Ferroresonance in Electric Distribution Systems

An Online Continuing Education Course for Engineers

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Ferroresonance in Electric Distribution Systems

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Introduction

Ferroresonance is a condition that can cause severe transient over-voltages with some transformer designs under very specific conditions. Ferroresonance is a resonant condition that occurs between the magnetizing impedance of a transformer and the capacitance of a phase conductor.

The effects of ferroresonance include sustained over-voltages, both phase-to-phase and phase-to-ground, and sustained overcurrents. The over-voltage maybe three to five times the primary voltage rating. These conditions cause excessive heating of the transformer core and coil, resulting in damage to the electrical windings and insulation. The temperature of the oil in the transformer can reach extreme temperatures in a short time, creating severe damage to the transformer and risk to operating personnel.

> The term ***ferroresonance*** was coined by French engineer Paul Boucherot in a 1920.

Ferroresonance is different from a normal resonant condition in that inductance is not a fixed value because the inductance of a transformer core changes as the core reaches saturation. As the current in a transformer winding increases, the magnetic flux density increases, and at some point, additional increases in current will yield smaller and smaller increases in magnetic flux density. This is known as the *saturation point*. As the current in the transformer winding increases beyond the saturation point, the inductance of the winding changes suddenly. The sudden change in inductance changes the frequency at which the resonance condition occurs. A characteristic of ferroresonance is that it is a non-linear condition, and it is hard to predict the exact operating point where ferroresonance will occur.

This phenomenon is dangerous to the system since more than one steady-state condition can be observed, and the normal steady-state response of a system could leap to a ferroresonant steady state characterized by large overvoltages and harmonics. Some notable consequences of ferroresonance previously observed include the unexpected activation of protection devices, potential damage to transformers, and significant increases in power losses resulting in considerable heat dissipation.

Attempts to set precise limits for the prevention of the phenomenon have been frustrating, and no complete model of the underlying physics is known. Ferroresonance happens when a transformer driving a system with primarily reactive impedance experiences perturbation to a single electrical phase. The transformer must be operating close to its saturation point, at which a transformer's leakage inductance decreases dramatically.

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Following the perturbation, the transformer oscillates in and out of the saturated and unsaturated modes of operation each cycle, such that the cycle-average inductance cancels out the power line impedance. In situations where the primary impedance on the line is several-hundred-picofarad shunt capacitance to ground, the combined transformer-power line system effectively acts as a low-impedance fault.

> ***Ferroresonance*** is a resonance between network equipment and a ferromagnetic material. A common issue is the presence of underground supply cables and transformers when operating at no-load conditions.

As a nonlinear oscillation, ferroresonance exhibits substantial differences from a classical LC circuit. It occurs at a range of frequencies, which are often near harmonics of the utility frequency. Depending on the frequency, the transformer spends a different proportion of the cycle locked in the saturated mode. Ferroresonance is also resilient to the wave point of the initial perturbation and initial transformer core flux loading. Ferroresonant circuits exhibit a highly distorted waveform, and voltage and current at transitions in and out of the saturated mode typically show discontinuities or first-order singularities.

The effect of nonlinear inductance is found in both high and medium-voltage power transformers as well as voltage transformers. Numerous elements of the power system have enough capacitive effect for ferroresonance to occur. Equipment which may lead to ferroresonance are,

- Underground cables,
- Overhead conductors,
- Shunt capacitors,
- Capacitive coupling of double circuit lines,
- Stray transformer capacitance and
- Grading capacitance of circuit breakers.

In addition, the presence of low-loss systems increases the risk of ferroresonance. If system losses are considerable, the energy supplied by the source may not be sufficient to sustain the ferroresonance. Some of the typical cases of low-loss systems are low-loss transformer designs (amorphous core), no-load or low-load transformers such as voltage transformers or transformers connected to low-loss circuits.

A combination of some of these elements and/or situations may provide the conditions for a ferroresonant circuit. Although this phenomenon is more frequent in medium-voltage distribution networks, it may also appear in high-voltage networks due to the non-linear behavior of transformers and the capacitance of underground cables.

In a utility application, the most common condition for ferroresonance is a wye-delta three-phase, pad-mounted transformer that an underground feeder serves. The capacitance in the underground conductor may find a resonant point with the transformer inductance if one of the conductors is open-

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circuited and the neutral point of the ungrounded wye shifts. Single-phase switching during normal utility operations may result in the same condition as a faulted conductor.

Ferroresonance is a special case of disturbance that involves high levels of overvoltage and overcurrent distortion. In general, the word *ferroresonance* includes all the oscillatory phenomena that take place in an electric circuit comprising, at the least, a nonlinear inductance, a capacitance, a voltage source, and low losses. The appearance of the ferroresonant phenomenon of important oscillations 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.

Ferroresonant over-voltage conditions are associated with underground electrical distribution systems, but they can also occur at higher voltage levels on overhead distribution systems. The constant evolution of electrical power systems has given rise to a significant increase in the number of failures caused by ferroresonance. These failures have their origin in different causes, including factors such as increased use of underground cables in primary circuits, single-phase operations, amorphous core transformers, etc.

The practical measures that can be taken to mitigate ferroresonance are based on specific solutions adapted for each foreseeable situation. Although there are several techniques for damping the ferroresonance oscillations, the first step against ferroresonance is always to prevent it from appearing, so it is important to identify the electrical configurations prone to the appearance of the phenomenon.

This course explains the phenomenon of ferroresonant conditions and how it impacts the electric utility industry. The course is divided into five chapters. Chapter one describes the based electric circuits operating in a resonant condition and how varying magnitudes of magnetic flux can vary the impedance of a transformer's iron core. Chapter two explains the difference modes of ferroresonance. Chapter three discusses situations that are favorable to ferroresonance. Chapter four describes processes to predict ferroresonance and provides techniques to help ensure ferroresonance does not occur. The final chapter provides several case studies where ferroresonance disrupted electric service and/or damaged electrical equipment.

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Chapter 1
Explanation of Resonant Conditions

Any time-varying circuit with an inductor, capacitor, and resistor can achieve resonance. Ferroresonance is a form of resonance with a non-linear inductance. To understand ferroresonance, it is helpful to first examine a typical linear resonance scenario.

Linear Resonance Circuit

Figure 1 is a simple linear circuit containing an inductor, resistor, and capacitor and is frequently referred to as an "LRC" circuit. In this figure, we have a sinusoidal source, V_S, a resistor, R, an inductor, X_L, and a capacitor, X_C. The current, I_S, is flowing through this circuit.

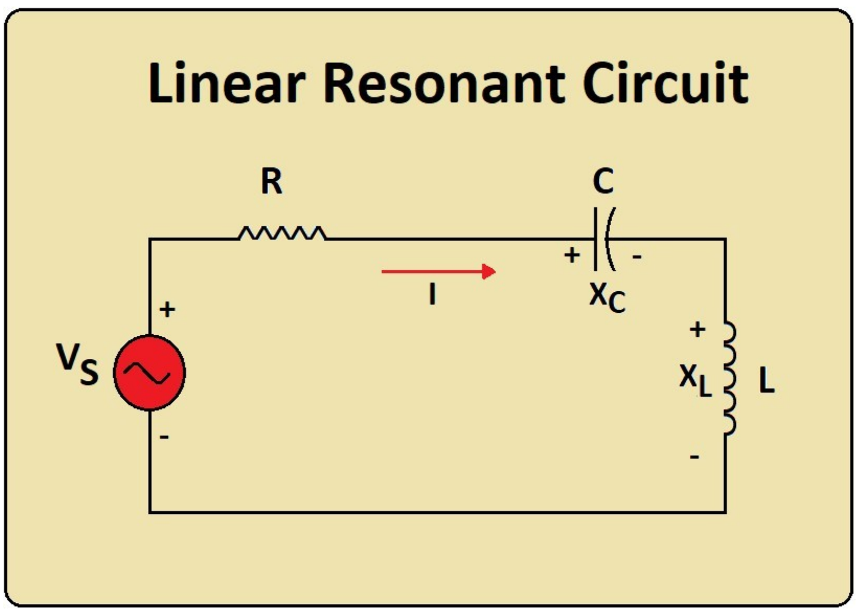

Figure 1

Impedance depends on reactance (inductance or capacitance) and a factor ω that includes frequency.

w = 2 * p * f

The reactance is:

For an inductor, $X_L = w * L$

For a capacitor, $X_C = \frac{1}{\omega * C}$

Terms:

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f = Frequency, Hz.
L = Inductance, Henries, H.
jX_L = Inductor impedance, ohms.
C = Capacitance, Farads, F.
jX_C =Capacitor impedance, ohms.
w = 2 * p * f
Z = Impedance, ohms
V_S = AC voltage source, volts
I_S = AC current, amps
j = Denotes the reactive current is in quadrature with the real current. Technically, it is $\sqrt{-1}$.

The impedance of an LRC circuit is,

$$Z = \sqrt{\mathbf{R}^2 + \mathbf{j}(\mathbf{X}_\mathbf{L} - \mathbf{X}_\mathbf{C})^2}$$

The current in the circuit is,

$$I_S = \frac{V_s}{Z}$$

Getting back to Figure 1, if the frequency, f, is varied, it can reach a point where the reactance of the inductor and the capacitor will cancel each other, leaving only the resistance, which is quite small, to limit the current flow. Therefore, the current flow will increase dramatically, as shown in Figure 2. This is known as a first-order singularity.

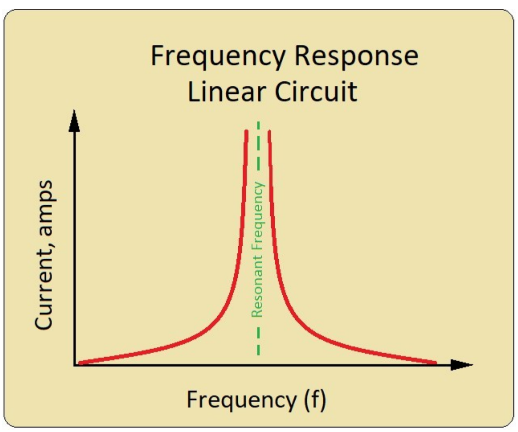

Figure 2

The frequency where resonant occurs is,

$$f_{resonant} = \frac{1}{2 * \pi * \sqrt{\mathbf{L} * \mathbf{C}}}$$

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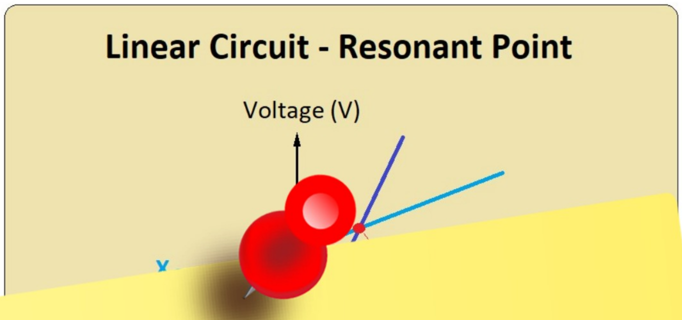
This is known as the resonant frequency, and since the inductance and capacitance are fixed values, this is known as *Linear Resonance*. Figure 3 shows the relationship between the inductive and capacitive reactance on a V-I diagram.



To view the remainder of the course material and to take the quiz for PDH credit, you must purchase the course.

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As you can s ... st (where X_C and X_L intersect). ... inductance and capacitance, s...

Ferroresona...

... traditionally ... is course all ... e shown as

In contrast to th... inductance is a f... contain transform... contains a transfo... only dependent on system frequency but also dependent on the magnetic fl... the transformer's iron core. See Figure 4 for an example of a saturation curve for the transformer core.

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