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Nonlinear Oscillations in Power Systems: A Review of Ferroresonance Phenomena

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Abstract

Ferroresonance is a complex and potentially destructive phenomenon that poses significant risks to the reliability and stability of power distribution systems. Despite more than a century of documented incidents, its underlying mechanisms and practical countermeasures remain only partially resolved. This review presents a comprehensive examination of the subject, combining key findings from historical, analytical, and practical perspectives. The paper also examines a range of mitigation strategies, including transformer magnetic core design, capacitive control, and the deliberate introduction of damping elements. The review further identifies critical knowledge gaps, particularly the need for more cost-effective and scalable solutions capable of addressing the limitations of current mitigation techniques. Considering the increasing use of underground cables, widespread deployment of non-linear devices, and growing integration of renewable energy sources, the study reinforces the continued relevance of ferroresonance research. It provides a valuable foundation for future work aimed at enhancing power system resilience and ensuring the protection of critical infrastructure components against ferroresonant disturbances.

Keywords: Ferroresonance, Power Transformers, Induction Machines, Quasi-Periodic, Chaotic Oscillation

I. INTRODUCTION

Ferroresonance is a non-linear electrical phenomenon that arises when a system containing capacitance and a non-linear iron-core inductance becomes energised under certain switching or fault conditions [1, 2]. Unlike traditional resonance, which involves a linear relationship between circuit components, ferroresonance is highly non-linear and unpredictable and is characterized by a sudden onset of high voltage and current oscillations. These oscillations are often sustained and may occur at subharmonic, harmonic, or chaotic frequencies [3, 4].

Typically, the phenomenon is initiated by the de-energisation of one phase of a multi-phase system or an open conductor in a cable-fed distribution transformer network, leading to an unbalanced excitation condition. The interaction between the system's capacitance (often due to long underground cables or unloaded lines) and the saturable transformer core inductance

gives rise to these persistent and potentially damaging oscillations [5, 6]. The phenomenon poses a significant threat to the reliability and stability of power distribution systems. It can lead to overvoltages exceeding 2–3 times the rated system voltage, excessive harmonic distortion, and high transient energy content [7, 8]. These conditions severely stress insulation systems, leading to premature failure of distribution-class transformers, surge arresters, and other connected apparatuses. Also, the unpredictable and intermittent nature of ferroresonance makes it difficult to detect using conventional protection schemes, often resulting in mis-operations and extended outages. The phenomenon is especially prevalent in isolated neutral systems, cable-fed substations, and lightly loaded or back-fed transformer configurations [9, 10].

II. HISTORICAL BACKGROUND

The earliest documented recognition of ferroresonance dates to 1911 when Dwight and Baker observed abnormal voltage conditions during a generator ground fault incident. They described the phenomenon as "double voltage," marking the first formal acknowledgement of ferroresonant behaviour in electrical networks [11].

In the 1930s, the study of ferroresonance progressed using graphical methods. These early analytical tools allowed engineers to visualise system behaviours under various configurations, thereby gaining deeper insights into the occurrence of oscillatory overvoltages [12]. A notable advancement was made by Rudenberg, who applied graphical techniques to study the impact of ferroresonance in power transformers. Subsequently, in 1941, Edith Clarke along with collaborators utilised a transient network analyser, an early form of analogue computer, to simulate and examine ferroresonant conditions in transformer-fed circuits [13].

The 1950s witnessed further analytical depth, led by Hayashi, whose studies introduced a more systematic and theoretical understanding of non-linear oscillations, paving the way for more sophisticated mathematical modelling techniques [14]. Interest in the topic was reignited during the 1960s, mainly due to an increase in operational failures involving underground cable-fed transformers. The widespread deployment of these configurations highlighted vulnerabilities in traditional system protection and spurred numerous investigations into the root causes and mitigation strategies for ferroresonance [15, 16].

By the 1990s, ferroresonance had become a prominent subject in power systems literature [13, 14]. In particular, a 1994 study by TA Short et al. highlighted the higher propensity of ferroresonance in cable-fed transformer arrangements. Their findings verified earlier empirical observations and provided a theoretical basis for further research [17]. In 2000, Jacobson expanded the body of knowledge by quantifying the increased losses within transformers operating under ferroresonant conditions. These findings underscored the thermal and mechanical stresses inflicted on transformers during such events [18].

Recent decades, from 2011 to the present, have seen the application of advanced computational tools such as MATLAB, EMTP-RV, PSCAD, and ATPDraw. These platforms have enabled detailed time-domain simulations of ferroresonance phenomena, facilitating parameter sensitivity studies, waveform analysis, and testing of mitigation techniques in a virtual environment [19-21].

III. DOCUMENTED DAMAGING EFFECTS

The damaging consequences of ferroresonance have been well-documented across various studies and technical reports [9, 22], with the phenomenon recognised as a leading cause of unexpected failures in medium-voltage distribution networks. Among the most vulnerable components consistently identified are transformers and surge arresters [23].

Several real-world incidents underscore the severity of such failures, which can be as destructive as sub-synchronous resonance events [24, 25]. For instance, a transformer and its low-voltage surge arresters experienced ferroresonance following an open-conductor fault adjacent to an underground cable. Field crews reported a loud, irregular growling noise from the transformer, with visible paint bubbling and tank charring due to overheating from magnetic saturation [26]. Similarly, during the commissioning of medium-voltage systems, lightly loaded potential transformers (PTs) were catastrophically damaged by ferroresonant oscillations triggered by switching operations [27].

In grid-connected renewable installations, a wind farm experienced voltage surges exceeding three times the nominal value during single-pole breaker operations. Although high-voltage surge arresters eventually mitigated the overvoltage, they were pushed to their energy-handling limits, absorbing approximately 173 kJ in just 0.22 seconds [28].

Another incident involved a 112 kVA pad-mounted transformer where ferroresonance occurred during phased re-energisation through underground cables. The arrester on the third phase violently failed and blew its fuse after approximately 10 seconds of resonant conditions [29]. In a separate event at a 115 kV substation, sustained ferroresonance during routine switching operations led to the failure of surge arresters on both the high- and low-voltage sides of the transformer [30]. On a 400 kV series-compensated transmission line, ferroresonance effect was also recorded [31]. The documented incidences of ferroresonance clearly demonstrate the substantial threat this phenomenon poses to power quality and system reliability, thereby reinforcing the critical need to develop and implement effective sustainable mitigation strategies.

IV. RELEVANCE OF FERRORESONANCE STUDIES

Despite being a well-known phenomenon for over a century, the study of ferroresonance remains of paramount importance in modern power systems. With the evolution of power network architectures and the increasing complexity of distributed energy integration, the operating conditions that give rise to ferroresonance are now more common than ever [32, 33]. Not only does the phenomenon persist, but its manifestations have become more varied, unpredictable, and damaging, posing new challenges to power system reliability, equipment protection, and system design.

In today's distribution networks, ferroresonance is no longer confined to rare switching operations or obscure system faults. Instead, it has emerged as a recurrent issue in systems that operate under light-load conditions, contain long cable runs, or employ isolated or floating neutral configurations [34,35]. The growing interconnection of distributed generation sources, along with evolving grid topologies, further complicates the predictability and mitigation of ferroresonant events [35].

Iron-core transformers remain the backbone of medium and low-voltage power distribution networks. These transformers are inherently non-linear due to magnetic core saturation, a critical condition for ferroresonance initiation. The continual reliance on conventional transformer technology, especially in regions where solid-state transformers or advanced mitigation technologies are not yet economically viable, means the threat of ferroresonance cannot be overlooked. Also, many distribution networks are undergoing asset life extension initiatives, where old transformers are retained beyond their design life. These aging units are more susceptible to magnetic saturation, insulation breakdown, and thermal stress during ferroresonant conditions [36].

The global transition towards renewable energy has led to the proliferation of wind power systems, many of which are based on Doubly-Fed Induction Generator (DFIG) technology. DFIG-based systems introduce additional power electronic components and control dynamics into the grid, which may inadvertently create or amplify conditions favorable to ferroresonance [37]. The DFIG stator is typically connected directly to the grid through a step-up transformer, which is again a potential candidate for ferroresonant excitation under certain operating scenarios, such as open-phase faults or islanding conditions [38]. Also, modern grids are increasingly equipped with adaptive control schemes, intelligent switchgear, and automated fault management systems. While these technologies improve operational efficiency and resilience, they may also introduce rapid switching transients or isolated conditions that unintentionally set the stage for ferroresonant oscillations [39].

There is also a growing trend toward replacing overhead lines with underground cables, especially in urban environments and renewable plant interconnections. These cables introduce significant line-to-ground capacitance, which when combined with lightly loaded or isolated transformers, can form the classic L-C circuit that gives rise to ferroresonance [40, 41].

Cable-fed transformers are widely recognised in literature as particularly susceptible to ferroresonance. This concern is compounded in renewable energy networks and smart grid environments, where cable connections are common and operational conditions are dynamic [23].

V. PHYSICS OF FERRORESONANCE

One of the key physical mechanisms underpinning ferroresonance is magnetic core saturation [42, 43]. Under abnormal conditions such as single-phase switching, or open conductor faults, the voltage applied to a transformer can exceed the linear range of its magnetic core. Once the core saturates, the inductance of the device decreases sharply, introducing significant non-linearities into the circuit. This saturation causes the transformer to draw large harmonic currents, particularly at odd harmonic orders (3rd, 5th, 7th, etc.) [44, 45]. These harmonic currents can excite natural resonant points within the power network. If the frequency of the harmonic component coincides with the system’s resonant frequency (or one of its harmonics), it can trigger sustained voltage and current oscillations, even in the absence of an external harmonic source. These oscillations can have extremely high peak values, far exceeding nominal ratings, and may persist until the circuit topology or loading conditions change [45].

Mathematically, ferroresonance is often modeled using differential equations [46]. The simplest ferroresonant system consists of a nonlinear inductor (L) representing the transformer's inductance, a resistor (R) representing the equivalent resistance that accounts for the transformer's no-load losses, and a capacitor (C) representing the system capacitance, as illustrated in Fig. 1 [47].

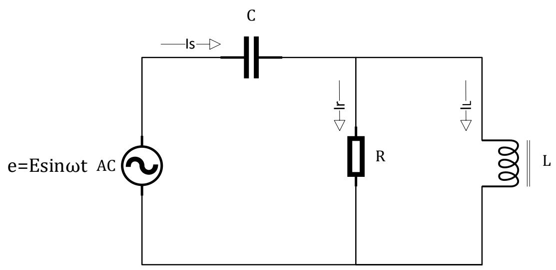


Fig. 1: A Simplified Ferroresonant Circuit

Using the fundamental circuit laws that govern the relationships between voltage, current, and flux linkage, the differential equation of the circuit can be obtained as follows.

Voltage across the non-linear inductor:

$$v_L = \frac{d\lambda}{dt} = e - v_c \qquad (1)$$

Where:
λ is the flux linkage in the non-linear inductor and v_c is the voltage across the capacitor.
Current across the capacitor:

$$i_c = C\frac{dv_c}{dt} = I_s = i_l + \frac{1}{R}v_l \qquad (2)$$

If we substitute $v_L = \frac{d\lambda}{dt}$ and $i_l = a\lambda + b\lambda^n$ into (4) we have:

$$C\frac{dv_c}{dt} = a\lambda + b\lambda^n + \frac{1}{R}\frac{d\lambda}{dt} \qquad (3)$$

Where $i_l = a\lambda + b\lambda^n$ is the non-linear current through the inductor,
a and *b* are constants that characterize the magnetizing behavior of the transformer, while the value *n* represents the degree of saturation.

Dividing (3) through by C:

$$\frac{dv_c}{dt} = \frac{a\lambda + b\lambda^n}{C} + \frac{1}{RC}\frac{d\lambda}{dt} \qquad (4)$$

From (1):

$$v_c = e - \frac{d\lambda}{dt} \qquad (5)$$

Therefore,

$$\frac{dv_c}{dt} = \frac{de}{dt} - \frac{d^2\lambda}{dt^2} \qquad (6)$$

Substitute (6) into (4):

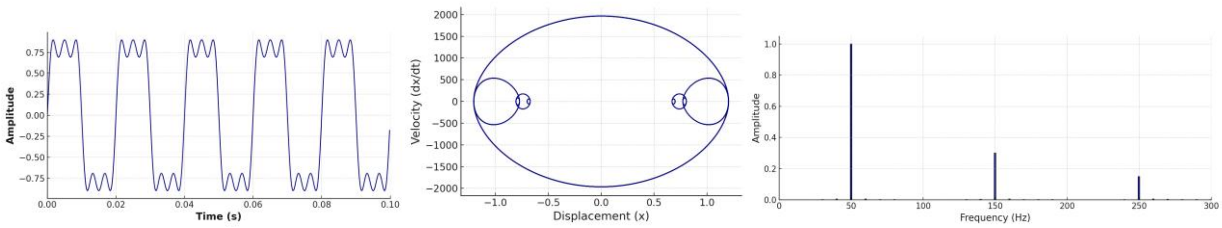
$$\frac{de}{dt} - \frac{d^2\lambda}{dt^2} = \frac{a\lambda + b\lambda^n}{C} + \frac{1}{RC}\frac{d\lambda}{dt} \qquad (7)$$

Equation (7) can be rearranged as:

$$\frac{de}{dt} = \frac{d^2\lambda}{dt^2} + \frac{1}{RC}\frac{d\lambda}{dt} + \frac{1}{C}(a\lambda + b\lambda^n) \qquad (8)$$

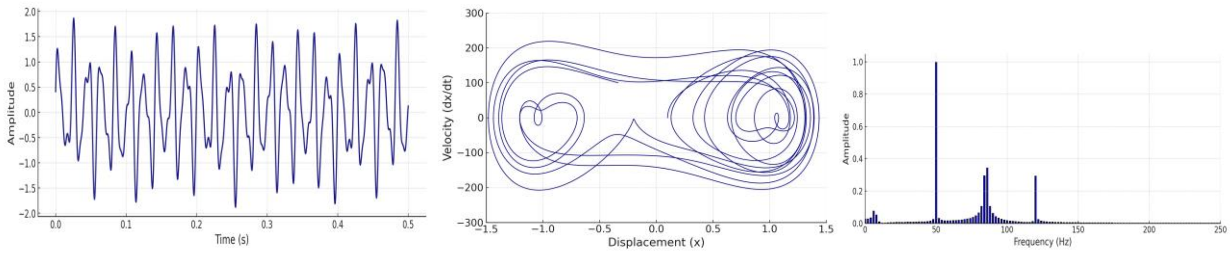
Equation 8 therefore represent a differential equation of the ferroresonant circuit shown in Fig. 1. It relates the input voltage e to the flux linkage λ and its derivatives. This equation can be further analyzed to study the ferroresonance phenomenon but the non-linear term λ^n makes solutions difficult to obtain in general.

Others have used phase plane plot and frequency spectrum to visualize the phenomenon. Depending on the excitation level and system damping, the system can settle into [46-48]:



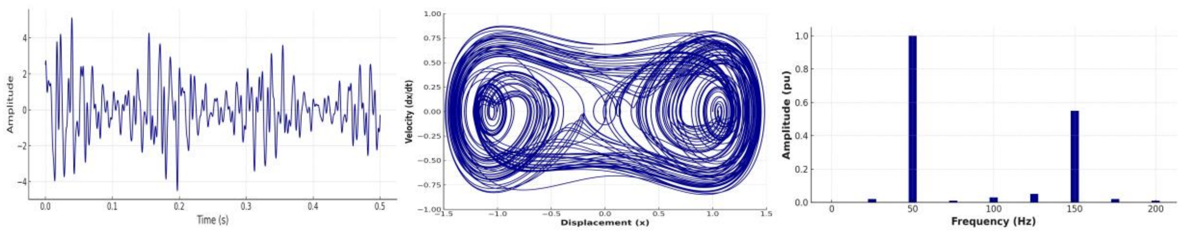
(a) (b) (c)

Fig 2. Ferroresonance in periodic-state: (a) Time domain waveform, (b) Plane phase plot, (c) Frequency spectrum



(a) (b) (c)

Fig. 3. Ferroresonance in quasi-periodic state: (a) Time domain waveform, (b) Plane phase plot, (c) Frequency spectrum



(a) (b) (c)

Fig 4. Ferroresonance in chaotic-state: (a) Time domain waveform, (b) Plane phase plot, (c) Frequency spectrum

- A periodic steady-state oscillation (classical ferroresonance),
- A quasi-periodic oscillation, or
- A chaotic oscillation

These modes are elaborated below.

A. Periodic Steady-State Oscillation

In a periodic steady-state oscillation, ferroresonance occurs when a power system, typically comprising a transformer, circuit breaker, and underground cable, experiences sustained, nonlinear oscillations at a constant amplitude and waveform. This is commonly referred to as the classical ferroresonance mode, which arises when the nonlinear inductance of the transformer core interacts with the system capacitance under specific switching or fault conditions.

The waveform in Fig. 2(a) displays a repetitive shape over time, characterized by a non-sinusoidal but periodic pattern. The sustained oscillations at a constant amplitude indicate the presence of nonlinear distortion, commonly caused by transformer core saturation.

In the phase plane, Fig. 2(b), the trajectory forms a closed loop, indicating that the system returns to the same state repeatedly. This closed loop signifies periodic steady-state motion, characterized by constant energy oscillations. The non-elliptical shape of the loop is a reflection of the waveform distortion, which is a hallmark of nonlinear behaviour.

The frequency spectrum (Fig. 2(c)) reveals a dominant peak at the fundamental frequency, likely around 50 Hz. This is expected in a periodic waveform. However, the spectrum also shows prominent harmonic peaks, particularly at odd-order harmonics such as 150 Hz. The presence of these significant harmonic components is an indication of waveform distortion.

B. A quasi-periodic oscillation

In a quasi-periodic oscillation, the system exhibits two or more oscillations with incommensurate frequencies. This means the frequency components do not share a common multiple, in contrast to a periodic oscillation where the frequencies are harmonically related.

Fig 3(a) shows a waveform that is clearly distorted and oscillatory, yet it does not repeat within any finite time interval. The waveform resembles a modulated sine wave, likely resulting from amplitude or frequency modulation caused by the interaction of incommensurate frequency components.

The phase plane plot in Fig 3(b) reveals a complex, non-repeating behavior. Instead of forming a closed, periodic loop, the trajectory generates a series of nested, interwoven patterns. This woven appearance indicates that the oscillation is not purely periodic, but rather exhibits a quasi-periodic nature.

The frequency spectrum, depicted in Fig 3(c), reveals a complex pattern with multiple frequency components. Two prominent peaks dominate the spectrum, corresponding to two distinct frequency components. In addition to these dominant peaks, several sidebands and secondary frequency components are evident, indicating a rich and complex frequency response.

C. Chaotic Oscillation

Chaotic oscillation represents the most unstable and destructive regime of ferroresonance, a highly nonlinear phenomenon in power systems. This chaotic behaviour arises when the nonlinear magnetic inductance, particularly in transformer cores, interacts with the network capacitance under specific switching or fault conditions. Common triggers include open-phase operations, light load conditions, or long cable runs.

In the chaotic oscillation regime, the power system exhibits unpredictable, bounded, and non-repeating oscillations. These oscillations are extremely sensitive to initial conditions, meaning that even small changes in the system parameters or initial state can lead to vastly different long-term behaviours.

From a practical standpoint, the chaotic oscillations pose significant challenges for power system stability and equipment protection. The unpredictable nature of the waveforms can lead to high-magnitude voltage and current spikes, which can potentially damage transformers, circuit breakers, and other critical components. This makes chaotic ferroresonance a serious concern for power system operators and engineers.

The waveform in Fig. 4(a) exhibits an irregular and non-repetitive pattern, even over extended periods. It appears as a sequence of erratic peaks and troughs, lacking a consistent frequency or amplitude. Despite its unpredictability, the oscillation remains bounded, meaning it does not grow indefinitely.

The phase plane plot in Fig. 4(b) reveals a dense, tangled trajectory that never settles into a loop or repeats. Instead, it fills a strange attractor—a bounded region of state space that appears disordered but is deterministic. The trajectory never intersects itself exactly, yet is confined to a complex shape.

The frequency spectrum in Fig. 4(c) is broad and continuous, with energy distributed across many frequencies. Unlike periodic signals, which exhibit sharp peaks at integer multiples (harmonics), the spectrum appears "noisy" and non-discrete. Although a dominant frequency may be faintly visible, it is embedded in a cloud of side frequencies.

VI. MITIGATION STRATEGIES

A broad range of measures has been proposed in the literature to curb the harmful consequences of ferroresonance and to safeguard network assets [50, 51]. The most widely cited techniques fall into three complementary categories: transformer-core design, capacitance management, and deliberate damping, as elaborated below.

A. Transformer-Core Design Optimization

A widely recommended mitigation measure for ferroresonance is to reduce the transformer's operating flux density so the magnetisation curve remains within its quasi-linear region [52, 53]. Kulkarni and Khaparde observe that holding the working point below the knee of the B-H characteristic sharply lowers the core's incremental non-linear inductance, depriving the network of the energy needed to sustain resonant oscillations [54]. Other studies place the preferred flux window at 0.4–0.7 T [55]. Above this range the core enters saturation rapidly, amplifying its non-linear behaviour. Field evidence compiled by Horák confirms that transformers designed for these lower flux densities, often sold as "ferroresonance-resistant" units, seldom suffer destructive over-voltages during open-phase or back-feeding events [56].

Recent finite-element investigation also confirms that when the fundamental flux is limited to approximately 0.6 T, ferroresonant inrush currents fall by roughly an order of magnitude compared with cores designed for 1.6 T, and the peak air-gap flux remains well below the saturation knee [57]. Complementary IPST (2015) results show that enlarging the core cross-section or specifying higher-grade, flatter-knee silicon steel shifts the system's bifurcation point, removing several unstable branches from the ferroresonance locus [58].

In practice, attaining the 0.4–0.7 T target entails increasing the core cross-sectional area and/or using high-permeability grain-oriented steel so the required volts-per-turn are achieved at a lower flux level. Constraining the core to this low-flux operating window keeps its magnetising inductance nearly linear under both steady-state and transient conditions, thereby disrupting the LC feedback loop that drives sustained ferroresonant oscillations.

B. Capacitance Management

Capacitive coupling introduced during abnormal network conditions, particularly single-phase open circuits, has long been recognised as a decisive trigger for ferroresonance. Chen et al [59, 60] showed analytically and in field trials that when the effective line-to-ground capacitance exceeds a critical threshold, $C_{crit} \approx \frac{1}{\omega^2 L_m}$, the nonlinear magnetising inductance of the transformer (Lm) can resonate with that capacitance, producing sustained over-voltages. Subsequent case confirmed that cable runs longer than roughly 800 m to 1 km (equivalent to 0.15–0.25 µF per phase) exceed the critical threshold and can hence trigger ferroresonant events [61].

Because isolated-neutral and lightly loaded circuits provide little inherent damping, modern guidelines recommend maintaining line-to-ground capacitance less than critical threshold wherever practical [62]. Field retrofits have proven that adding a small neutral resistor (50–200 Ω) or installing R-C snubber networks across open-phase switches can lower the system's quality factor and pull the resonant frequency away from the fundamental. By keeping the aggregate shunt capacitance below the calculated critical limit, utilities dramatically reduce the probability that a single-phase fault or open-switch condition will energise the nonlinear LC tank that drives ferroresonant oscillations [5].

C. *Damping Techniques*

A complementary and often decisive approach to curbing ferroresonance is to inject deliberate damping into the resonant circuit so that any transient energy is quickly dissipated. Hamid and Fathi [63] first showed that adding a modest resistive component raises the system's overall damping ratio and collapses the quality factor of the inductive–capacitive tank, preventing the oscillation from building to destructive levels. Subsequent field experience reinforces this principle. Utilities frequently employ neutral-earthing resistors in the 50–200 Ω range or temporary load banks that are switched in during energisation; both methods attenuate first-cycle over-voltages by 70–90 % and reduce ferroresonant bursts from seconds to cycles [64]. Where single-pole switching or long cable runs cannot be avoided, R-C snubbers placed across voltage-transformer primaries or open-phase switches provide broadband loss, shifting the resonant frequency and absorbing residual energy. Modern "ferroresonance-proof" voltage transformers go a step further by incorporating higher-loss core steel and built-in burden resistors, delivering intrinsic damping without external hardware [65]. Finally, metal-oxide surge arresters fitted with grading resistors add both over-voltage clamping and extra resistive loss, shortening chaotic oscillatory bursts before thermal runaway can occur.

VII. Practical Challenges with existing Mitigation Measures

While the technical countermeasures discussed in the preceding section offer effective solutions in principle, their widespread adoption and large-scale implementation are hindered by three significant challenges as discussed below.

A. Economic Viability of Low-Flux-Density Core Designs

Designing a distribution transformer to operate in the 0.4–0.7 T flux invariably means either enlarging the core cross-section or specifying premium, high-permeability steel laminations. Both approaches raise the initial capital cost and shipping weight. Anibal De Almeida et al. estimates that a 25 % reduction in flux density can increase material costs by 15–30 % and add 8–12 % to active mass [66], a burden that many utilities regard as uneconomic for medium-voltage plant. Similar conclusions are drawn by Kulkarni and Khaparde, who note that low-flux designs are "technically attractive yet commercially prohibitive except for niche installations" when evaluated on a first-cost basis [67].

B. Conflict with Utility Loss-Reduction Programmes

Many utilities are already under regulatory pressure to trim network losses. Introducing intentional resistive damping adds continuous I^2R losses to the system. Ampcontrol's application guide shows that a 100 Ω neuteral earthing resistor on a 33 kV feeder dissipates roughly 3 kW under steady-state conditions, a non-trivial addition to the loss budget for a lightly loaded circuit. Consequently, operators are reluctant to adopt mitigation schemes that appear to erode hard-won efficiency gains [68].

C. Damping versus Efficiency

A third, more subtle dilemma is that modern "high-efficiency" transformers employ low-loss magnetic steels to meet efficiency mandates. While this reduces no-load losses, it also removes intrinsic core damping, making the unit more susceptible to ferroresonant build-up. Walling et al. demonstrate that halving core loss can double the peak ferroresonant over-voltage in a cable-fed substation [69]. Recent nonlinear simulations confirm that critical core-loss values exist below which the system's bifurcation diagram blossoms into multiple unstable branches [70,71]. Thus, the industry faces a trade-off between energy efficiency and ferroresonance resilience.

VIII. Evaluating the performance of surge arresters as a mitigation measure

Building upon existing research and advancing the development of ferroresonance mitigation strategies, our recent study examined the susceptibility of diverse transformer vector groups to ferroresonance. The primary objective was to identify specific configurations that offer greater resilience to this phenomenon [39]. Among the findings, the Y-D11 configuration exhibited strong resilience, showing limited tendency to support sustained ferroresonant oscillations. In contrast, the D11-Y configuration was identified as particularly vulnerable, with high peak voltages, significant harmonic distortion, and elevated energy content observed under open-phase and light-load conditions.

Despite its vulnerability, the D11-Y transformer remains widely deployed in power distribution systems, primarily due to its compatibility with legacy infrastructure and its ability to facilitate three-phase voltage transformation without requiring a neutral conductor on the primary side. On the other hand, Y-D11 transformers are less commonly applied in distribution systems, as their secondary side lacks a neutral point, making them less suitable for low-voltage applications where single-phase loads are present. This inherent vulnerability of the D11-Y transformer highlights the importance of implementing effective ferroresonance mitigation strategies wherever this configuration is used. One promising approach is the use of surge arresters, which offer the potential to clamp excessive overvoltages and dissipate oscillatory energy during ferroresonant events.

In this section, the performance of surge arresters as a mitigation measure is evaluated. The study employed the same simulation setup described in [39], with the addition of a surge arrester connected across the transformer secondary. The arrester used in the simulation is based on a metal oxide varistor (MOV) element, known for its strong non-linear voltage-current characteristics.

Fig. 5 illustrates the modified circuit setup incorporating the surge arrester. For the purposes of the simulation, a cable length of 1.5 km is connected between the source and the transformer—this length was previously identified as a critical parameter influencing ferroresonance severity [39].

The comparative results of the simulations, both with and without the surge arrester, are summarised in Table 1. The results show that the incorporation of the arrester significantly reduced the peak voltage, peak current, and total energy content associated with ferroresonance. However, the analysis also revealed elevated levels of Total Harmonic Distortion (THD) in both voltage and current during arrester conduction.

Table 1: Comparative results

Vector Group	THD-V (%)	THD-A (%)	Peak Voltage (kV)	Peak Current (kA)	Energy Content kWh
D (11)/Yn (Without arrestor)	6.83	17.96	28.7	7.7	1.1
D (11)/Yn (With arrestor)	24.49	350	11.25	1.22	0.75

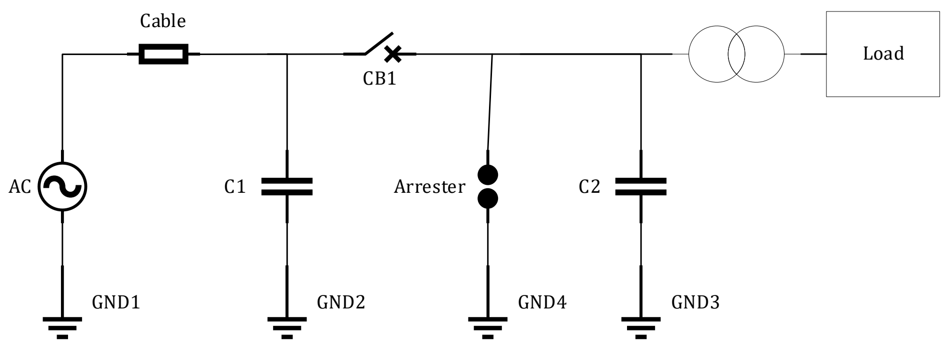


Fig. 5: Simulation setup circuit

This increase in THD is attributed to the non-linear behaviour of the MOV element, which operates in a highly non-linear region once its conduction threshold is exceeded. Importantly, this distortion is transient and occurs only during the arrester's conduction phase, meaning its impact on long-term power quality is limited.

This assessment demonstrates that surge arresters can be effectively employed to suppress ferroresonant overvoltages in D11-Y transformer applications, with only a minimal and short-duration impact on power quality. This makes them a practical and cost-effective mitigation strategy, particularly in installations where replacing or reconfiguring transformers is not feasible.

IX. CONCLUSION

This review is aimed to provide an in-depth and structured exploration of ferroresonance, offering a consolidated understanding of the phenomenon and identifying critical gaps for future study. The discussion traced the historical evolution of the concept, from its early detection in the early 20th century to the more sophisticated analytical and simulation tools used today. Central to the review was a detailed account of the key characteristics of ferroresonance, including its non-linear, oscillatory behaviour and the variety of its manifestations including periodic, quasi-periodic and chaotic states. The study further evaluated various mitigation strategies. While these mitigation methods have demonstrated theoretical effectiveness, the review pointed out practical challenges that complicate their widespread implementation.

The study identified specific knowledge gaps that warrant further research. This includes the need to develop more practical and cost-effective methods to address the limitations of existing mitigation measures.

Importantly, this study provides the foundation for future investigations focused on improving grid resilience and protecting equipment against the growing challenges posed by the increasing prevalence of underground cabling connections with nonlinear devices and the integration of renewable energy sources.

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Data Availability Statement

The datasets used and analyzed during the course of this study are available from the corresponding author upon
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Author Contribution

Tere are no persons or third-party services involved in the research or manuscript preparation who are not listed as an
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