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Ferroresonance: An Insight into the Phenomenon

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Abstract — *This paper highlights the importance of ferroresonance awareness and a consolidated review on the research conducted on ferroresonance to highlight its initiation, various conditions giving rise to its occurrence, and impact and suppression techniques. Nowadays, with the increasing complexity of power systems, the occurrence of ferroresonance has become relatively more frequent, which can cause subsequent catastrophic damage to electrical equipment affecting the reliability of power networks. This significant evolution of the electrical networks has led the phenomenon to a more complex analysis. Due to its complex non-linear dynamic behavior, it is also sometimes called "fuzzy-resonance". Despite the extensive available literature on this phenomenon, ferroresonance prediction and behavior characterization still remain widely unknown. This lack of knowledge makes it a probable culprit responsible for the unexplained destruction and malfunctioning of equipment. This paper aims to provide an insight into this phenomenon.*

Keywords- *Ferroresonance, Non-linear Dynamics, Over-currents, Over-voltages, Power Quality, Transformer Core.*

I. INTRODUCTION

The power community recognizes that any disturbance in the fundamental power frequency waveforms of voltage and current will pose a danger to the electricity utility's operation. As such, these disturbances have been commonly described as power quality problems with the following definition: 'Any power problem manifested in voltage, current or frequency deviations that result in failure or maloperation of customer equipment'. The main power quality problems include voltage sag, voltage swell, transients and harmonic distortions [1].

Transient events generally occur due to switching actions in the system and also depend on system parameters like resistance, inductance and capacitance of transmission line, transformer load condition, capacitive and inductive shunt reactors. Due to these parameters and eventually the stacking of various capacitive and inductive components into the system, the frequency range of transient phenomena can vary from DC to several MHz [2].

Ferroresonance is one such transient phenomenon studied by power system engineers. The awareness and knowledge on ferroresonance incidences in electrical power system is relatively low, and they are commonly regarded as an unexplained phenomenon. The phenomenon has been recognized and investigated in numerous technical literatures as early as the beginning of the twentieth century. First work on ferroresonance dates back to 1907, when Joseph Bethenod described it as transformer resonance phenomenon. During that time, the word 'ferroresonance' had not been coined. In 1920, French engineer Paul Boucherot coined the term 'ferroresonance', describing it as the unusual coexisting operating points and oscillations in a series circuit with nonlinear inductance. It became a noted problem in the 1930s when series capacitors were being used to improve voltage regulation in distribution systems. The first analytical work was done by Rudenberg [3] in the 1940s where he used graphical methods to display multiple operating points and show the effect of parameter variations. More exacting and detailed work was done later by Hayashi in the 1950s. The coupling of nonlinear dynamics with ferroresonance began in 1964 with the pioneering work of Hayashi. Frame et al. developed piecewise-linear methods of modeling the nonlinearities in saturable inductances. Hopkinson performed system tests and simulations on the effect of different switching strategies on the initiation of ferroresonance in three-phase systems. Arturi and Mork demonstrated the use of duality transformations to obtain transformer equivalent circuits. Kieny and Mork have shown that the theories and experimental techniques of nonlinear dynamics and chaotic systems can be applied to better understand ferroresonance and limitations inherent in modelling a nonlinear system [4]. Important breakthroughs in nonlinear dynamics and chaos theory were made in 1970s; and finally, in the late 1980s, some useful engineering references that could be applied to ferroresonance began to be published. Digital simulation began to replace transient network analyzers (TNA) following pioneering work in digital computer solution methods by Dommel [5]. The 1990s had seen an explosion of research papers applying techniques based on nonlinear dynamics to ferroresonant circuits. Topics such as bifurcation theory, global dynamic behavior or the Galerkin method were common for ferroresonance analysis during the 1990s. Thereafter, engineers began to use variety of mathematical techniques to gain a simplified solution of nonlinear differential equations. These methods enabled to find a steady state solution without requiring computation of transient state. Computers helped engineers to apply numerical methods and utilize spectral analysis [6], bifurcation theory and Poincare maps which are very good tools for detecting and identification of ferroresonant oscillations. [7]-[8]

Developments in the near future are expected to be in the areas of developing improved transformer models and applying nonlinear dynamics to the simulation of ferroresonance.

The term ferroresonance is now firmly established in the power system engineer's vocabulary and is used not only to describe the jump to a higher current fundamental frequency state but also bifurcations to sub-harmonic, quasi-periodic and even chaotic oscillations in any circuit containing a nonlinear inductor.

IEEE 100 defines ferroresonance as: "A phenomenon usually characterized by over voltages and very irregular wave shapes and associated with the excitation of one or more saturable inductors through capacitance in series with the inductor [1]."

For ferroresonance to occur, a circuit must contain at least an alternating power supply source, a saturable nonlinear inductor, a capacitor and a low resistive load system like an unloaded transformer. The capacitance may be the capacitance of cables, transmission lines, capacitive voltage transformers, series or shunt capacitor banks, lumped stray capacitance in transformer windings, and grading capacitors in circuit-breakers. The origin of saturable inductor can be single-phase or three-phase power transformers, shunt reactors, and inductive voltage transformers. [9]

In general, ferroresonance can occur in the power network consisting of series and shunt capacitances interacting with the magnetizing inductances. The following are necessary but not sufficient, to give rise to the occurrence of ferroresonance, as shown in Fig. 1.

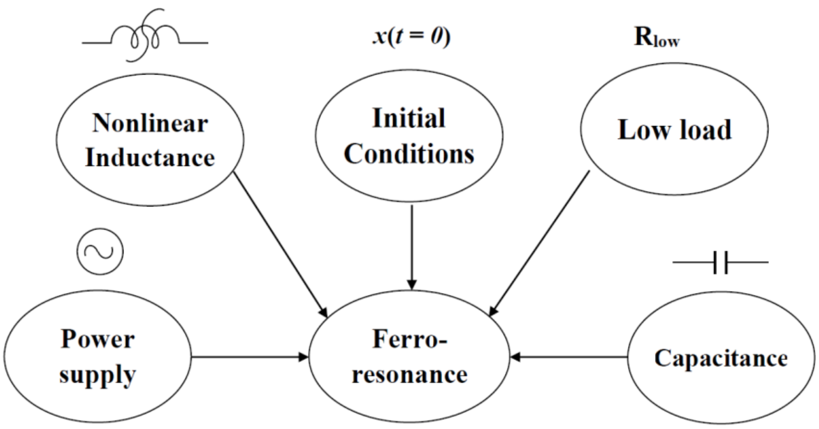

Fig. 1. Conditions affecting appearance of ferroresonance [10]

The initial conditions such as remanent flux in the core of transformers, initial charge on capacitors and switching point on the wave determines the resultant steady-state response. [11]

While much progress has been made in the general study of ferroresonance, treatment is lacking in an accurate description of, perhaps, the most interesting part of the phenomena, namely, the so-called critical points at which the current suddenly changes in value. From a practical viewpoint, it is this characteristic property that makes ferroresonant circuits useful as sensitive elements in relay and control apparatus. Accordingly, there is a definite need for simple quantitative information that completely predetermines the behavior of the circuit under critical conditions and specifies the required circuit parameters in terms of known quantities.

The remainder of the paper is organized as follows: Section II discusses the fundamental details of the phenomenon followed by the various modes of its occurrence in section III. Consequences and the various approaches to mitigate it are presented in section IV. Concluding remarks are presented in Section V.

II. THEORETICAL PRINCIPLES OF FERRORESONANCE

Ferroresonance is a special case of disturbance that involves high levels of overvoltage and overcurrent distortions. Even though the phenomenon involves a capacitance and an inductance, there is no definite resonant frequency, and more than one response is possible for the same set of parameters, and gradual drifts or transients may cause the response to jump from one steady-state response to another. The main cause of its occurrence is the interaction of a nonlinear magnetic device with a capacitive component of the installation in a low dissipative circuit configuration powered by a voltage source. Thus, the magnetic device operating point, which under normal conditions lies in the linear region of flux-current characteristic, periodically (every half cycle of the energy source) enters and leaves the magnetic core saturation area. Consequently, multiple values for the device inductance are established which exhibit extremely low values in the highly saturated zone of magnetization characteristics of the iron core and determine distorted voltage and current waveforms with high amplitude values. In the region of low current characterized by the nonlinear portion of reactor characteristic, critical conditions for both sudden increase and decrease of current are theoretically possible. Due to the variability of the apparent resistance and the characteristic constants in the nonlinear region, it is advantageous to choose current as an independent variable in order to make a theoretical investigation of critical conditions.

In a linear circuit as shown in Fig 2(a), the resonance occurs when the capacitive reactance equals the inductive reactance at the circuit source frequency and can result in excessive currents and voltages. Table 1 provides a comparison of resonance and ferroresonance phenomenon.

In the majority of ferroresonance cases, a series path including a saturable inductance and a capacitance is formed, constituting a series ferroresonance circuit as shown in Fig. 2(b). The graphical solution of Non-linear LC Circuit is shown in fig. 3.

Table 1: Comparison of Linear and Non-linear Resonance [2]

Network System	Parameters	Resonance	Response
Linear circuit	Resistance, capacitance and inductor	Resonance occurs at one frequency when the source frequency is varied.	Only one sinusoidal steady state overvoltage and overcurrent occurs.
Non-linear circuit	Resistance, capacitance and non-linear inductor (ferromagnetic material)	Ferroresonance occurs at a given frequency when one of the saturated core inductances matches with the capacitance of the network.	Several steady state overvoltages and overcurrents can occur.

Under a normal three-phase operation, the magnetizing inductance of the transformer is in parallel with the system capacitance and if the transformer voltage is held below the saturation point, ferroresonance does not occur. Another type of ferroresonance can occur during temporary power frequency overvoltage conditions; during which, if the system voltage is not maintained below the core saturation point, the core is saturated and an exchange of energy between the system capacitance and the highly nonlinear magnetizing inductance of the transformer can occur. The rapid changes in core flux during this period can produce high overvoltages, resulting in parallel ferroresonance. An example of this type is the ferroresonance phenomenon of the inductive voltage transformer (VT) in an isolated neutral system.

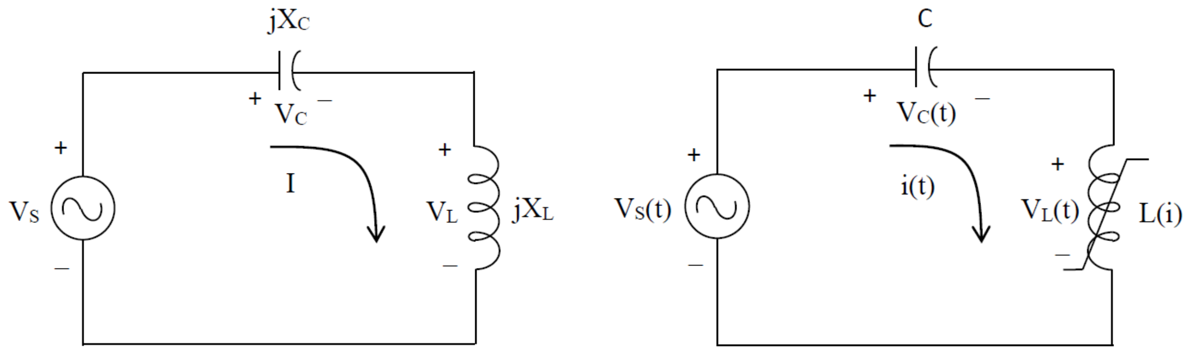

Fig. 2. (a) A Predictable Linear LC Circuit (b) A Non-linear LC circuit capable of Ferroresonance [12]

The occurrence of both types of ferroresonance causing abnormal voltage (either low or high), across the transformer terminals and from terminals to ground is often unpredictable, as both depend on various parameters such as the cable length, the amount of system capacitance, the connection type and saturation characteristics of the transformers, and the amount of load or burden. System events that may initiate ferroresonance include single-phase switching event such as transformer energization or fusing, fault clearing, breakers opening, or loss of system grounding.

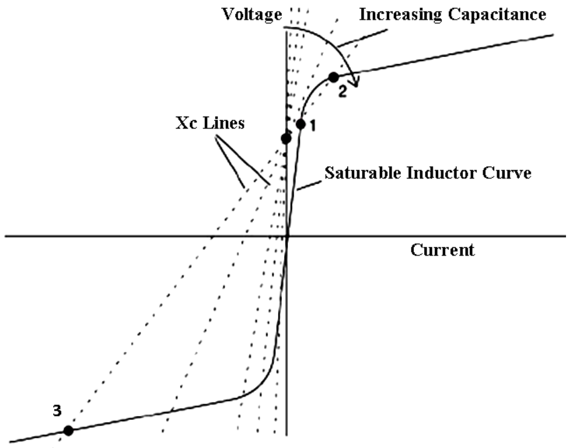

Fig.3. A graphical solution of Non-linear LC Circuit [2], [13]

Configurations that may allow ferroresonance to happen are endless. But there are some typical configurations that may lead to ferroresonance, viz. [12]

- Voltage transformer energized through grading capacitance.
- Voltage transformers connected to an isolated neutral system.
- Transformer accidentally energized in only one or two phases.
- Voltage transformers and HV/MV transformers with Isolated Neutral.
- Power system grounded through a reactor.
- Transformer supplied by a highly capacitive power system with low short circuit power.
- Power transformer connected to a series compensated transmission line.

Due to the existence of many sources of capacitors and non-linear inductances, and a wide range of operating states, configurations under which the ferroresonance takes place are innumerable. [14]

III. FERRORESONANT MODES

When the core of a nonlinear circuit is driven into saturation, the circuit can exhibit multiple values of inductances because the value of a nonlinear inductor is different for current magnitudes above the saturation point. Due to the device inductance constantly changing values, multiple ferroresonant modes (types) with no definite resonance frequency are to be identified. Hence, the nonlinear behavior of ferroresonance falls into two main categories. In the first, the response is a distorted periodic waveform, containing the fundamental and higher-order odd harmonics of the fundamental frequency. The second type is characterized by a non-periodic response. [7]

This classification corresponds to the steady state condition, as it is difficult for a ferroresonant circuit to distinguish the normal transient state from ferroresonant transient states. The type of ferroresonance can be identified [14]:

- Either by the spectrum of the current and voltage signals,
- By a stroboscopic image obtained by measuring current I and voltage V at a given point of the system and by plotting in plane V, I the instantaneous values at instants separated by a system period.

The two periodic modes are classified as fundamental and sub-harmonic mode while the two non-periodic modes are classified as quasi-periodic mode and chaotic mode. The description of these four modes is as follows.

1. Fundamental mode: Periodic oscillations at the fundamental frequency of the power system (as shown in fig. 4). Voltages and currents are periodic with a period T equal to the system period and can contain a varying rate of harmonics. The signal spectrum is a discontinuous spectrum made up of the fundamental f_0 of the power system and its harmonics ($2f_0$, $3f_0$...).

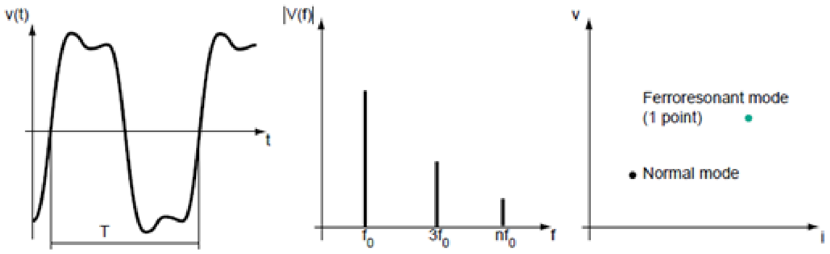

Fig. 4. Fundamental Mode [1]

2. Sub-harmonic mode: Periodic oscillations at submultiple values of the fundamental frequency (as shown in fig. 5). The signals are periodic with a period nT which is a multiple of the source period. This state is known as sub-harmonic *n* or harmonic *1/n*. Subharmonic ferroresonant states are normally of odd order. The spectrum presents a fundamental equal to f_0/n (where f_0 is the source frequency and *n* is an integer) and its harmonics (frequency f_0 is thus part of the spectrum). A stroboscopic plotted line reveals *n* points.

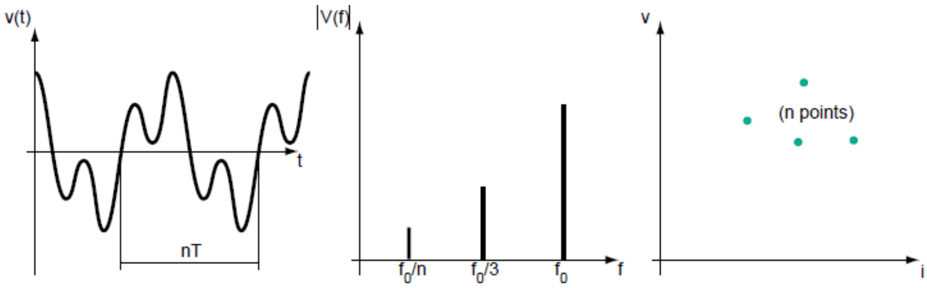

Fig. 5. Sub-harmonic Mode [1]

3. Quasi-periodic mode: Non-periodic oscillations with a discontinuous frequency spectrum (as shown in fig. 6). This mode (also called pseudo-periodic) is not periodic. The spectrum is a discontinuous spectrum whose frequencies are expressed in the form: nf_1+mf_2 (where n and m are integers and f_1/f_2 an irrational real number). The stroboscopic image shows a closed curve.

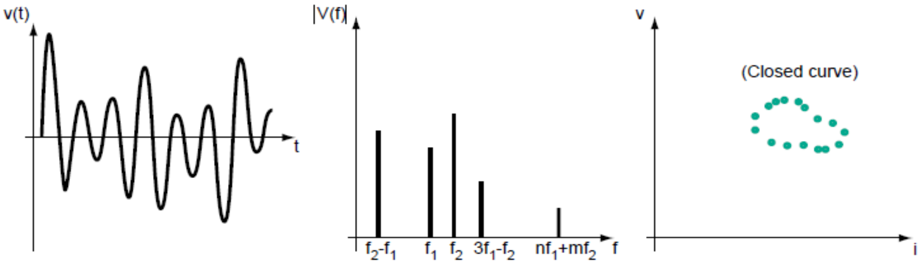

Fig. 6. Quasi-periodic Mode [1]

4. Chaotic mode: Non-periodic chaotic oscillations with a continuous frequency spectrum (as shown in fig. 7). The corresponding spectrum is continuous, i.e. it is not cancelled for any frequency. The stroboscopic image is made up of completely separate points occupying an area in plane V, I known as the strange attractor.

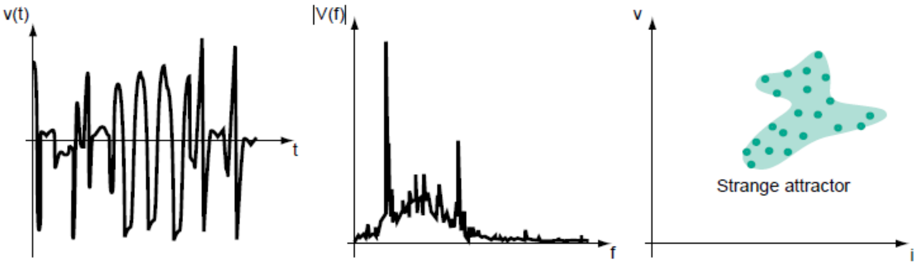

Fig. 7. Chaotic Mode [1]]

The ferroresonant modes are identified and represented by three different techniques: the spectral-density analysis, the phase-plane analysis and the Poincaré map. [1], [8], [14]

IV. EFFECTS AND MITIGATION

The appearance of the ferroresonant phenomenon provokes important oscillations that may lead to catastrophic failures in the electrical power system. Furthermore, considering the large number of factors that may exert influence over its appearance, most of them hardly quantifiable, its consequences have a higher degree of severity. If this phenomenon persists, it may pose a hazard to an electric power system because it causes over-voltages and hence over-currents. The high abnormal voltage due to ferroresonance is accompanied by abnormal transformer sound (magnetostriction) and, if sufficiently high, by equipment damage. Flicker is an example of this abnormality, which considerably affects electronic devices resulting in immediate failure and/or shortening expected life. [15]

The practical measures that can be taken in order to mitigate the ferroresonance are mainly based on specific solutions adapted for each foreseeable situation. These measures basically consist of introducing some losses in the system, in order to make the energy supplied by the power source insufficient to maintain this phenomenon [14]. If the introduction of these losses is permanent, they may affect the efficiency of the installation in a considerable way, even provoking thermal failures under unbalanced situations.

Damping added to the circuit will attenuate the ferroresonant voltage and current. Although some damping is always present in the form of resistive source impedance, transformer losses and even corona losses in high-voltage systems, most damping is due to the load applied to the secondary of the transformer. A lightly loaded or unloaded transformer fed through capacitive source impedance is the most frequent scenario for ferroresonance. The resistance needed for effective damping of ferroresonant oscillations is often very small and the resulting power dissipated in the damping resistor may be greater than several hundreds of watts that can cause thermal damage. In addition, disconnection of resistance means a step change in circuit parameters what may lead to ferroresonance again. The ideal way of mitigation can be reached by continuous change of resistance. Another way is to use metal oxide surge arrester. The problem with this method can be that a threshold voltage of surge arrester is set to a higher value than overvoltage caused by ferroresonance. [15]

A distributed circuit is optimal if the size of the capacitance bank is appropriate to the values of the system to avoid ferroresonance, and a good size of the line lengths is chosen.

Other than these, common strategies for managing ferroresonance include:

- Prevention of open phase condition
- Limiting cable length
- Location of switching at transformer terminals
- Resistance grounding of wye-connected primary
- Use of Ferroresonant transformers

Although there are several techniques for damping the ferroresonance oscillations, the first step against ferroresonance is always to not let it occur in the first place by changing initial design or conditions of the system and also having pre-set mitigation actions in place to suppress it. Hence, it is important to identify those electrical configurations prone to the appearance of the phenomenon which is currently a problem of the utmost importance in many electrical facilities. [11],[12],[16]

V. CONCLUSION

Ferroresonance in power networks involving nonlinear transformers and capacitors has been well researched for nearly a century. It can be understood as a complex oscillatory energy exchange between magnetic field energy of nonlinear magnetizing inductances of transformer/reactor cores and electric field energy of nearby capacitances. Its occurrence and evidence is extremely sensitive to the transformer characteristics, system parameters, transient voltages and initial conditions. The constant evolution of electrical power systems has given rise to a significant increase in the amount of failures caused by ferroresonance. In this paper, an insight into the phenomenon of ferroresonance has been provided along with discussion on the ferroresonant operating states, circuit configurations and mitigation techniques.

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