

About the Non-Observability of flux Peaks in Ferro-Resonant Nonlinear Magnetic Circuits

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Abstract: - In this paper, a nonlinear analysis is provided for a simplified version of a ferro-resonant circuit with a non-linear hysteresis to exhibit sudden peaks in voltage/current/flux, which endanger and stress the components and shorten the lifespan of the component circuit. The approach relies on a toy model circuit (simplified version of a ferro-resonant power circuit), which is nonlinear due to magnetic hysteresis. Utilizing a well-known local analysis to evaluate the occurrence of this phenomenon, it is shown that the classical sufficient condition for local observability may fail around operating points associated with peak behavior when only voltage/current measurements are considered. This result is local and model-dependent and does not preclude the use of alternative measurements or other new practical detection methods.

Key-Words: - Ferroresonance, Observability, Lie derivative, toy model, nonlinear circuit, magnetic hysteresis, overvoltage, state-space model.

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1 Introduction

The ferroresonance is a nonlinear phenomenon that can affect electrical networks, manifested as sustained overvoltages, overcurrents, or distortions in voltage and current waveforms, neutral displacement, and premature deterioration of power system components. Unlike linear resonance, it can occur at multiple frequencies, including frequencies far from the fundamental and its harmonics, [1]. Four main regimes can be distinguished: fundamental (when the oscillation period coincides with that of the network, leading to the appearance of harmonics), subharmonic (characterized by frequencies lower than the fundamental), quasiperiodic (with higher frequencies but without stable periodicity), and finally, chaotic (with a wide spectrum of frequencies above the fundamental and sensitivity to initial conditions). These regimes are characterized by the existence of multiple steady states and a high sensitivity to small variations in the system parameters. The probability of this phenomenon occurring increases when capacitors and coils with nonlinear (saturable) inductance are connected simultaneously, as well as in systems that exhibit unfixed potential points or components (mainly transformers) operating well below their rated power.

To study this anomaly, several approaches have been developed, including analytical methods (such as spectral density analysis or nonlinear dynamics), simulations, and experimental procedures. These methods reproduce the phenomenon but provide practical solutions only for specific situations, [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24].

The existing literature suffers from the lack of the following issues:

1. A significant portion of the studies focus on specific networks, and the proposed solutions are only applicable within those contexts; therefore, they cannot be generalized.
2. Some publications merely simulate the effect using software, without providing practical solutions to the phenomenon.
3. In other cases, nonlinear dynamics, Poincaré mapping, and/or phase-plane analysis are employed. For these methods to be effective, real values of the fundamental properties of the dynamic system must be used; however, such values vary considerably across the reviewed literature. This variability arises from the different simplifications adopted during the modeling process. It also highlights the inherent difficulty of modeling the system, given its high

sensitivity to initial conditions and the chaotic behavior of ferroresonance under certain circumstances.

4. The PSCAD or MATLAB-Simulink software is powerful and suitable simulation tools that employ robust numerical solvers capable of accurately handling nonlinear equations and high-frequency phenomena, which are essential for transient analysis. Nevertheless, their accuracy largely depends on the equations and parameters defined by the programmer.

In this way, the ferroresonance phenomenon still requires further research and improved assessment techniques to obtain results that effectively mitigate its effects. This implies the need for a methodological approach that can be generalized while maintaining an acceptable level of accuracy.

In this paper, due to the nonlinear nature of the model (circuit), local nonlinear conditions will be given to detect (measure) possible overvoltage/currents suddenly appearing due to ferromagnetic phenomena. It turns out that the focus is on the voltage/current/flux peaks that abruptly appear in some real power circuit, [8].

To capture those peaks analytically, they will be considered as maximums and treated as local maximums in the voltage/current or flux variables. In this way, taking derivatives and equating to zero provides sufficient local conditions for a maximum around a working point. This interpretation is strictly local, aiming to bring attention to a phenomenon that is hiding the nature of these elusive overvoltage/currents and does not aim to capture the full nonlinear dynamical behavior of ferro-resonance, which may involve oscillatory regimes, bifurcations, or chaotic dynamics. However, this maximum location will provide a working point around zero for the flux, becoming a limitation of the classical local observability rank condition in this operating region.

This observation suggests a potential limitation of the local observability framework in simplified models and motivates further analysis using more general approaches, as well as possible new sensors that require a more elaborate construction.

This paper is organized as follows: Section 2 presents a formal introduction to the problem considered, Section 2.1 recasts the complete nonlinear model, Section 3 presents the main theorems and lemmas in this paper, and Section 4 shows examples using PSCAD and Matlab-Simulink. Finally, some conclusions are depicted in Section 5.

2 The Problem Considered

Given an electrical power system connected to an inductive load (Figure 1) (power grid injection, motor control, etc.), and considering the simplified circuit for analysis provided in [6]:

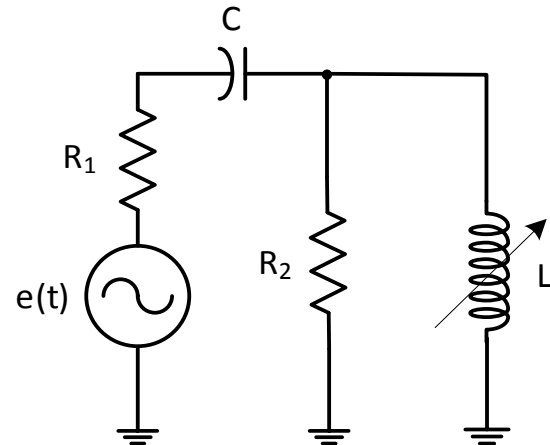


Fig. 1: Simplified electric circuit.

Source: created by the authors.

The non-linear ordinary differential equation (ODE) depicted in (1) can be written:

$$\left(1 + \frac{R_1}{R_2}\right) \cdot \frac{d^2\phi}{dt^2} + R_1 \cdot \frac{di(\phi)}{dt} + \frac{1}{C \cdot R_2} \cdot \frac{d\phi(t)}{dt} + \frac{1}{C} \cdot i(\phi) = \frac{de(t)}{dt} \quad (1)$$

Where the nonlinear inductance can be modelled using its ϕ - i relationship as shown in Figure 2:

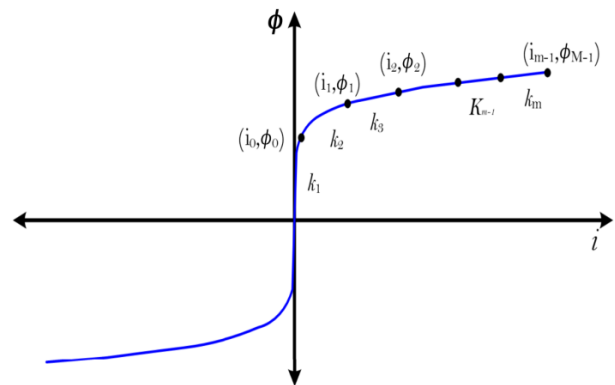


Fig. 2: Nonlinear inductance hysteresis curve.

Source: created by the authors.

Then, equation (1) can be rewritten in the well-known state-space form:

$$\dot{x} = \begin{bmatrix} x_2 \\ -\left(1 + \frac{R_1}{R_2}\right)^{-1} \cdot \left(R_1 \cdot \frac{di(x_1)}{dx_1} \cdot x_2 + \frac{1}{C \cdot R_2} \cdot x_2 + \frac{1}{C} \cdot i(x_1)\right) \end{bmatrix} + \begin{bmatrix} 0 \\ \left(1 + \frac{R_1}{R_2}\right)^{-1} \end{bmatrix} \cdot \dot{e}(t) \quad (2)$$

where $x = [\phi \ \dot{\phi}]'$, with the symbol ' as the classical matrix transpose. Equation (2) is, in fact, a nonlinear ODE with a forcing term. Moreover, this

system can be compactly written in matrix form as shown in (3):

$$\dot{x} = f(x) + g \cdot u(t) \quad (3)$$

where:

$$f(x) = \begin{bmatrix} x_2 \\ -\left(1 + \frac{R_1}{R_2}\right)^{-1} \cdot \left(R_1 \cdot \frac{di(x_1)}{dx_1} \cdot x_2 + \frac{1}{C \cdot R_2} \cdot x_2 + \frac{1}{C} \cdot i(x_1) \right) \end{bmatrix}, g = \begin{bmatrix} 0 \\ \left(1 + \frac{R_1}{R_2}\right)^{-1} \end{bmatrix}, u(t) = \dot{e}(t) \quad (4)$$

For the sake of clarity in (4), let's define:

$$K = 1 + \frac{R_1}{R_2} \quad (5)$$

Then, using (5) in model (3), the model (6) is obtained:

$$\dot{x} = \begin{bmatrix} x_2 \\ -\frac{1}{K} \cdot \left(R_1 \cdot \frac{di(x_1)}{dx_1} \cdot x_2 + \frac{1}{C \cdot R_2} \cdot x_2 + \frac{1}{C} \cdot i(x_1) \right) \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{K} \end{bmatrix} \cdot u(t) \quad (6)$$

In the following sections, a sufficient condition will indicate that observability is a crucial concept to detect over-peaks in ferro-resonant circuits. Moreover, the local working point, where possible peaks occur, will prove to be around zero flux.

3 Conditions for Maximum (Peaks) In Flux, Current, and Voltage

The focus of this paper is on overpeaks occurring in the state variables. In this context, classical analysis considers chaos using Lyapunov exponents, phase-portrait with bifurcation analysis, and exhaustive simulations.

Looking for those peaks in flux will show a path connecting these conditions with known conditions for observability, leading to conclusions and discussions for possible new research needed around sensors and measurements. To present the results straightforwardly and a formal derivation, the well-known condition for a local maximum can be evaluated by taking derivatives and equating them to zero:

$$\dot{\phi} = 0 \Leftrightarrow x_2 = 0 \Rightarrow \dot{x}_2 = \frac{1}{K} \dot{e}(t) - \frac{1}{K \cdot C} \cdot i(x_1) \quad (7)$$

The condition in (7) for maximums can be interpreted as a capacitive circuit around $x_2=0$, with the voltage across $R_1=0$, as indicated in (8):

$$\dot{\phi} = 0 \Leftrightarrow x_2 = 0 \Rightarrow \dot{x}_2 = \frac{1}{K} \dot{e}(t) - \frac{1}{K \cdot C} \cdot i(x_1) \Rightarrow i(x_1) \cdot R_1 = 0 \Rightarrow i(x_1) = 0 \quad (8)$$

According to the nonlinear curve in Figure 2, this implies that the possible peaks (maxima) occur

at $x_1=0$. In the next section, the rank of the nonlinear observability distribution will be analyzed around this point for the two possible measurements (in real circuits): flux and derivative of flux(current).

4 Main Results

In this section, the main result of the paper is presented. For the sake of completeness, a series of intermediate results will be proved before arriving at the main contribution of the paper.

Assumption: A classical plane curve around zero will be considered in Figure 2 resulting (9):

$$\left. \frac{di(x_1)}{dx_1} \right|_{x_1=0} = 0 \quad (9)$$

Linearization

If a local linearization is considered around the point $\{x_1=0, x_2=0\}$, then system (6) will lead:

$$\dot{\tilde{x}} = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{1}{K \cdot C \cdot R_2} \end{bmatrix} \cdot \tilde{x} + \begin{bmatrix} 0 \\ \frac{1}{K} \end{bmatrix} \cdot u(t) \quad (10)$$

Lemma 1: Given the linear system (10) with two possible output measurements (sensors):

$$\begin{aligned} h_1 &= x_1 = \phi \\ h_2 &= x_2 = \dot{\phi} \end{aligned} \quad (11)$$

Then, only the direct flux measurement is observable in (11).

Proof: The observability matrix in both cases leads (see, for instance, [22], pp. 148-150):

$$O_1 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad O_2 = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{1}{K \cdot C \cdot R_2} \end{bmatrix} \quad (12)$$

Clearly in (12), only the first case is observable. This completes the proof.

Based on this result, a nonlinear extension is intended, adding an extra possible (real) measurement:

Theorem 1: Given a nonlinear ferro resonant circuit (3)-(5) with three possible output measurements as shown in (13):

$$\begin{aligned} h_1 &= x_1 = h(\phi), & \left. \frac{\partial h(x_1)}{\partial x_1} \right|_{x_1=0} &\neq 0 \\ h_2 &= x_2 = h(\dot{\phi}) \\ h_3 &= h(i(x_1)) \end{aligned} \quad (13)$$

The classical sufficient condition for local observability is only satisfied for h_1 around the operating point $x_1 = 0$ and $x_2=0$.

Proof: A sufficient condition for local observability can be found at, [23], pp. 418 as described in (14):

$$\text{rank} \left[d_{\{L_f h, L_g h\}} \Big|_{x_0} \right] = 2 \quad (14)$$

where $d_{\{L_f h, L_g h\}} \Big|_{x_0}$ denotes a distribution evaluated at a working point x_0 (see, [23] for details), $L_f h$ the classical Lie derivative, and $\text{rank}[\cdot]$ means the matrix rank.

In this way, three output measurements will be rewritten in (15):

$$\begin{aligned} h_1 &= x_1 = h(\phi) \\ h_2 &= x_2 = h(\dot{\phi}) \\ h_3 &= h(i(x_1)) \end{aligned} \quad (15)$$

Then, the local observability distribution in these cases leads:

$$O = \frac{\partial}{\partial x} \begin{bmatrix} h(\cdot) \\ L_f h \\ L_g h \\ \vdots \end{bmatrix} \quad (16)$$

h₁:

$$O_1 = \frac{\partial}{\partial x} \begin{bmatrix} h(x_1) \\ \frac{\partial h(x_1)}{\partial x_1} \cdot x_2 \end{bmatrix} = \begin{bmatrix} \frac{\partial h(x_1)}{\partial x_1} & 0 \\ \frac{\partial^2 h(x_1)}{\partial x_1^2} \cdot x_2 & \frac{\partial h(x_1)}{\partial x_1} \end{bmatrix} \quad (17)$$

According to (16) and (17), if $\frac{\partial h(x_1)}{\partial x_1} \Big|_{x_1=0} \neq 0$, then the system is locally observable.

h₂:

$$O_2 = \frac{\partial}{\partial x} \begin{bmatrix} h(x_2) \\ \frac{\partial h(x_2)}{\partial x_2} \cdot () \end{bmatrix} \quad (18)$$

So, every term in (18) will contain $L_f(\cdot)=0$ when evaluated at $x_1=0$ and $x_2=0$. In this case, the sufficient condition is not satisfied.

h₃:

Under the same local assumptions, the previous analysis can be extended to other measurable variables of practical interest.

$h(i(x_1)) \Leftrightarrow$ The same analysis as for $y = x_1$ can be applied locally around the considered operating point.

This completes the proof.

Remark: This result is local in nature and depends on the specific operating point and measurement choice. Under these conditions, if local observability is not satisfied, then global analysis is not expected to produce better outcomes. It turns out that alternative measurement configurations could restore local observability. Furthermore, it does not preclude practical detection or mitigation of ferro-resonance phenomena in real systems. Moreover, even voltage measurement could fail due to local observability: $v_L = N \cdot \dot{\phi} \Rightarrow$ Theorem 1 extends to this case under the same local assumptions and measurement framework.

5 Discussion

As shown, the local impossibility of measuring current/voltage to detect flux peaks to avoid ferroresonance makes this phenomenon and its solution very elucidated, and it conducts further and profound research on other measurements or ways to measure them. Some examples in this direction can be found using optical pumping magnetometers, [24] or diamond sensors with nitro [25]. In any case, it will be necessary to redefine the paradigm on "how to measure" or "how much to measure."

6 Applications Example

Example 1

As an application example, consider a 33-kV generation system, represented by a Thévenin equivalent of the network, which supplies electric power to a 300-kVA, 33/0.40-kV power transformer operating at full load, as shown in Figure 3:

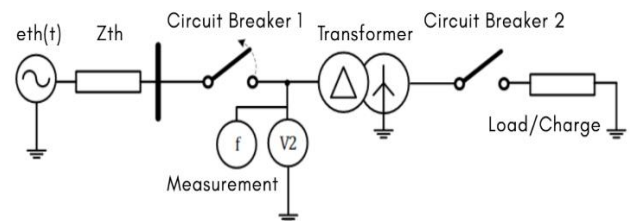


Fig. 3: Single-line schematic of the 33 kV generation system with a Thévenin equivalent and a 300 kVA transformer.

Source: created by the authors.

The typical parameters considered in the analysis are presented in Table 1.

Table 1. The typical parameters considered.

Equipment	Magnitude	Value	Unit
Generator	Voltage	33	kV
	Resistance	0,609	ohm
	Inductance	0,0193	Henry
Parasitic capacitances	Capacitor	0 a 0,4	μF
Transformer	Power	300	kVA
	Primary connection	Triángulo	---
	Secondary connection	Estrella	---
	Primary voltage	33	kV
	Secondary voltage	0,4	kV
	Positive-sequence impedance	0,04	pu
	Eddy-current losses	0,0017	pu
	Core losses	0,017	pu
	Magnetizing inrush time	1	second
	Magnetizing current	1,6	%
	Knee-point voltage	1,12	pu
Load/Charge	Voltage	0,4	kV
	Power	300	kVA

Source: created by the authors.

With the parameters shown in Table 1, using the PSCAD/EMTDC simulation software and considering two linearizations of the transformer's magnetization curve, the system was successfully simulated. At a given instant (1 second in the simulation), breaker 1 opens. The voltage and frequency values measured at the transformer's primary terminals, as well as the resulting flux, are shown in the following figures:

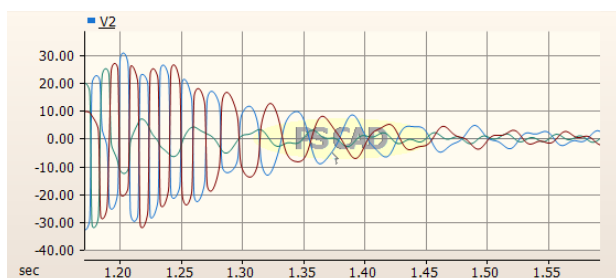


Fig. 4: Primary-side terminal voltage V2 as a function of time.

Source: created by the authors.

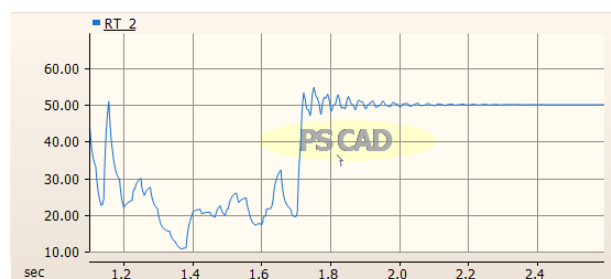


Fig. 5: Primary-side terminal frequency f as a function of time.

Source: created by the authors.

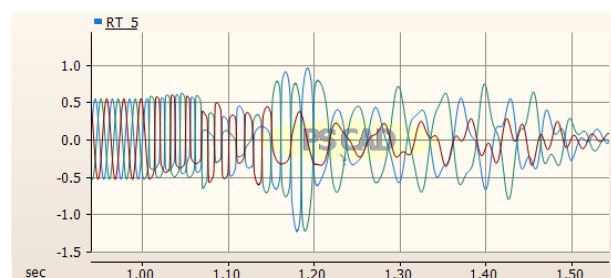


Fig. 6: Transformer flux as a function of time.

Source: created by the authors.

As can be observed in Figure 4, Figure 5, and Figure 6, the phase-to-neutral voltage produced greatly exceeds the nominal voltage, potentially causing damage to the various pieces of equipment installed in the system. The voltage values exceed 30 kV, whereas the nominal value is 19 kV.

Example 2

In this case, a Simulink model will be considered in order to explore the observability in flux. To these aims, two different initial conditions will be considered, with the results shown in Figure 7.

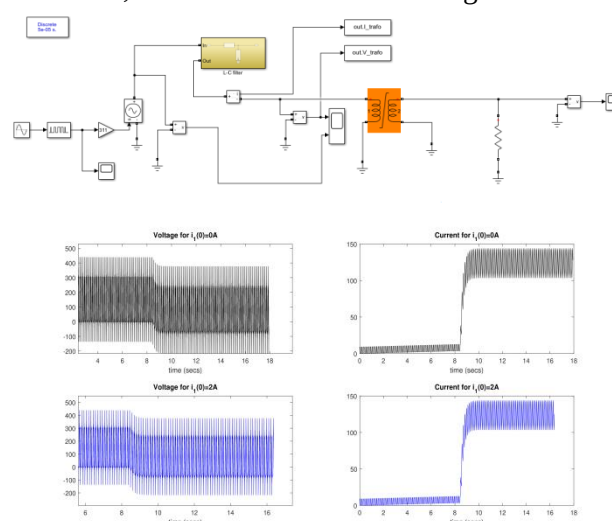


Fig. 7: A real transformer simulation with two different initial conditions and PWM applied.

Source: created by the authors.

Clearly, neither the current nor the voltage can be identified for the two different initial conditions.

7 Conclusion

In this paper, a complete analysis of a simplified nonlinear ferro resonant circuit has been presented. Utilizing a state-space model, the possible point for maximums in both flux and flux derivative (inductance voltage) was derived.

Based on the classical nonlinear observability (local) sufficient condition using Lie derivatives, it was shown that this condition is not satisfied at the identified operating point when considering flux or its derivative as outputs. This highlights a limitation of the local observability framework within the context of the adopted simplified model. However, this does not imply that ferro-resonant phenomena cannot be detected or mitigated in practice. In real systems, alternative measurements such as waveform distortion, harmonic content, or energy-based indicators may provide effective detection mechanisms.

Future work will focus on extending the analysis beyond local conditions, including global observability properties, richer measurement configurations, and more detailed nonlinear models, as well as experimental validation.

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Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the author(s) utilized artificial intelligence (AI) technologies solely for the purpose of linguistic refinement and grammatical correction. Following the application of these tools, the author(s) comprehensively reviewed, verified, and edited the resulting text. The author(s) maintain full accountability and responsibility for the accuracy, integrity, and final content of the publication.

References:

- [1] Rezaei, S., Aref, S., Sedighi Anaraki, A. A review on oscillations in Wind Park due to ferroresonance and subsynchronous resonance. 2021. IET Renew. Power Gener. Vol. 15, pp. 3777–3792. <https://doi.org/10.1049/rpg2.12287>.
- [2] Uyaroglu, Y.; Varan, M.; Emiroglu, S. Chaotic ferroresonance and its control with sliding mode technique for voltage transformer circuits: A case study of manual single phase switching operation in three-phase transmission system. 2012. Optoelectronics and Advanced Materials, Rapid Communications. Vol. 6, pp. 498-503, [Online]. <https://oam-rc.inoe.ro/articles/chaotic-f-erroresonance-and-i-ts-c-ontrol-with-s-liding-m-ode-technique-for-voltage-transformer-circuits-a-case-study-of-manual-single-phase-switching-operation-in-three-phase-transmission-system/> (Accessed Date: March 15, 2026).
- [3] Pal, R. S; Roy, M. Investigation on the Occurrence of Ferroresonance with the Variation of Core Loss of a Transformer using Nonlinear Dynamic Model of the Transformer. 2021 7th International Conference on Electrical Energy Systems (ICEES), Chennai, India, pp. 445-447. <https://doi.org/10.1109/ICEES51510.2021.9383708>.
- [4] Sakarung, P.; Chatratana, S. Application of PSCAD/EMTDC and Chaos Theory to Power System Ferroresonance Analysis. 2005. Rajamangala University of Technology Suvarnabhumi and King Mongkut's University of Technology North Bangkok.Proceedings of the International Conference on Power Systems Transients (IPST), Montreal, Canada, [Online]. https://www.ipstconf.org/papers/Proc_IPST2005/05IPST227.pdf (Accessed Date: March 15, 2026).
- [5] Rezaei, S. An intelligent algorithm for Negative Sequence Directional Element of DFIG during Ferroresonance in smart grid, 2019. IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Genova, Italy, pp. 11-14, <https://doi.org/10.1109/EEEIC.2019.8783495>.
- [6] Bin, W.; Chao, Z.; Yu, X.; Fan, Z. Analytical solution of serial ferroresonance triggered by circuit breaker operation in solidly grounded

- power grids. 2023 *International Journal of Electrical Power & Energy Systems*, Vol. 154. <https://doi.org/10.1016/j.ijepes.2023.109447>.
- [7] Y. Akinrinde, A. Swanson, and R. Tiako, Effect of ferroresonance on wind turbine. comparison of ATP/EMTP and matlab/simulink 2019. *Indonesian Journal of Electrical Engineering and Computer Science* Vol. 14, Issue 3, pp. 1581-1594. <http://doi.org/10.11591/ijeecs.v14.i3.pp1581-1594>.
- [8] M. Kutija; L. Pravica, Effect of Harmonics on Ferroresonance in Low Voltage Power Factor Correction System—A Case Study Faculty of Electrical Engineering and Computing. 2021. University of Zagreb, Unska 3, 10000 Zagreb, Croatia, *Appl. Sci.* Vol. 11, Issue 10, 4322; <https://doi.org/10.3390/app11104322>.
- [9] Corea-Araujo, J.; Barrado-Rodrigo, J.; Gonzalez-Molina, F.; Guasch-Pesquer, L. 2016. Ferroresonance Analysis on Power Transformers Interconnected to Self-excited Induction Generators. *Electric Power Components and Systems*, Vol. 44, Issue 4, pp. 359–368. <https://doi.org/10.1080/15325008.2015.1115921>.
- [10] Valverde, V.; Mazon, A.; Zamora, I.; Buigues, G. 2007. Ferroresonance in Voltage Transformers: Analysis and Simulations. *Renewable Energy and Power Quality Journal*. Vol. 1, Issue 7, [Online]. <https://www.icrepq.com/icrepq07/317-valverde.pdf> (Accessed Date: March 15, 2026).
- [11] Thanomsat, N.; Plangklang, B. Ferroresonance phenomenon in PV system at LV side of three phase power transformer using of PSCAD simulation. 2016. 13th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), Chiang Mai, Thailand, pp. 1-4, <https://doi.org/10.1109/ECTICon.2016.7561384>.
- [12] Tang, M.; Ding, L.; Tang, F.; Chen, G. 2016. Analysis on ferroresonance over-voltage of UHV converter transformer bushing. 2015 4th National Conference on Electrical, Electronics and Computer Engineering. <https://doi.org/10.2991/ncece-15.2016.230>.
- [13] Mora Reinozo, F.; Quituizaca Tigre, K.;. 2021. Analysis of the Ferroresonance Phenomenon in Power Transformers. UTC. Latacunga. 89 p. Ecuador: Latacunga: Technical University of Cotopaxi (UTC), [Online]. <https://repositorio.utc.edu.ec>. (Accessed Date: March 15, 2026).
- [14] Siahpoosh, M.; Dorrell, D.; Li, L. Ferroresonance assessment in a case study wind farm with 8 units of 2 MVA DFIG wind turbines. 2017 20th International Conference on Electrical Machines and Systems (ICEMS), Sydney, NSW, Australia, 2017, pp. 11-14. <https://doi.org/10.1109/ICEMS.2017.8056530>
- [15] Ershadi Oskouei, A.; Vaziri, A.; Sadatian Moghaddam, P. Identification and Detection of Ferroresonance Phenomenon in Active Distribution Networks Using Long Short-Term Memory Neural Networks Enhanced by Genetic Algorithm. 2025. *Journal of Information Systems Engineering and Management*, Vol. 10, Issue 21. <https://doi.org/10.52783/jisem.v10i21s.3401>.
- [16] Oliveira, D.; Leal, G.; Costa, J.; Emmerik, E.; Aredes, M. Phenomena Analysis of Ferroresonance and Self-Excitation in Subsea Power Systems. 2020. Congresso Brasileiro de Automática, [Online]. <https://ojs.sba.org.br/index.php/cba/article/view/1211/1562> (Accessed Date: March 15, 2026).
- [17] IEC International Standard -Instrument transformers – Part 102: Ferroresonance oscillations in substations with inductive voltage transformers, 2014. IEC TR 61869-102-2014, pp.1-60, [Online]. <https://webstore.iec.ch/publication/6113>. (Accessed Date: March 15, 2026).
- [18] Mosaad, M.; Sabiha, N.; Abu-Siada, A.; Taha, I. Application of Superconductors to Suppress Ferroresonance Overvoltage in DFIG-WECS. 2022. *IEEE Transactions on Energy Conversion*, Vol. 37, Issue. 2, pp. 766-777. <https://doi.org/10.1109/TEC.2021.3126602>.
- [19] Perez Pineda, R.; Rodrigues, R.; Aguila Tellez, A. Analysis and Simulation of Ferroresonance in Power Transformers using Simulink, 2018. *IEEE Latin America Transactions*, Vol. 16, Issue 2, pp. 460-466. <https://doi.org/10.1109/TLA.2018.8327400>.
- [20] Heidary, A.; Radmanesh, H.; Bakhshi, A.; Samandarpour, S.; Rouzbehi, R.; Shariati, N. Compound ferroresonance overvoltage and fault current limiter for power system protection. 2020. *IET Energy Systems Integration* Vol. 2, Issue 4. <https://doi.org/10.1049/iet-esi.2019.0106>.

- [21] Zirka, S.; Moroza, Y.; Zhuykov, A.; Matveev, D.; Kubatkin, M.; Frolov, M.; Popov, M. Eliminating VT uncertainties in modeling ferroresonance phenomena caused by single phase-to-ground faults in isolated neutral network. 2021. JO. International Journal of Electrical Power & Energy Systems, Vol. 133. ISSN: 0142-0615. <https://doi.org/10.1016/j.ijepes.2021.107275>.
- [22] Rugh, Wilson. Linear system theory. 1994. Automatica, Vol. 30, Issue 11, pp. 1811-1813. ISSN: 0005-1098. [https://doi.org/10.1016/0005-1098\(94\)90090-6](https://doi.org/10.1016/0005-1098(94)90090-6).
- [23] Vidyasagar, M. Nonlinear Systems Analysis (Classics in Applied Mathematics). 2002. Springer-SIAM: Society for Industrial and Applied Mathematics. ISBN: 978-0898715262. <https://doi.org/10.1137/1.9780898719185>.
- [24] Zhao, B.; Li, L.; Zhang, Y.; Tang, J.; Liu, Y.; Zhai, Y. Optically Pumped Magnetometers Recent Advances and Applications in Biomagnetism: A Review. 2023. IEEE Sensors Journal, Vol. 23, Issue 17, pp. 18949-18962. <https://doi.org/10.1109/JSEN.2023.3297109>.
- [25] Liu, J.; Hu, H.; Wang, H.; Zeng, F. A Voltage and Current Sensing Device Based on Diamond Nitrogen-vacancy Quantum Sensing, 2025. 6th International Symposium on New Energy and Electrical Technology (ISNEET), Hangzhou, China, 2025, pp. 758-763. <https://doi.org/10.1109/ISNEET68549.2025.1406929>.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

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Conflicts of Interest

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