this phenomenon are:

- possibility of more than one type of stable and unstable operating point for the same set of parameters. The steady state response may be fundamental, quasi-periodic, period 2^n (subharmonic, n = 1, 2, 3, 4…), period m (*isolated* subharmonic, m = 3, 5, 7, 9…) and chaotic (non-periodic).

- abrupt transition or jump from normal steady state to a new state with severe harmonic distortion that can result in equipment damage. This jump can be triggered by a disturbance, a switching action or a gradual change in the values of parameters.

Ferroresonant circuits can be described by a system of non-autonomous first order nonlinear differential-algebraic equations. Several experimental investigations have been carried out to understand this phenomenon. Among the early analytical methods is the harmonic balance and describing function methods. It consists of assumed approximate solutions and working backwards to see if the solution satisfies the basic equations. It is therefore possible to predict ferroresonance without ever considering the process that engenders it. The harmonic balance method is based on some restrictive assumptions, such as, the sinusoidal time-variation of the flux-linkages or the validity of the truncated Fourier series that describes each state variable.

An alternate approach to study this phenomenon is by using the deterministic tools of chaos such as Poincaré map, phase plane and bifurcation diagrams. The theory of nonlinear and chaotic dynamics has been applied to several areas of power systems. Abed and Varaiya (1984) are the first to spot subcritical Hopf bifurcation on a voltage stability model of a single machine infinite busbar power system. Tan et al (1995) investigated the relationship of chaos and voltage collapse conditions. Mamishev et al (1996) used the concepts of fractal geometry to analyse chaotic properties of high impedance faults. The use of chaotic dynamics to describe the operation of nonlinear load such as arc furnace has been presented by O'neill-Carrillo et al (1999).

The recognition that ferroresonance is a nonlinear and some times chaotic process attracted many investigators. The qualitative change in solutions of a dynamical system upon a small variation in the system parameters is referred to as bifurcation. The simplest method to detect bifurcation is by plotting the solution for a state variable as a function of the parameter. This is referred to as bifurcation diagram. The locations at which a qualitative change occurs are referred to as bifurcation points. Successive bifurcations can lead to chaos. Chaotic ferroresonance analysis requires time domain simulation with dynamic representation of power system components. The phase plane projection, Poincaré section, basin of attraction and bifurcation diagram have to be generated by time domain simulation over a specific time span. These tools make it possible to predict which parameter values are critical in a given configuration and to allow for a safety margin in order to operate the system without risk. The modelling of nonlinearities is essential in ferroresonance analysis.

1.2 LITERATURE REVIEW

Many interesting investigations on the occurrence of ferroresonance have been reported in the literature. Notable among them is the investigation by performing tests.

Dolan et al (1972) described the field test on an actual ferroresonance case. Fundamental and subharmonic ferroresonance were observed in a transformer-terminated line due to an energised parallel line on the same right-of-way. Recommendations for preventing or damping ferroresonance were also described.

A full scale laboratory test has been carried out by Guuinic and Janssens (1983) to investigate the ferroresonant oscillations of a circuit composed of three single phase voltage transformers connected to an ungrounded source with a zero sequence capacitance. The sensitivity of the circuit with respect to the core loss has also been presented. The core loss has been modelled by a constant resistance.

Walling et al (1993) described the results of an extensive test designed to identify the influence of core losses and transformer winding capacitance on ferroresonance. It was shown that core loss and distributed winding capacitance can play a significant role in determining the ferroresonance susceptibility of a transformer.

An approach to determine the susceptibility of ferroresonance condition in a voltage transformer was developed by Andrei and Halley (1989). The approach was based on the energy transferred from the system to the voltage transformer during the switching transient.

In what follows is the literature review based on solution methodologies and analysis of modes of ferroresonance.

1.2.1 Review based on solution methodologies

The analysis of ferroresonance can be classified into two main groups. The first group employs approximate analytical methods and the second group relies on nonlinear dynamic tools.

The early attempts to investigate ferroresonant behaviour were based on approximate methods such as harmonic balance method and describing function method. The harmonic balance method has been applied by Hayashi (1964), Santesmases et al (1970), Makhlad and Fahmy (1980), Aggarwal et al (1981), Akpinar and Nasar (1990), Marti and Soudack (1991), Janssens et al (1996), Jacobson and Menzies (2001). Ferroresonance analysis based on describing function method has been reported in Swift (1969), Makhlad and Zaky (1976), Prusty and Sanyal (1977, 1979) Prusty and Panda (1984), Saied et al (1984). In the above investigations, the core loss has been modelled as constant linear resistance and the chaotic ferroresonance has not been addressed.

The recently developed techniques for analysis of nonlinear dynamical systems and chaos have been applied successfully to ferroresonance problem by many investigators.

Kieny (1991) first suggested application of bifurcation theory to the study of ferroresonance in electric power circuits. Ferroresonance phenomenon observed on a 400 kV French power system was analysed by constructing a bifurcation diagram. It revealed the existence of Hopf bifurcation. However, the chaotic aspect of ferroresonance was not addressed.

A technique has been developed by Kieny et al (1991a) to enhance Galerkin method for studying ferroresonance phenomenon. The technique is based on the pseudo-arclength continuation method.

Araujo et al (1993) studied a ferroresonant case, which occurred when one supply conductor of an unloaded power transformer was being interrupted. The resulting circuit was described as a damped forced nonlinear oscillator. Poincaré maps and phase plots were generated, for visualising chaotic behavior, for some values of the parameter.

Mork and Stuehm (1994) proposed a simplified method of descriptively categorising periodic and chaotic modes of ferroresonance. EMTP simulations were used to generate the bifurcation diagrams, which showed different modes of ferroresonance. Poincaré sections of measured chaotic voltage waveforms were also presented.

Mozaffari et al (1995) investigated the impact of different magnetisation characteristics on the behaviour of a transformer when it is being driven into ferroresonance. Bifurcation diagrams were generated from time domain simulations by using fourth order Runge-Kutta method.

A methodical approach for identifying all possible initial conditions and consequently, the different types of oscillations that can occur in a series ferroresonant circuit has been presented by Chakravarthy and Nayar (1995). The approach presented is based on obtaining the integral form of the system equations, which describe the ferroresonant circuit and is limited to series resonant circuits. The core loss was modelled as a constant resistance.

Chakravarthy and Nayar (1995a) studied the conditions for the occurrence of quasi-periodic oscillations in a parallel ferroresonant circuit by using both analytical and numerical methods.

An attempt to examine the ferroresonant behaviour of a nonlinear power system circuit using the diagnostic tools of deterministic chaos has been carried out by Bodger et al (1996). The digital electromagnetic transients simulation program (EMTDC) was used to model the system.

Emin et al (1997) presented the study of voltage transformer ferroresonance. The analysis presented is based on nonlinear dynamics. It was shown that the fundamental frequency and subharmonic ferroresonance could occur under normal conditions.

Mozaffari et al (1997) demonstrated the effect of initial conditions on the chaotic behaviour of ferroresonance. The basin of attraction was generated for different conditions. The core loss was represented by a constant resistance.

A Newton-Raphson scheme to determine the several steady state solutions of a typical ferroresonant circuit has been presented by Naidu and Souza (1997, 1997a). The results have been verified with a hybrid technique.

Al Zahawi et al (1998) investigated the damping effects of core losses upon the ferroresonant behaviour of a voltage transformer using nonlinear dynamical methods.

Mork (1999) developed a lumped parameter model for a five-legged wound-core distribution transformer by using duality transformations. The core saturation, losses and coil capacitances have been included in the model. The model was implemented in EMTP to study a ferroresonance case. The conventional bifurcation diagram was generated for which the capacitance was considered as the bifurcation parameter.

A general modelling approach for ferroresonance analysis has been presented by Iravani et al (2000). Ferroresonance in three phase grounded-wye distribution system was described and the importance of accurate modelling of transformer's nonlinearities was emphasized.

Ben-Tal et al (2001) demonstrated a route to banded chaos in an actual power system equipped with a voltage transformer. It was found that banded chaos arises from a sequence of period doubling bifurcations. The core loss was represented by a constant resistance.

1.2.2 Review based on analysis of modes of ferroresonance

Steady state response of a ferroresonant circuit can be one of the following types: fundamental, subharmonic, quasi-periodic or chaotic. Many investigators report the occurrence and analysis of different modes of ferroresonance.

Fundamental mode

Methods based on theory of bifurcation and chaos are more general and suitable for analysing ferroresonance. Kieny (1991) analysed the fundamental mode of ferroresonance in power systems and produced a bifurcation diagram indicating stable and unstable area of operation. The bifurcation diagram was obtained by pseudo-arclength based continuation technique.

In Naidu et al (1997,1997a) fundamental mode of ferroresonance has been obtained using a time domain Newton-Raphson procedure. The results have been verified with a hybrid technique. The bifurcation diagrams were generated by a continuation procedure.

Al-Anbarri et al (2001) analysed the fundamental mode of ferroresonance in a MOV connected transformer. The analysis presented is based on nonlinear dynamics. The bifurcation diagrams were generated by local parameterisation based continuation technique.

In all the above investigations, solutions hidden in the unstable segments were not explored. The subharmonics produced due to period doubling bifurcations, their range and stability were not investigated.

Subharmonic mode

The subharmonic solutions can be classified in to two groups. The first is due to period doubling bifurcations. It is denoted as period 2^n solution, where n = 1, 2, ... As n approaches ∞, the resultant response is chaotic. The period doubling route to chaos is illustrated in Fig.1.1a.

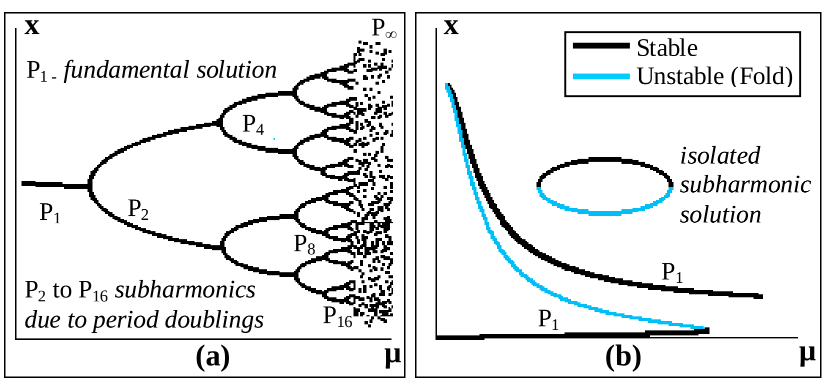

Fig.1.1 Bifurcation diagrams.
(a) Illustration of period doubling route to chaos.
(b) Illustration of isolated subharmonic solution.

The range and stability of subharmonics, due to period doubling bifurcations, are not reported in early literature. In this thesis the continuation algorithm based on local parameterisation is used to trace the subharmonics. The stability of subharmonic solutions is obtained by computing Floquet multipliers.

The second type of subharmonic mode is *isolated* subharmonic solutions, Fig.1.1b. They do not occur as a natural evolution following period doubling bifurcation. Isolated subharmonic mode of ferroresonance has been reported by Kieny (1991, 1991a), Naidu (1997, 1997a), Philippe Ferracci (1998) and Ben-Tal (2001). Kiney (1991a) analysed the continuum of 1/3 subharmonic and Naidu (1997a) investigated the continuum of 1/2 and 1/3 subharmonic solutions. The amplitude of source voltage was considered as the bifurcation parameter. In these investigations, the evolution of subharmonic solutions is not explored. Ben-Tal et al (2001) presented the continuum of subharmonics limited to period 2, period 3 and period 5 in a voltage transformer circuit equipped with a damping reactor. The resistance of the damping reactor was taken as a bifurcation parameter. This investigation did not address the higher order subharmonics, their continua and their evolution to chaos.

Existence, continuation and multiplicity of higher order isolated subharmonics form part of the investigations reported in this thesis. It is to be noted that Philippe Ferracci (1998) was the first one to use the terminology “isolated subharmonic solution”, even though earlier investigations fall under this category.

Quasi-periodic mode

Araujo et al (1993) and Chakravarthy et al (1998) presented the time domain simulation of quasi-periodic oscillations. It was pointed out that the possibility of quasi-periodic oscillation is more when the transformer core loss is negligible. The continuum of quasi-periodic solution and its evolution to chaos are not addressed by the investigators.

Chaotic mode

Chaotic mode of ferroresonance has been reported by Mork et al (1994), Mozaffari et al (1995), Bodger (1996), Al-Zahawi (1998) and Al-Anbarri (2002). They analysed the chaotic behaviour using bifurcation diagram based on time domain simulation, which also provided the range of chaotic solutions.

In this thesis analyses of chaotic solutions and evolution of quasi-periodic solutions are presented.

1.3 OBJECTIVE OF THE THESIS

The limitations of the investigations carried out hitherto as presented in the previous section can be summarised as follows:

- The bifurcation diagrams generated using time domain simulation are deficient for the following reasons:
    - It is difficult to unearth the multiple modes of operation and information about their stability.
    - It is difficult to distinguish between some types of solution, e.g. between period 1 and quasi-periodic.
    - Extended period of integration is needed for lightly damped system.
- The bifurcation diagrams generated using continuation technique are deficient for the following reasons:

  - It does not provide any information about non-periodic solutions and their range.
  - The nature of the solution sequence in an unstable flip segment cannot be identified.
- The state-of-the-art industry standard software for power system transients like EMTP (Dommel 1996) does not give any insight into ***all*** possible steady state solutions.
- The evolution of quasi-periodic oscillation to chaos and crisis induced intermittency have not been explored.
- Analysis of higher order isolated subharmonic solutions and their evolution to chaos have not been addressed.
- The sensitivity of isolated subharmonics with respect to system and arrester parameters has not been reported.
- The likelihood of subharmonic ferroresonance induced due to an energised parallel line in the same right-of-way has not been explored.

In this thesis, an approach that combines the advantages of conventional time domain and continuation approaches is adopted. It is referred to as “hybrid” approach.

Here, the bifurcation diagram generated by time domain simulation is referred to as conventional bifurcation diagram. The bifurcation diagram generated by continuation technique is referred to as bifurcation diagram of steady state period 1 / period m / period 2^n solution. The bifurcation diagram based on unification of both the approaches is referred to as hybrid bifurcation diagram.

The major objectives of the thesis are to analyse:

- The subharmonic mode of ferroresonance due to period doubling bifurcations.
- The evolution of quasi-periodic oscillation to chaos and crisis induced intermittency.
- The higher order isolated subharmonics and their relation to chaos.
- The effect of circuit parameters on the isolated subharmonic behaviour of a ferroresonant circuit.
- The existence of isolated subharmonic solutions in practical systems and impact of system parameters such as line length and core loss.
- The mitigative effect exhibited by some power system components like MOV arresters.

Formulation of the state equations that describe the dynamics of ferroresonant circuits is based on a topological approach (Chua and Lin 1975), which ensures non redundancy in the choice of state variables.

1.4 ORGANISATION OF THE THESIS

The thesis is organised into eight chapters including this chapter. In what follows the summary of each chapter highlighting the contribution of the author, investigations undertaken, significant results and conclusions, wherever applicable is presented.

Chapter 2 begins with the brief description of the existing tools for analysis of dynamic behaviour of nonlinear systems. It also presents the mathematical background and computational procedure for phase plane, Poincaré map, Lyapunov exponent, time domain plot and conventional bifurcation diagram. The topological technique used for deriving non redundant set of state equations and an algorithm to develop bifurcation diagram of steady state (period 1 / period m / period 2^n) solution are also presented in this chapter.

Chapter 3 describes investigations carried out to assess the subharmonic (period 2^n) ferroresonance behaviour. The associated period 2^n solutions are hidden in the flip segments in the continuum of period 1 solutions. A hybrid approach, which is the combination of conventional time domain and continuation techniques, is adopted for clear visualisation and understanding of bifurcation and chaos that occur en route. The systems under investigation include a simple illustrative system and a practical 1100 kV system of Bonneville Power Administration, U.S.A. The linear and nonlinear core loss models are adopted and results compared. The equivalent circuit of the systems are described by a set of nonlinear algebraic-differential equations in state space.

In Chapter 4, analysis of quasi-period oscillations that occur in the two phase open configuration is presented. The evolution of quasi-periodic oscillation to chaos and crisis induced intermittency is also presented here. To the author’s knowledge crisis induced intermittency in ferroresonance problems has not been reported in the literature so far. However, it has been reported in other areas such as quantum mechanics (Becker et al 1999). The hybrid approach is used for the analysis. Initially period 1 unstable solution segments are obtained by the continuation approach. These are further examined for period doubling, quasi-periodicity and intermittency by the conventional time domain approach. The different frequencies involved in a 2-torus quasi-periodic oscillation are identified using Fourier analysis. The equivalent circuit of the system is described by a set of differential equations, which are derived using the topological approach.

Chapter 5 is concerned with the isolated subharmonic ferroresonant solution. They do not occur as a natural evolution following period doubling bifurcation. The investigations related to subharmonics due to period doubling bifurcations have already been reported in Chapter 3. Detection of isolated subharmonic solutions requires computation of appropriate initial conditions. In this chapter, the initial conditions are obtained by a class of temporal methods and it is referred to, here, as “temporal bifurcation diagram” approach. The temporal bifurcation diagram has not been applied by the earlier researchers. This method is related to Poincare` map fixed point method. Starting with initial conditions provided by temporal bifurcation diagram, a continuation procedure predicts multiple subharmonic solutions. The hybrid approach is used for unearthing the solutions hidden in unstable flip segments in the period m continuation path. Typical single phase open configuration is considered for analysis.

The analysis of isolated subharmonic solutions in practical systems is presented in Chapter 6. Two reported cases of ferroresonance involving the network of Bonneville Power Administration (BPA), U.S.A., are considered for analysis. The system corresponding to the first case is same as the one described in Chapter 3. The second case involves the 525 kV transmission system of BPA between Big Eddy and John Day stations (Dolan et al 1972) where ferroresonance was sustained by the energised parallel line. The impact of system parameters such as line length and transformer core loss on isolated subharmonic solutions is also presented in this chapter. The temporal bifurcation diagram and bifurcation diagram of period m solution are used for the analysis. The deterministic tools of chaos such as time domain plots, phase plots and Poincaré maps are also used for the analysis.

Chapter 7 presents the effect of metal oxide arrester and system parameters such as transformer saturation, core loss and source capacitance on the isolated subharmonic behaviour of a transformer. The single phase open configuration in parallel with arrester is considered for analysis. Analysis reveals the occurrence of higher order banded chaotic solutions, namely, 9-band, 11-band and 21-band. Time domain simulation has been carried out using fourth order Runge-Kutta method and results corroborated using MicroTran. Phase plots, conventional and evolving Poincaré maps are used to identify periodic and chaotic motions.

In Chapter 8, the significant contributions of this thesis are presented. The scope for further work in this area is discussed.