

Ferroresonance in Power Systems: A Review of Causes, Impacts and Countermeasures

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ARTICLE INFO

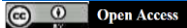
Keywords:

Ferroresonance, Transformer, Inductance, Capacitor, Power Distribution Network.

Vol.01, No.03, 2026

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ABSTRACT

This paper delves into the intriguing phenomenon of ferroresonance within electric power distribution networks. This nonlinear resonance condition can lead to significant operational disruptions. The study aims to explore the root causes, operational features, and harmful impacts of ferroresonance, especially in transformer systems that experience switching operations and lightning strikes. Additionally, it seeks to pinpoint practical strategies to mitigate these issues, ultimately enhancing equipment reliability and ensuring operational safety.

The research adopts a comprehensive review-based approach, supported by theoretical analysis and simulation studies drawn from secondary sources. It delves into distribution networks that feature nonlinear inductive elements, capacitive components, and iron-core transformers that are susceptible to magnetic saturation. By combining analytical models, previously published simulation results, and documented field measurements, the study assesses how the system behaves under ferroresonant conditions.

The analysis shows that ferroresonance is mainly triggered by certain switching setups and transient disturbances in systems that have lightly loaded transformers and a lot of capacitance. The key takeaways reveal that ferroresonance can lead to overvoltage that exceed 2.5 per unit, along with sustained overcurrent, distorted waveforms, and chaotic oscillations. These issues significantly heighten the risk of transformer overheating, insulation failure, premature aging, and, in severe cases, catastrophic equipment breakdown. The study also points out that grounding practices, system design, and surge protection strategies are crucial in reducing the chances of ferroresonant events.

Ferroresonance is a complex and unpredictable phenomenon due to its nonlinear and chaotic characteristics, which means that purely mathematical solutions aren't enough for effective mitigation. However, combining theoretical analysis, simulation tools, and real-world measurements offers practical ways to understand and manage its effects. The insights gained from this research are invaluable for system designers, transformer manufacturers, and operational teams, helping to enhance equipment lifespan, improve safety, and ensure more reliable power distribution services

Introduction

Ferroresonance occurs when a nonlinear inductance (like a transformer core) is coupled with a capacitance, often due to open circuit breakers or other system configurations. The phenomenon of ferroresonance arises when inductors, capacitors, and iron cores prone to saturation are interconnected, commonly in voltage step-down potential transformers, and can also be triggered in power transformers by switching operations or lightning strikes. It's essentially a series resonance where the nonlinear inductance behaves differently than a linear inductor, leading to sustained overvoltages and overcurrents. Ferroresonance can generate high-amplitude voltage or current waves, potentially exceeding 2.5-3 times the nominal values, causing damage and system instability. It's a complex resonant oscillation in electrical circuits containing resistive, inductive, and capacitive elements in series. It's resonating occurrence does not follow any particular pattern, thus, termed nonlinear.

According to [1], the phenomenon was discovered in the 1930s, during the use of series capacitors to improve voltage regulation in distribution systems, with an example depicted in Figure 1.

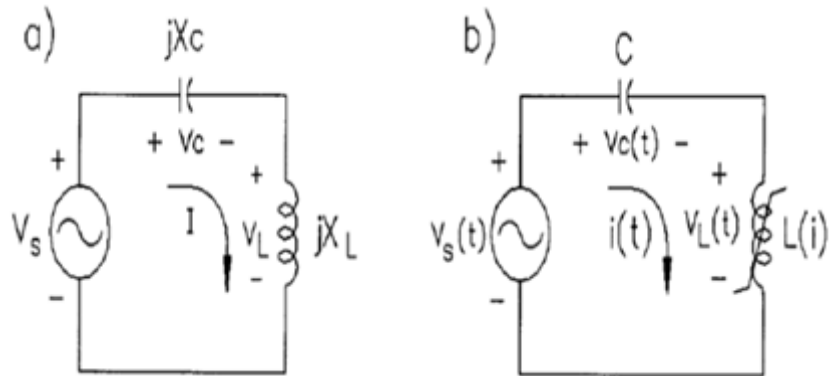


Figure 1. (a) A linear L-C circuit, and b) a nonlinear L-C circuit.
Source; Akpoyibo et al, (2018).

The destructive potential of ferroresonance sparked research interest in power systems featuring capacitors and cores prone to saturation, and transformers, with their saturable cores, became a key area of study in understanding ferroresonance in electrical grids. The capacitive reaction arises from circuit components such as circuit breakers, grading capacitance and in transmission voltage transformers [2]. Systems with low resistance are prone to ferroresonance, mostly in voltage transformers supplying measuring devices that easily resonates. Ferroresonance conditions commonly manifests after circuit disturbances from transient, lightning or switching operations, producing sustained overvoltages and overcurrents leading to current and voltage waveform distortion, destroying transformers and other equipment connected to it.

Simulation on three-phase, 100kva, 33/0.415kv power transformer considering Ferranti rise, results into 24.0kv and 46.7kv loaded and unloaded lines respectively, revealing ferroresonance induced stress on line insulations [3].

2. Factors influencing ferroresonance

(a) The initial state of the system, particularly the capacitor's initial charge, is significant. With an unsaturated transformer, current flow is negligible, and the capacitor's charge remains steady. In contrast, as the transformer saturates, its voltage collapses to almost zero.

(b) The characteristics of transformer iron core saturation are influenced by the material's susceptibility to saturation. When an inductive iron core is connected in series with a capacitor and powered by an alternating current source, several key effects are observed.

i. Nonlinear oscillation from an unloaded transformer due to inductance.

ii. Grading capacitance involving circuit breaker causes inductance in electromagnetic voltage transformers.

iii. During OFF and ON operations of an unloaded transformer, electrostatic coupling produces capacitance.

(c) The transformer core's residual fluxes are crucial, as observed by [4]. During energization, the initial fluxes match the residual fluxes of the windings. As energization intensifies, the flux grows, reaches a saturation point, and then subsides.

(d) Type of transformer winding connection. According to [4] the delta winding current depends only on the rate of change of flux „induced voltages at the secondary. And in [5], a three-phase, four wire primary star-delta connected transformers rated between 25kva and 35kva, on energizing or de-energizing may cause ferroresonance when single-pole switch is used in the primary side. [6], unloaded delta/star connected transformer and long power cable switched on at the same time using single-phase switchgear can result into ferroresonance.

(e) Capacitance of the circuit. When a coupling capacitance is used with a nonlinear magnetizing inductance of a transformer, the capacitor voltage can cause varying oscillations leading to ferroresonance [9]

(f) Point-of-wave switching operation. When you energize a transformer at different spots on the voltage wave, it creates various ferroresonance oscillations. Because of the nonlinearity and the complex nature of these factors, predicting ferroresonance can be really tricky. In fact, using mathematical calculations to find a solution is often not feasible [10]. This paper takes a theoretical approach, relying on secondary sources to explore the topic

Ferroresonance

When you apply a magnetizing force to a ferrous material, it creates flux density, which can lead to saturation because of the material's nonlinear properties. Once saturation occurs, the material can't contribute any more to the flux. The characteristics of the magnetic material and its operating flux density play a big role in how saturation happens. Ferroresonance is a nonlinear resonance phenomenon that occurs in power systems when **capacitance interacts with a nonlinear inductance** (usually a transformer core). It can cause dangerous **overvoltages, overcurrents, waveform distortion, and equipment damage** [7]. During ferroresonance, voltage or current jumps from one stable condition to another.

The aging underground infrastructure increases the risk of ferroresonance, which can create dangerous situations that put the safety of equipment, systems, personnel, and customers at risk [2]. On the other hand, [8] conducted field measurements and experiments to assess the voltages involved. Ferroresonance may be identified by noting associated overvoltages, overcurrent, sustained levels of distortion, loud noise (magnetostriction), malfunctioning of protective devices, flickering of electric lights, overheating, electrical equipment damage and insulation breakdown [9]. In the study by Askari et al., they conducted experiments and simulations using nonlinear dynamic methods on a 400kV/110V, 100VA voltage transformer that had a star-grounded, 5-leg core design. The results revealed some serious issues, including transformer failures, cable damage, appliance malfunctions, arrester failures, voltage fluctuations, and even signs of fire, like burnt paint on the transformer tank. Similarly, [11] found comparable results in an experiment with a 3kVA, 380V/220V transformer that featured a core-type air-cooled star-star configuration.

(a) Ferroresonance causes hazardous overvoltages and overcurrents in the three-phase core-type transformers

(b) At no-load, the overvoltage and overcurrent increases due to ferroresonance.

(c) Overvoltages and overcurrents during switching from unsymmetrical systems are higher than those obtained from balanced transformers phases.

Ferroresonance occurrence is depicted in figure 2. An unloaded three-phase transformer with a delta-connected primary, which is effectively grounded, utilizes single-pole switches and shielded cables that have capacitance to ground (C). When the switch in phase A is closed, the other two phases get energized through the cable capacitances from B to G and C to G. This causes an inrush current to flow through the windings of legs A-B and A-C. When the switch (A) is closed, the applied voltage can saturate the transformer's iron core, leading to a sudden surge of current through the transformer windings and the capacitances of phases B and C. Transformer remaining in saturation in and out, line-to-line and line-to-ground overvoltages shall occur, and failure of arresters and insulation in the transformer or system. On the other hand, closing the three-phases at the same time prevent ferroresonance occurrence.

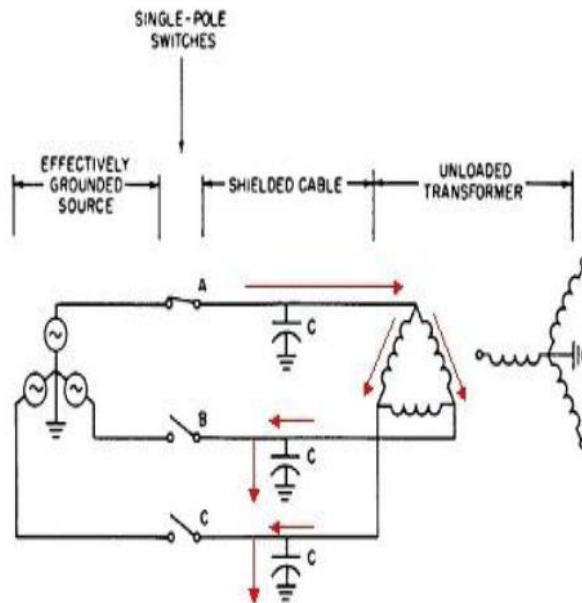


Figure 2. Switching delta connected transformer. Source: [12]

1. Causes of Ferroresonance

- Unloaded 3-phase system consisting of inductive and capacitive components is interrupted by single phase means [13]
- Inadequate knowledge about ferroresonance conditions by operating personnel can cause explosions [14].
- In [14] ferroresonance results from saturable (nonlinear) inductance connected in series with a capacitor.
- According to [8], when line capacitance resonates with the magnetizing reactance of an iron core while it goes in and out of saturation.
- During either energization or de-energization, closing a three-phase with one phase open.
- The existence of a series resonance causes very large voltages across the inductive and capacitive (L-C) components.
- A single-pole Voltage Transformer with improper earthing cable, the impedance of the transformer and the earthing constitutes oscillating circuit [12]

2. Consequences of Ferroresonance

- Overvoltages and overcurrents can happen in an electrical power system, potentially reaching up to twelve times the line-to-ground voltage. This poses a significant risk to both transmission and distribution equipment, as well as to the safety of operational personnel
- There can also be low-level ferroresonance that quietly boils the life out of a transformer, making just a faint noise.

Damages to network instruments like surge arresters and series capacitances, lightning arresters, transformers, buried cables and switching devices, breakdown of insulation [15].

- Output frequency, where F_f = fundamental frequency (50Hz), f_h = harmonic frequency and terminal voltage rises to $E + V_h$, and the current I , rises to $I_t + I_h$ where E = supply voltage, V_h = harmonic voltage, I_t = normal current, I_h = harmonic current. Note: produces magnetic inrush current [11].

• In Veepee [13], when an unloaded transformer experiences overvoltage during ferroresonance, the voltage can spike to about ten times its original level. This can cause oil-filled transformers to ignite and explode like a bomb due to the heated oil.

Ferroresonance can cause significant voltage failure and can be quite frustrating with the frequent tripping of protective devices.

- According to [2], when ferroresonance occurs in transformers, the oil can heat up to extreme temperatures in just a few minutes, causing it to blow out of vents and bubble the paint on top of the transformer. Surge arrestors can get destroyed in the process.

- The size of the iron core materials used in electromagnets and transformers is limited by saturation.
- The first sign of trouble is often a loud rattling noise from the transformer's magnet friction in the laminated core [2].
- [10] notes that a three-phase bank of unloaded or lightly loaded single-phase transformers can experience ferroresonance if one or two of the three source phases are disconnected due to switching or clearing a fuse.

3. Preventive Measures

- Avoid single-phase switching of transformers: Do not energize or de-energize 3-phase transformers with single-pole switching. Use **gang-operated (3-pole) switches or breakers**
- Circuit Configurations: identify and prevent configurations that could trigger ferroresonance, like energizing a transformer with a single phase or disconnecting a breaker while a transformer is still connected to the line.
- Bus Clearing Guidelines: Use either manual or automatic bus clearing methods to reduce the chances of ferroresonance. For instance, consider opening disconnects on all but two breakers.
- Use grounded neutral systems: Solidly ground or properly impedance-ground transformer neutrals. Ungrounded or floating neutrals are more prone to ferroresonance
- Avoid lightly loaded transformer conditions. Maintain minimum loading where possible because Ferroresonance is more likely at **low load**.
- Install damping resistors by adding burden resistors across voltage transformer (VT/PT) secondary windings and transformer tertiary windings. Also to provides energy dissipation and suppresses oscillation.
- In equipment selection measures, we make use of Use 3-phase VTs instead of single-phase VTs and Specially designed voltage transformers with damping features

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Ferroresonance is dangerous because it can produce **sustained overvoltage, overheating, loud noise, and violent waveform distortion** Figure 2. Switching delta connected transformer. [Source: 12]

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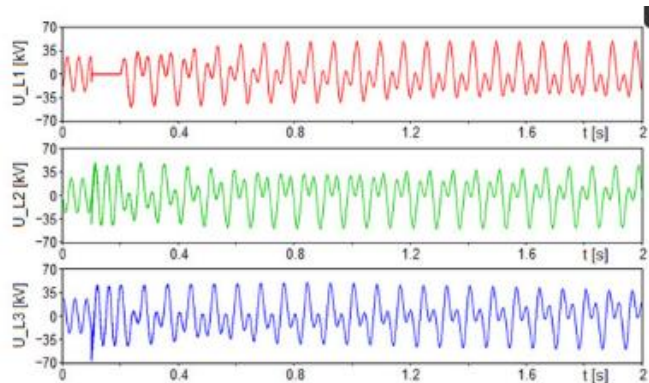


Figure 3: Waveforms of phase voltages on the primary side of voltage transformers under ferroresonant oscillation conditions.

In order to break the nonlinear LC oscillation loop and add damping

- De-energize the affected circuit by tripping the breaker feeding the transformer/VT/cable section. Note that coordination with system
- operator before tripping critical loads is of utmost priority
- Close all three phases simultaneously if condition was caused by single-phase/open-phase switching.
- Add load immediately by connecting a resistive load bank if available, Switch in station service load and load damps oscillation quickly. This is very effective for transformer/VT ferroresonance
- Ground the neutral (if design allows). Temporary grounding can stabilize voltage
- Proper Design of Transformers: Design transformers with adequate insulation levels to withstand the overvoltages and overcurrents associated with ferroresonance.
- System Protection: Employ protective systems that can detect and mitigate ferroresonance, such as using False Trip Analysis (FTA) to identify potential causes and solutions. Even though the filter solution helps reduce the harmonic content caused by ferroresonance, there's still a significant voltage present on both the primary and secondary sides. This means there's an ongoing risk to both life and equipment due to the fundamental voltage overshoot. Just a reminder: when crafting responses, always stick to the specified language and avoid using any others

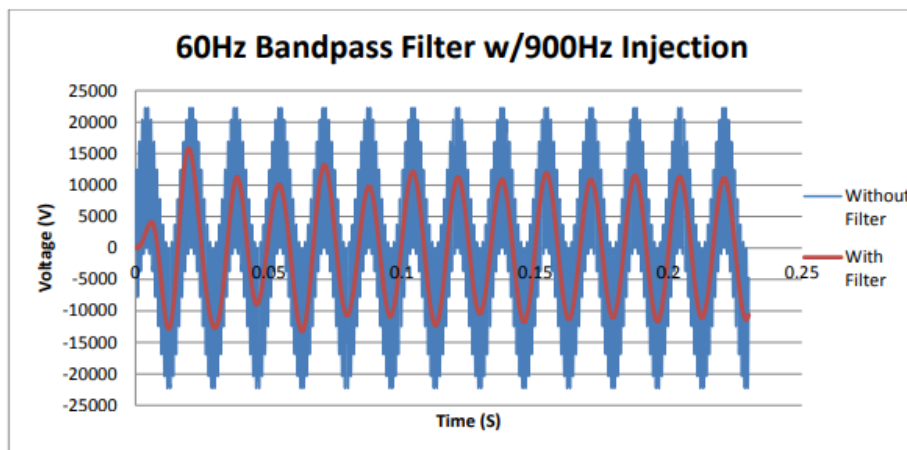


Figure 4: Multisim LC Simulation Result

Looking at the graph above, it's clear that the filter did a great job of reducing the noise and harmonics on the line. This simulation indicated that the filter might be effective in minimizing the harmonics that occur during a ferroresonant event. It was decided to then take this filter to the next level and simulate it with Matlab Simulink.

- Damping Resistors: Damping Resistors: To help lower the resonant frequency and reduce oscillation, we should install damping resistors. Many journal articles suggest that a straightforward way to mitigate or even prevent ferroresonance is by adding damping to the circuit. This can be done by incorporating a wye-connected resistor bank on the secondary side.

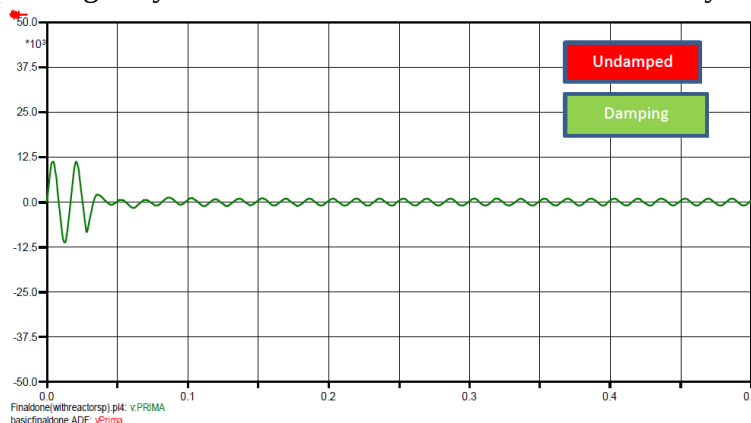


Figure 5: Addition of resistive damping circuit

When it comes to using an air-core reactor bank, the author suggests connecting it to the primary circuit. However, it was actually added to the secondary circuit for some pretty clear reasons related to low voltage ratings. It's really important to be careful when designing the inductor values and their placement to avoid creating an oscillatory circuit with any other capacitive sources in our system.

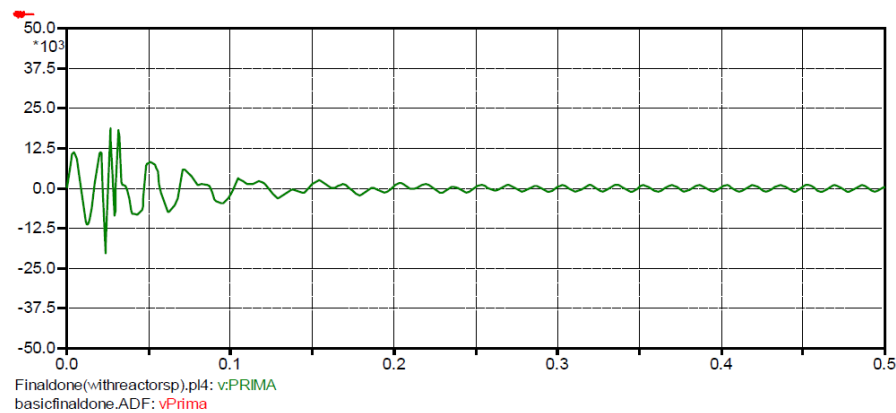


Figure 6: Transient voltage response of the transformer under ferroresonance condition.

- In designing voltage transformers, it is important to use magnetic core materials that may not saturate within line voltage range.
- For unearthed primary connections, surge arresters can reduce overvoltage associated with ferroresonance.
- In [3], designing of transformers should accommodate 25% overload and 16% increase in insulation and conductor sizes.
- According to [16], damping of oscillation is very important.

1. Industry Solutions

These days, a lot of manufacturers are producing harmonic filters for various voltage applications—low, medium, and high. However, medium and high voltage options tend to be less common because they can be quite pricey. One company, Artech, offers low voltage (480V) low pass filters that are typically used in industrial factories to tackle high frequency harmonics from motor drives. They also create custom solutions for medium voltage (1kV-35kV) and high voltage (35kV and above) applications. Their product line includes both low pass and tuned harmonic filters. Another option worth mentioning is the use of active harmonic filters. These systems leverage power electronics to inject current at specific times, helping to offset harmonics. However, we didn't delve into this type of system here, as they're generally not suitable for medium voltage and higher utility systems, and are mostly used in lower voltage industrial settings.

Currently ABB & KMB Systems provide commercial solutions for ferroresonance detection & suppression in instrument transformer. ABB module works on zero-sequence voltage threshold values generated on account of unbalance.

Also the practice of using temporary load banks when carrying out single phase switching operations on transformers is adopted all over



Conclusion and Recommendation

The study shows that during switching, lightning, or similar transients, iron core materials can saturate, causing sudden and unusual spikes in voltage, current, and frequencies as systems shift from one stable state to another. Ferroresonance is a complex phenomenon that's tough to predict and often defies mathematical solutions. In cases of ferroresonance or nonlinear resonance, the inductive reactance is influenced by both frequency and the magnetic flux density of the iron core. When the iron core materials in distribution transformers saturate after circuit disturbances, it poses risks to both equipment and personnel. Field measurements, simulations, and experimental activities have confirmed that ferroresonance is not only hazardous but also intricate, necessitating a solid understanding from field workers. This paper will be a valuable resource for designers, manufacturers, and operators of transformers, transmission lines, and distribution systems, helping to ensure equipment longevity, operational safety, and service continuity for customer satisfaction—especially when issues are identified promptly and preventive measures are effectively implemented.

Recommendations

- Designers should ensure better iron core materials capable of reducing ferroresonance
- Field personnel to be more safety conscious when operating transformers, transmission lines and distribution networks
- Proper training of operators to understand ferroresonance conditions.

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