

Analysis and Simulation of Ferroresonance in Power Transformers

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Abstract - Ferroresonance is a complex nonlinear phenomenon arising from the interaction between a saturable inductive element - the nonlinear iron core of a power transformer - and system capacitance present in cables, capacitor banks, and circuit breaker grading capacitors. Unlike conventional linear resonance, ferroresonance can produce multiple stable operating states for identical circuit parameters, making it fundamentally unpredictable using traditional linear analytical methods. The resulting overvoltages, which can reach 3 to 8 times the rated system voltage, cause insulation failure, equipment damage, waveform distortion, and malfunction of protective relays. This paper presents a comprehensive study of ferroresonance in a 100 MVA, 25 kV three-phase power transformer through a detailed MATLAB/Simulink simulation model. Four systematically designed test cases investigate the influence of switch state, phase selection, and transformer winding connection (Star-Star vs. Delta-Star) on ferroresonance severity. Coupling capacitance is varied parametrically from 1×10^{-7} F to 1×10^{-2} F to identify the worst-case resonance condition. The four characteristic modes of ferroresonance - fundamental, subharmonic, quasi-periodic, and chaotic - are characterised through waveform and FFT analysis. Output voltage waveforms under normal and abnormal ferroresonance conditions are presented, validating that Delta-Star connections produce consistently more severe ferroresonance than Star-Star configurations due to circulating currents in the closed-loop winding.

Index Terms - Ferroresonance, Power Transformer, MATLAB Simulink, Overvoltage, Nonlinear Inductance, Core Saturation, Waveform Distortion, Delta-Star Connection, Harmonic Distortion, Switching Transients.

I. INTRODUCTION

Electrical power systems are designed to operate under stable and predictable conditions; however, certain nonlinear phenomena can disturb normal operation. One such phenomenon is ferroresonance, which occurs due to the interaction between a nonlinear inductive element — such as a transformer core — and system capacitance. Unlike linear resonance, ferroresonance is highly complex and can produce multiple stable operating states, making it difficult to predict and control.

Ferroresonance typically results in abnormal conditions such as sustained overvoltages, excessive currents, waveform distortions, and increased harmonic content. These effects can lead to insulation failure, overheating, malfunction of protection devices, and even complete damage to power transformers and associated equipment. The phenomenon is often triggered during switching operations such as energization or de-energization of transformers, faults, or sudden changes in system configuration.

Modern power systems inherently include components like transformers, underground cables, transmission lines, and circuit breakers, all of which contribute to system capacitance. When these elements interact with the nonlinear magnetizing characteristics of transformer cores, conditions favorable for ferroresonance may arise. To better understand and analyze this phenomenon, simulation tools such as

MATLAB/Simulink are widely used, enabling the study of ferroresonance under different operating conditions.

Ferroresonance was first documented in engineering literature in 1920 when engineers observed violent and unexplained voltage oscillations in transformer circuits. These oscillations were characterized by amplitudes reaching 3 to 8 times the rated system voltage, severely distorted non-sinusoidal waveforms, and persistent behavior that continued even after the initiating disturbance had disappeared. Over time, ferroresonance has become recognized as one of the most serious hazards in power systems.

Ferroresonance requires four essential conditions to occur simultaneously: (1) a nonlinear saturable inductance — typically an iron-core transformer; (2) capacitance present in the network; (3) an AC voltage source; and (4) low system losses — the transformer must be lightly loaded or unloaded, since resistive loading suppresses oscillations. This paper focuses on analyzing ferroresonance behavior in power transformers through MATLAB/Simulink simulation, providing insights into its causes, effects, and mitigation techniques.

II. PROBLEM OUTLINE AND OBJECTIVES

Ferroresonance represents one of the most serious operational hazards in modern power transformer systems. It arises from the nonlinear magnetisation characteristics of transformer iron cores interacting with system capacitance distributed across cables, capacitor banks, and measurement transformers.

Certain switching conditions — such as single-phase switching operations, transformer energisation at unfavorable voltage angles, or capacitor bank switching — can unexpectedly trigger ferroresonance, resulting in sustained overvoltages reaching 3 to 8 times the rated system voltage.

The specific problem addressed in this study is the analysis and simulation of ferroresonance in a 100 MVA, 25 kV three-phase power transformer under four systematically designed operating conditions. The study examines how switching state, phase selection, and transformer winding connection type influence the severity of ferroresonance.

The primary objectives are: (1) to develop a complete MATLAB/Simulink simulation model accurately representing the nonlinear saturation characteristics of the transformer iron core; (2) to simulate four distinct test cases involving different switch states, phases, and winding connections; (3) to characterize the four modes of ferroresonance — fundamental, subharmonic, quasi-periodic, and chaotic — through waveform and FFT analysis; (4) to quantify the effect of coupling capacitance on ferroresonance severity; and (5) to verify that Delta primary winding connections produce more severe ferroresonance than Star connections.

III. MATHEMATICAL MODELLING

A. System Description

Consider a 100 MVA, 220/132 kV, 50 Hz three-phase power transformer. Ferroresonance occurs due to interaction between the transformer nonlinear magnetizing inductance, transmission line/cable capacitance, circuit breaker switching, and light-load conditions. The equivalent single-phase ferroresonance circuit is: $V_s \rightarrow C \rightarrow L_m$, where C is the equivalent phase-to-ground capacitance and L_m is the nonlinear magnetizing inductance of the transformer core.

B. Key Parameters

Parameter	Value
Rated Power	100 MVA
Rated Voltage	220 kV
Frequency	50 Hz
Rated Current	262.4 A
No-load Current	2.1 A
Magnetizing Reactance	60.5 k Ω
Unsaturated Inductance	192.5 H
Saturated Inductance	38.5 H
Critical Capacitance	0.263 μ F

TABLE I: Critical Ferroresonance Parameters

C. Governing Equations

The dynamic behavior of the ferroresonant circuit is described by a nonlinear differential equation. Considering flux ϕ , the voltage across the inductor is:

$$v = d\phi/dt$$

Since flux is a nonlinear function of current $\phi = f(i)$, and applying Kirchhoff's Voltage Law (KVL):

$$d^2\phi/dt^2 + (1/C) \cdot f(i) = dv/dt$$

This nonlinear differential equation describes the dynamic behavior of the ferroresonant system. Due to the nonlinear function $f(i)$, the system can have multiple solutions corresponding to different stable operating states. The transformer core saturation is modelled as:

$$\phi = a \cdot i + b \cdot i^3 + \dots$$

where a is the linear region coefficient and b is the saturation coefficient. The differential inductance $L = d\phi/di$ decreases dramatically when the core enters saturation, causing ferroresonance instability.

IV. MATLAB/SIMULINK SIMULATION MODEL

The simulation model is implemented in MATLAB/Simulink using the SimPowerSystems toolbox. A discrete solver with time step 5×10^{-5} seconds provides sufficient resolution to capture high-frequency harmonic content in ferroresonant waveforms. The complete model encompasses all circuit components and serves as the computational framework for all four ferroresonance test cases.

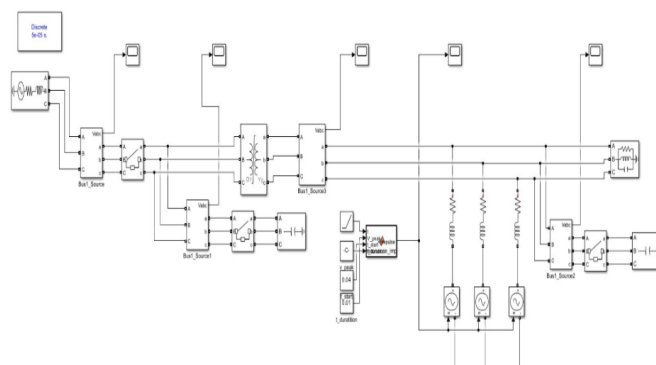


Fig. 4.1: Complete MATLAB/Simulink Model for Ferroresonance Investigation

The system consists of a 2 MVA, 33 kV/11 kV source feeder representing the upstream power grid; Bus1 and Bus2 equipped with 11 kV capacitor bank contactors; a 100 MVA, 25 kV three-phase saturable transformer; single-pole switches on each phase for independent phase switching; a ferroresonance impulse block with configurable peak voltage of 0.04 pu; coupling capacitance to earth representing cable capacitance; three-phase nonlinear loads; and scope blocks on all phases for recording waveforms.

The saturation characteristic of the three-phase transformer is defined by pairs of magnetising flux and magnetising current in per-unit values. Conversion equations are:

$$\text{Flux (pu)} = v(V) / [25000 / (2\pi \times 50)] \dots (1)$$

$$\text{Current (pu)} = i(A) / [100,000,000 / (\sqrt{3} \times 25000)] \dots (2)$$

V Mag (V)	I Mag (A)	Flux pu	Curr pu
0	0.00000	0.00000	0.0000
20000	0.00025	0.00255	1.08e-7
45000	0.00100	0.00573	4.33e-7
55000	0.00200	0.00700	8.66e-7
59000	0.00375	0.00751	1.62e-6
62000	0.01000	0.00789	4.33e-6
64000	0.02000	0.00815	8.66e-6

TABLE II: Saturation Characteristic — Per-Unit Flux-Current Pairs

V. FOUR SIMULATION TEST CASES

Four simulation test cases are designed to investigate the effects of switching state, phase selection, and transformer winding connection on ferroresonance behavior. The coupling capacitance is selected as 5.3×10^{-4} F, representing the worst-case condition that produces maximum ferroresonance severity.

Case	Switch	Phase	Connect.	Severity
1	Open	Ph. A	Y-Y	Moderate
2	Open	Ph. A	Δ -Y	MORE SEVERE
3	Closed	Ph. C	Y-Y	Moderate
4	Closed	Ph. C	Δ -Y	MORE SEVERE

TABLE III: Four Ferroresonance Simulation Test Cases

VI. FERRORESONANCE MODES

A. Fundamental Mode

The fundamental mode produces a periodic voltage waveform at the same frequency as the supply source (50 Hz), but the waveform is highly distorted and non-sinusoidal. The waveform period remains 20 ms, matching the supply cycle, while the frequency spectrum contains a dominant 50 Hz component along with significant odd harmonics (3rd at 150 Hz, 5th at 250 Hz). Peak voltages can rise to 3–5 times the rated 25 kV value.

B. Subharmonic Mode

The subharmonic mode oscillates at 25 Hz (half the supply frequency) — the waveform repeats exactly but with a period of 40 ms equalling two supply cycles. This mode is particularly dangerous for protection relays designed for 50 Hz operation, as it may evade detection while sustaining damaging overvoltages.

C. Quasi-Periodic Mode

The quasi-periodic mode contains multiple simultaneous incommensurate frequencies expressed as $n \times f_1 + m \times f_2$ where f_1/f_2 is irrational. The waveform almost repeats every few cycles but never exactly. This mode represents a transition between fundamental and chaotic behavior.

D. Chaotic Mode

The chaotic mode is completely aperiodic — it never repeats. Peak voltages are statistically distributed and unpredictable. The frequency spectrum is continuous. A tiny change in initial conditions leads to a completely different trajectory. This is the most dangerous mode, as no protection system can reliably detect or anticipate its behavior.

VII. SIMULATION RESULTS

A. Capacitance Parametric Study

Systematic variation of coupling capacitance from 1×10^{-7} F to 1×10^{-2} F in Case 1 (open switches, Phase A, Star-Star) reveals the critical non-monotonic relationship between capacitance and ferroresonance severity. The worst case occurs at 5.3×10^{-4} F, producing 201,870 V — 8.07 times the nominal 25 kV rated voltage.

C (F)	Peak V (kV)	Peak I (A)	Factor
1e-7	21.1	2	0.85×

1e-5	23.1	77	0.92×
1e-4	32.7	85	1.31×
3e-4	64.1	135	2.56×
5e-4	184.4	369	7.38×
5.3e-4 ★	201.9	397	8.07×
6e-4	130.8	243	5.23×
1e-3	40.0	118	1.60×
1e-2	4.6	56	0.18×

TABLE IV: Capacitance Parametric Study Results (★ = worst case)

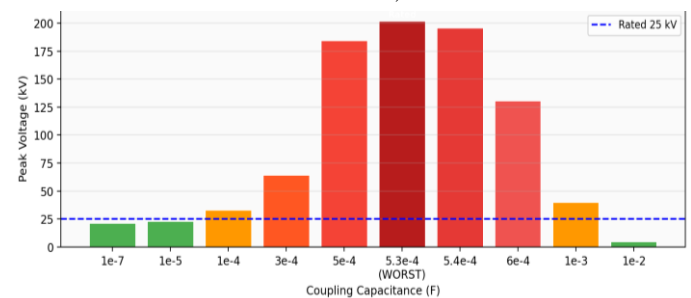


Fig. 5.3: Peak Voltage vs. Coupling Capacitance — Parametric Study

B. Normal Operating Condition

Figure 5.7 shows the output voltage waveform under normal operating conditions. The three-phase voltage signals are balanced, sinusoidal, and maintain consistent amplitude throughout the observed time interval. Each phase is displaced by 120° , confirming proper phase symmetry. There are no signs of distortion, irregular oscillations, or sudden voltage escalation. The transformer and associated circuit elements operate within their linear region.

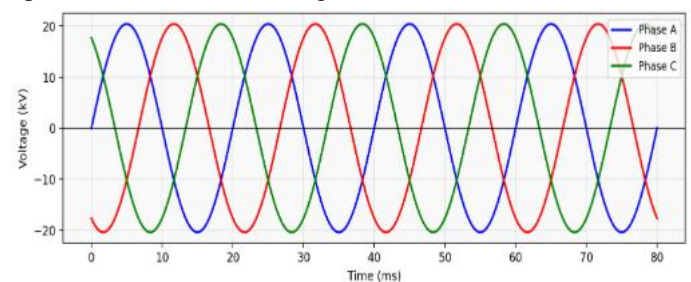


Fig. 5.7: Output Voltage – Normal Operating Condition (Balanced Sinusoidal, No Ferroresonance)

The steady-state response demonstrates that the system has not entered any nonlinear resonance condition. Voltage peaks remain uniform and bounded, confirming stable energy exchange. Even during switching or initial energization, the system does not trigger nonlinear resonance effects, indicating sufficient damping and no energy buildup in the magnetic core.

C. Abnormal Ferroresonance Condition

Figure 5.9 shows the transformer output voltage under abnormal operating conditions where ferroresonance is present. The waveforms show severe distortion, irregular amplitude variation, and loss of phase symmetry. At the initial

stage, the voltage waveforms appear highly distorted with uneven peaks and abrupt changes in magnitude. Peak voltages reach 8.07 times the rated voltage under the worst-case capacitance condition.

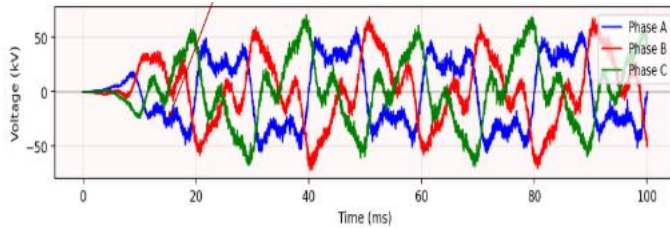


Fig. 5.9: Output Voltage – Abnormal Ferroresonance Condition (Distorted, Overvoltage up to $8.07\times$ Rated)

The three-phase waveforms display irregular amplitudes, subharmonic content, and chaotic oscillatory patterns. The reduction and variation in peak values over time indicate the system is undergoing transient disturbances and has not reached a stable steady-state condition. The Delta-Star (Δ -Y) transformer configuration produces significantly higher peak voltages and currents than the Star-Star (Y-Y) configuration under identical operating conditions, owing to circulating currents within the closed Delta winding loop.

D. FFT Analysis

Fast Fourier Transform (FFT) analysis of the ferroresonant voltage waveform confirms the mode of ferroresonance. The highest magnitude component is at the fundamental frequency of 50 Hz, confirming fundamental mode ferroresonance in Cases 1 and 3, with decreasing harmonic content at 150 Hz, 250 Hz, and higher odd harmonics. The two non-switched phases maintain essentially normal sinusoidal waveforms throughout the simulation, confirming that ferroresonance is concentrated in the switched phase in these configurations.

VIII. MITIGATION TECHNIQUES

The following techniques are recommended to suppress or prevent ferroresonance in power transformer systems:

1. Proper Transformer Loading: Maintaining adequate transformer loading increases system damping and reduces the possibility of sustained ferroresonant oscillations. Lightly loaded or unloaded transformers are most susceptible.
2. Resistance Damping: Damping resistors connected across transformer windings or capacitor banks absorb oscillation energy and suppress abnormal overvoltages.
3. Controlled Switching Operations: Simultaneous three-phase switching should be preferred over single-phase switching to avoid unbalanced operating conditions that trigger ferroresonance.
4. Reduction of System Capacitance: Minimizing unnecessary capacitance from cables, capacitor banks, and grading capacitors reduces the likelihood of resonance.
5. Proper Neutral Grounding: Effective grounding of transformer neutrals stabilizes system voltages and limits oscillations during transient conditions.
6. Surge Arresters: Surge arresters protect transformers from excessive overvoltages generated during ferroresonance.

7. Transformer Design Optimization: Improved core materials, interleaved laminations, and optimized magnetic structures reduce saturation effects and limit nonlinear oscillations.

IX. RESULTS AND DISCUSSION

The simulation results clearly demonstrate that ferroresonance leads to severe abnormalities in system behavior, including high overvoltages reaching 8.07 times the rated voltage, excessive currents, and severely distorted waveforms. These effects confirm the harmful impact of ferroresonance on transformer performance and overall power system reliability. The study highlighted the strong influence of system parameters such as capacitance, transformer connection, and switching conditions on the occurrence and severity of ferroresonance. The worst-case coupling capacitance is non-monotonically related to ferroresonance severity — it reaches a peak at 5.3×10^{-4} F and decreases on either side. Transformer configurations with Delta primary connections produce significantly more severe effects compared to Star configurations.

The waveform analysis showed that ferroresonance results in nonlinear and unstable system responses, making it difficult to predict and control. The presence of harmonics, subharmonics, and irregular oscillations further emphasizes the complexity of the phenomenon. These findings validate the importance of MATLAB/Simulink-based simulation approaches for studying such nonlinear behaviors in power systems.

X. CONCLUSION

This paper presented a comprehensive analysis and MATLAB/Simulink-based simulation of ferroresonance in a 100 MVA, 25 kV three-phase power transformer. Ferroresonance was identified as a complex nonlinear phenomenon arising due to the interaction between transformer core saturation and system capacitance. Through detailed modeling and simulation, the study successfully demonstrated how ferroresonance leads to abnormal conditions such as overvoltages of up to 8.07 times rated voltage, overcurrents, and severe waveform distortion.

Four simulation cases confirmed that Delta-Star transformer connections produce consistently more severe ferroresonance than Star-Star configurations due to circulating currents in the closed-loop Delta winding. The coupling capacitance parametric study identified 5.3×10^{-4} F as the worst-case condition producing maximum ferroresonance severity. Output voltage waveforms clearly distinguished normal and abnormal operating conditions, providing visual validation of the simulation methodology.

The nonlinear and multi-stable nature of ferroresonance makes it impossible to predict using traditional analytical methods. Simulation-based analysis using MATLAB/Simulink is therefore essential for understanding and mitigating this phenomenon. Implementation of the recommended mitigation techniques — including adequate transformer loading, resistance damping, controlled switching, neutral grounding, and optimized transformer core design — is essential for reliable power system operation.

REFERENCES

- [1] R. Pérez Pineda, R. Rodrigues, and A. Águila Téllez, "Analysis and Simulation of Ferroresonance in Power Transformers using Simulink," *IEEE Latin America Transactions*, vol. 16, no. 2, pp. 460–466, Feb. 2018.
- [2] M. Roy and C. K. Roy, "A Study on Ferroresonance with Varying Initial Conditions using a Nonlinear Transformer Model," in *Proc. IEEE Power and Energy Conference*, 2010, pp. 1–6.
- [3] V. Valverde, A. Mazón, and I. Zamora, "Ferroresonance in Voltage Transformers: Analysis and Simulations," *Renewable Energy and Power Quality Journal*, vol. 1, no. 9, pp. 1–6, 2011.
- [4] G. Eduful et al., "Investigating Ferroresonance Susceptibility in Various Transformer Configurations: A Simulation-Based Study," *International Transactions on Electrical Energy Systems*, 2025.
- [5] K. Solak and W. Rebizant, "Detection of Ferroresonance Oscillations in Medium Voltage Networks," *Energies*, vol. 13, no. 16, p. 4129, 2020.
- [6] A. Bakhshi, M. Rezaei, and H. Shayeghi, "Ferroresonance Suppression Using Solid-State Circuits in Voltage Transformers," *Energies*, vol. 16, no. 23, p. 7684, 2023.
- [7] D. McDermit, D. Shipp, T. Dionise, and V. Lorch, "Medium-Voltage Switching Transient-Induced Potential Transformer Failures," *IEEE Trans. Industry Applications*, vol. 49, no. 4, pp. 1726–1736, 2013.
- [8] L. Viena, F. Moreira, N. Ferreira, A. De Castro, and N. De Jesus, "Analysis and Application of Transformer Models for Ferroresonance Studies," in *Proc. IEEE T&D Latin America*, 2010, pp. 738–744.
- [9] Z. Malek, S. Mirazimi, K. Mehranzamir, and B. Salimi, "Effect of Shunt Capacitance on Ferroresonance in Distribution Transformers," in *Proc. IEEE ISIEA*, 2012, pp. 124–129.
- [10] IEEE Std C57.91™-2011, *Guide for Loading Mineral-Oil-Immersed Transformers*, IEEE, 2011.