NYU POLYTECHNIC SCHOOL OF ENGINEERING

Electromagnetic Transients in Transformers: Modeling and Simulation

by
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1. Basic Concepts and Definitions

A transient is a phenomenon of “short” duration producing:

- Overvoltages
- Overcurrents

The causes are:

- Switching operations (connection/disconnection)
- Lightning on lines (near transformers)
- Abnormal operations (resonances)

Transients determine much of the transformer design!

1. Basic Concepts and Definitions

- **White-box models**
  - ➢ The parameters are determined from the knowledge of the transformer design/construction
  - ➢ Problem: today only manufacturers can build these models
  - ➢ They allow for parametric analysis

- **Black-box models**
  - ➢ The parameters are determined from terminal measurements
  - ➢ Problems: measurements are not easy to make and cannot be applied to non-tested transformers

- **Gray-box models**
  - ➢ A combination of the above
  - ➢ A design can be estimated, but does it work?

F. de León, P. Gómez, J. A. Martinez-Velasco, and M. Rioual, Chapter 4, "*Transformers*" in *Power System Transients: Parameter Determination*, CRC Press, Boca Raton FL, 2009, pp. 177-250.

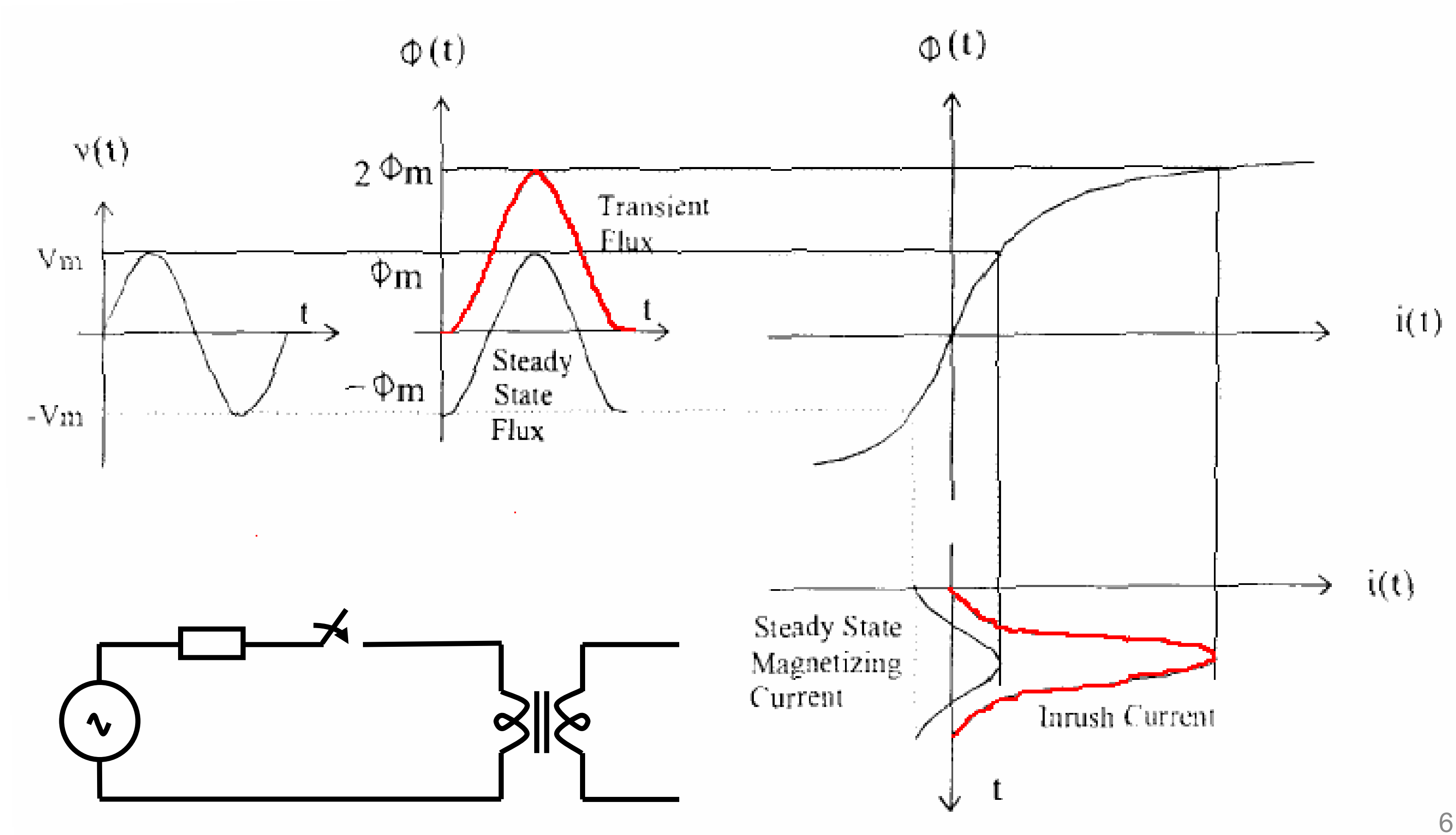
2. Electromagnetic Transients

- Energization: Inrush Currents
- De-Energization: Magnetizing Current Chopping
- Switching and Lightning Waves
- Internal (partial) resonances
- Ferrorresonance
- Geomagnetically Induced Currents
- High Frequency and Solid State Transformers

3. Inrush Currents (no Hysteresis)

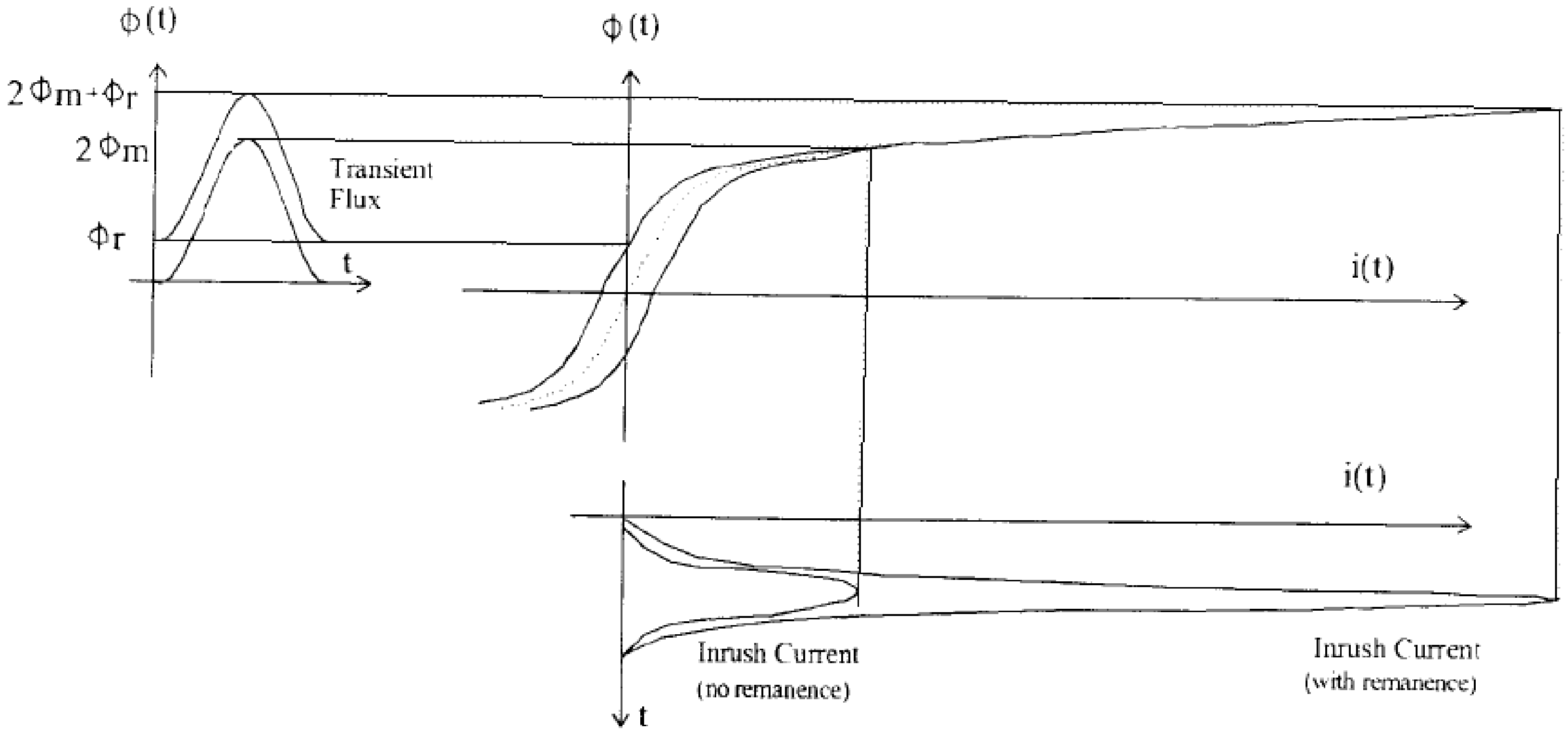
Transient flux

$$\phi(t) = \phi_m[1 - \cos(\omega t)]$$



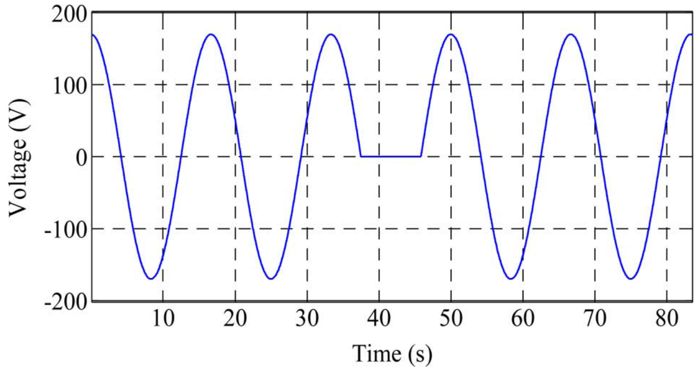
3. Inrush Currents (with Hysteresis)

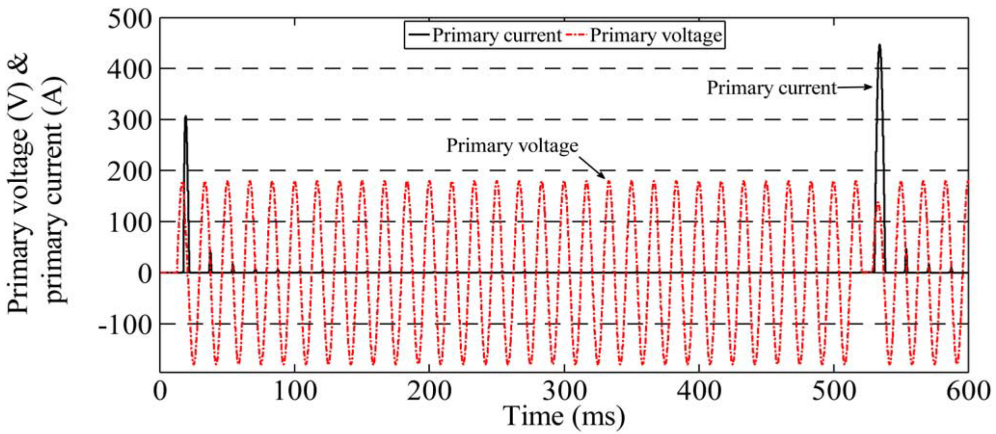
Transient flux (with remanence) $\phi(t) = \phi_m [\, e^{-\frac{L}{R}t} - \cos(\omega t)\,] + \phi_{rem}$

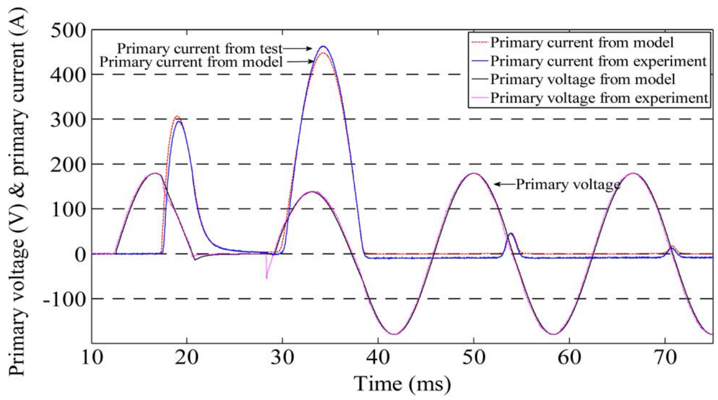


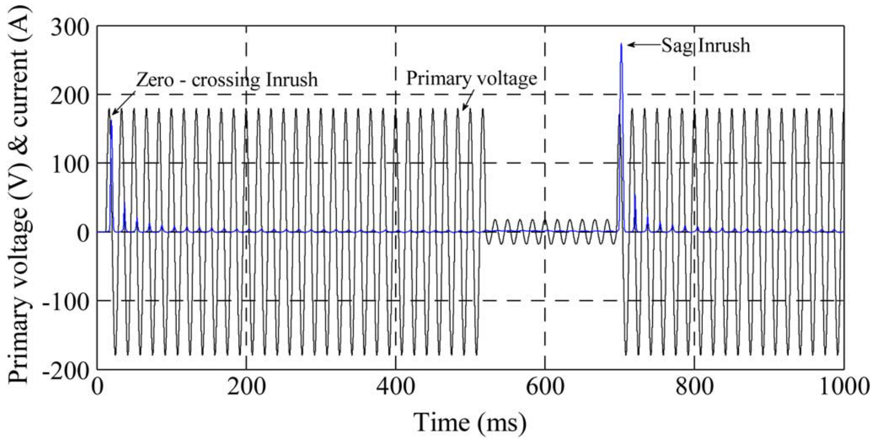
- Inrush currents **may** stress the windings more than short circuit currents

3. Phase Hop: The Worst Inrush Currents









A. Farazmand, F. de León, K. Zhang, and S. Jazebi, “Analysis, Modeling and Simulation of the Phase-Hop Condition in Transformers: The Largest Inrush Currents”, IEEE Transactions on Power Delivery, Vol. 29, No. 4, August 2014, pp. 1918-1926.

3. Inrush Control and Reduction

- External to the transformer
  - Pre-insertion resistors
  - Controlled switching
  - Reduction of residual flux (shunt secondary capacitors, demagnetizers)
- Internal to the transformer
  - Reduce magnetic flux density (B) – not economical
  - Gaps - Increase magnetizing current, but no losses
  - Careful selection of core material (Increase of losses)
  - Virtual gaps

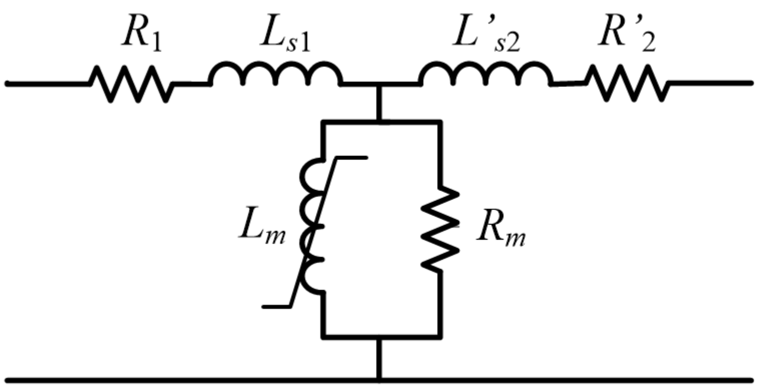
B. Kovan, F. de León, D. Czarkowski, Z. Zabar, and L. Birenbaum, "Mitigation of Inrush Currents in Network Transformers by Reducing the Residual Flux with an Ultra-Low-Frequency Power Source", IEEE Transactions on Power Delivery, Vol. 26, No. 3, July 2011, pp. 1563-1570.

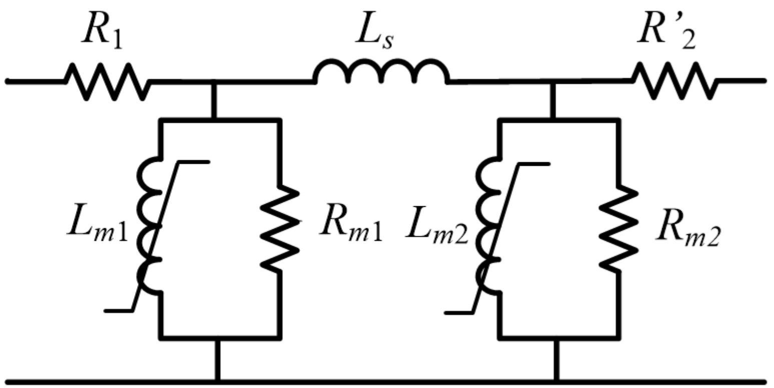
F. de León, S. Jazebi, A. Farazmand, D. Deswal, and R. Levi, "*Elimination of Residual Flux in Transformers by the Application of an Alternating Polarity DC Voltage Source*", IEEE Transactions on Power Delivery, Vol. 30, No. 4, August 2015, pp. 1727-1734.

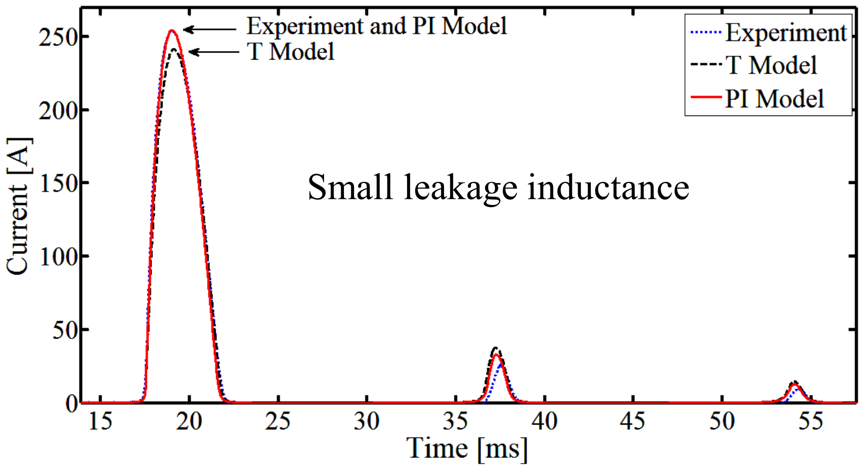
R. Doğan, S. Jazebi, and F. de León, "*Investigation of Transformer-Based Solutions for the Reduction of Inrush and Phase-Hop Currents*", IEEE Transactions on Power Electronics, Vol. 31, No. 5, May 2016, pp. 3506-3516.

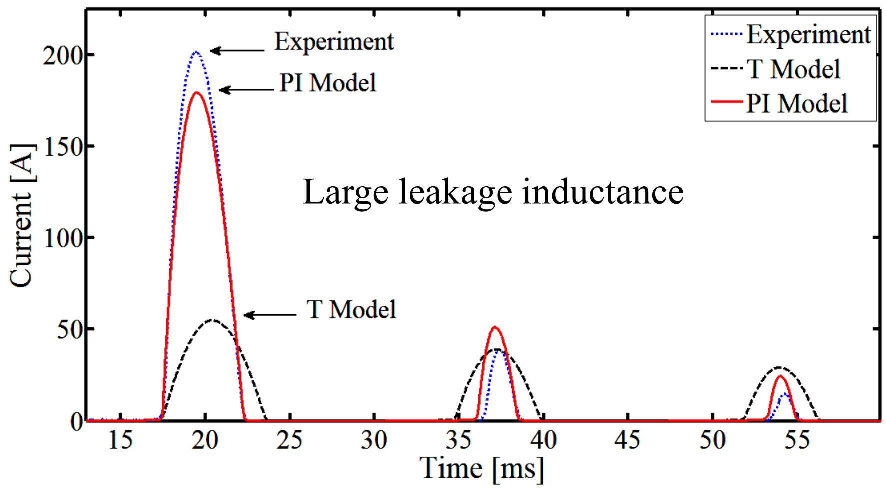
S. Jazebi, R. Doğan*, B. Kovan, and F. de León, "*Reduction of Inrush Currents in Toroidal Transformers by Sector Winding Design*", IEEE Transactions on Power Electronics, Vol. 31, No. 10, October 2016, pp. 6766-6780.

3. Models for Inrush Currents





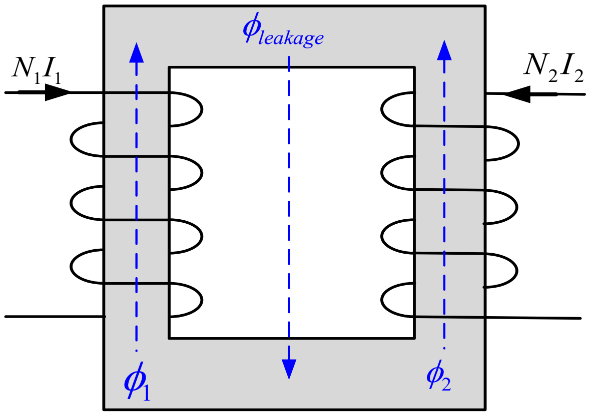


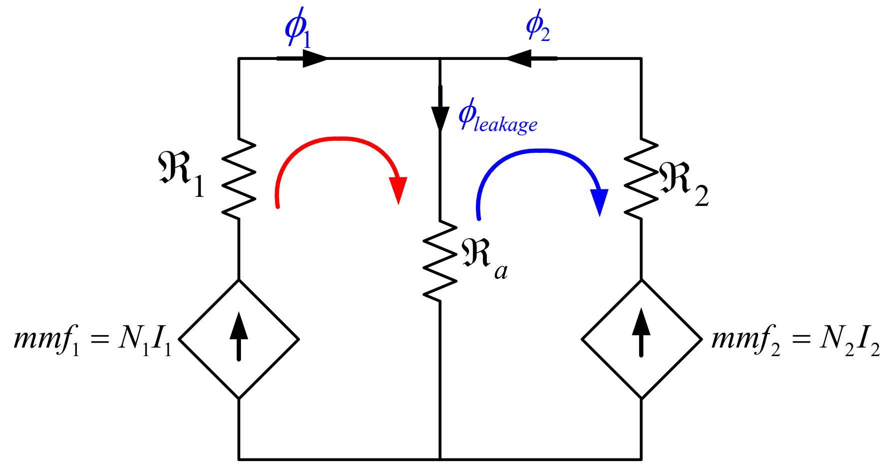


F. de León, A. Farazmand, and P. Joseph, "Comparing the T and PI Equivalent Circuits for the Calculation of Transformer Inrush Currents", IEEE Transactions on Power Delivery, Vol. 27, No. 4, October 2012, pp. 2390-2398.

S. Jazebi, F. de León, and N. Wu, "*Enhanced Analytical Method for the Calculation of the Maximum Inrush Currents of Single-Phase Power Transformers*", IEEE Transactions on Power Delivery, Vol. 30, No. 6, December 2015, pp. 2590-2599.

4. Principle of Duality





$$\begin{cases} mmf_1 = \Re_1\phi_1 + \Re_a(\phi_1 - \phi_2) \\ mmf_2 = \Re_a(\phi_2 - \phi_1) + \Re_2\phi_2 \end{cases}$$

Mesh Equations

$$\Re = \frac{N^2}{L}$$

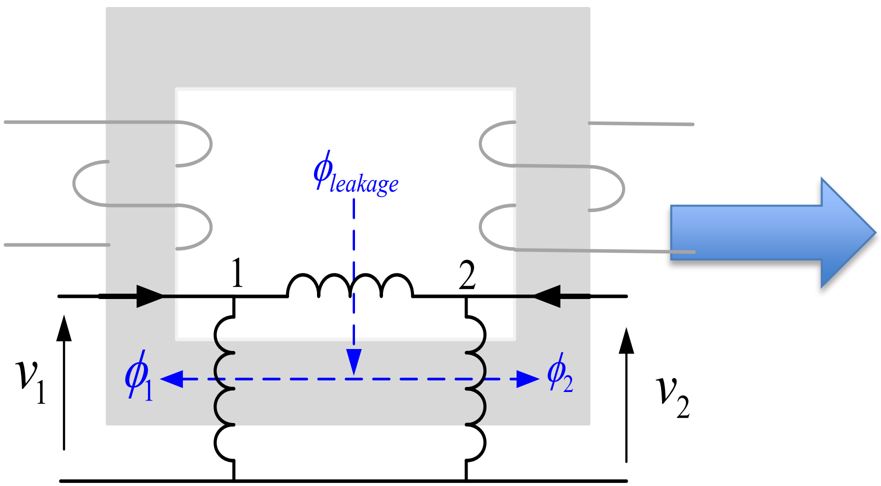
$$\phi = \frac{v}{N\omega}$$

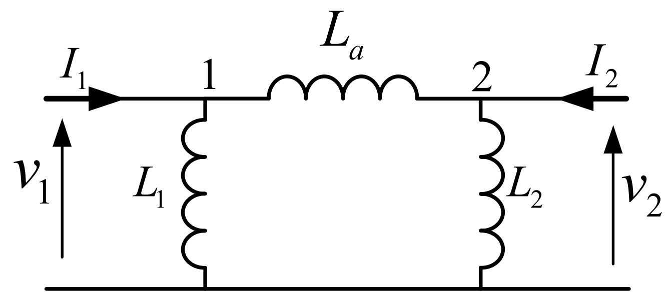
$$N = 1$$

$$\begin{cases} I_1 = \frac{1}{\omega L_1}v_1 + \frac{1}{\omega L_a}(v_1 - v_2) \\ I_2 = \frac{1}{\omega L_2}v_2 + \frac{1}{\omega L_a}(v_2 - v_1) \end{cases}$$

Node Equations

4. Principle of Duality





$$\begin{cases} mmf_1 = \Re_1 \phi_1 + \Re_a (\phi_1 - \phi_2) \\ mmf_2 = \Re_a (\phi_2 - \phi_1) + \Re_2 \phi_2 \end{cases}$$

Mesh Equations

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$$\phi = \frac{v}{N\omega}$$

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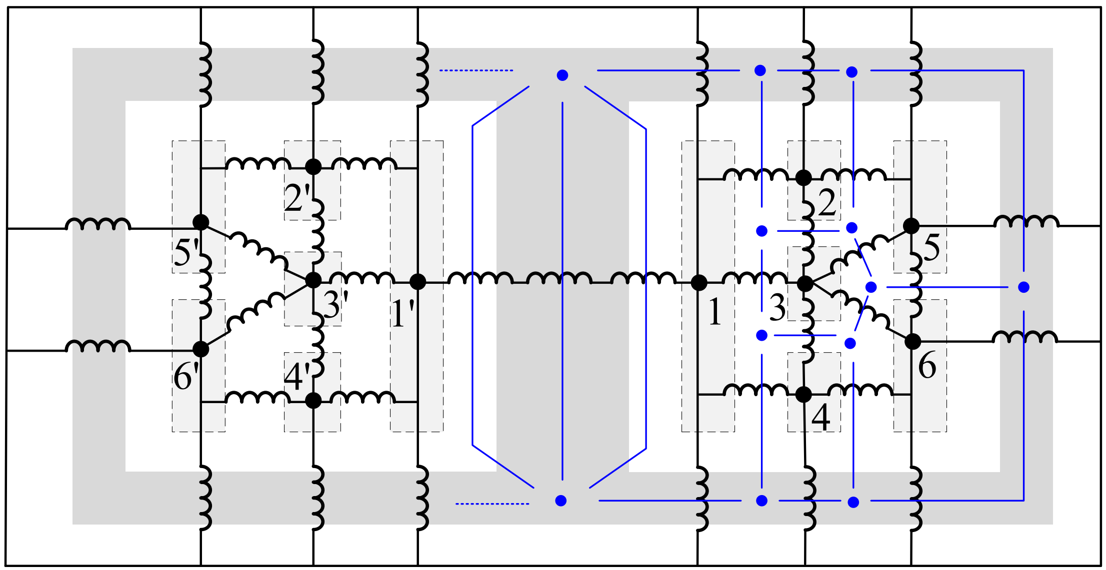
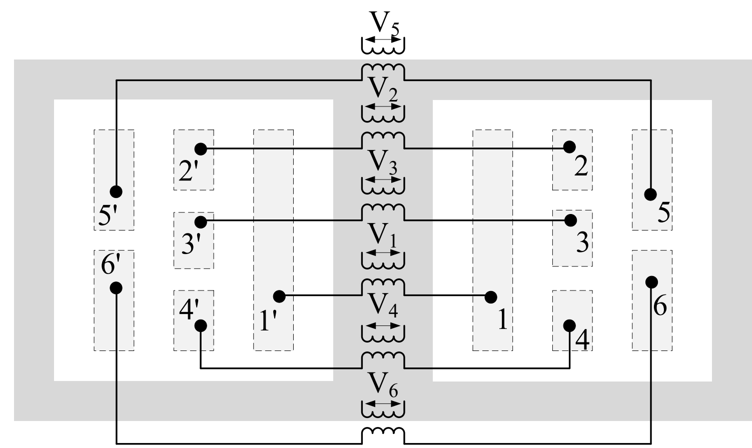
Node Equations

4. Principle of Duality

Principle of duality for complex magnetic devices

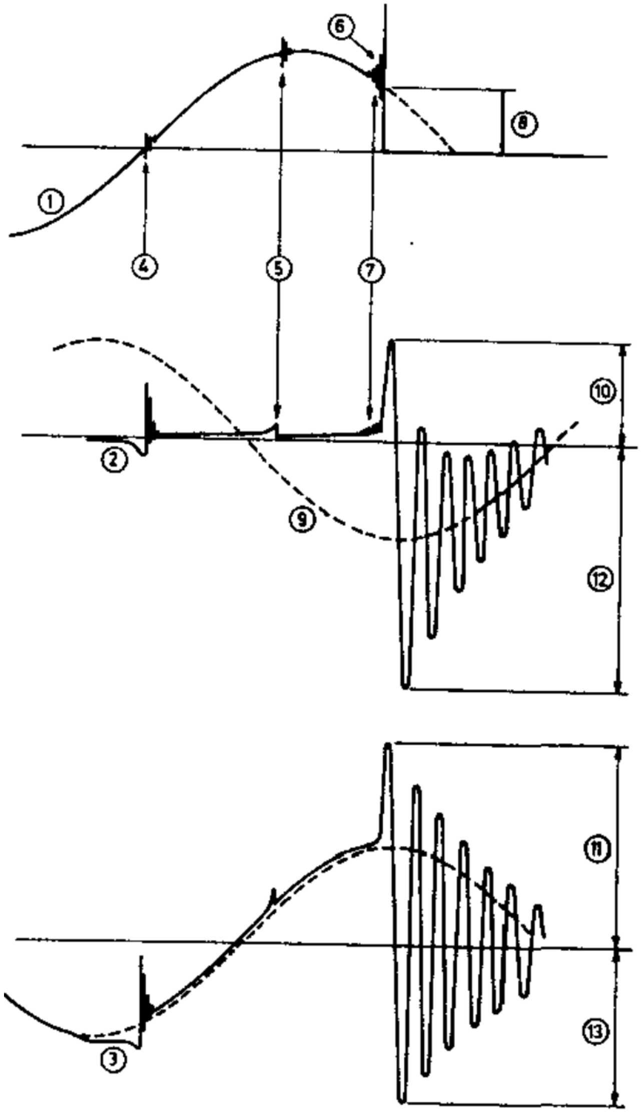




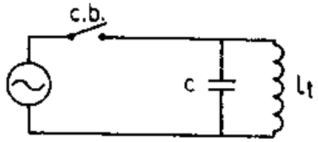
Connection points

S. Jazebi, S. E. Zirka, M. Lambert, A. Rezaei-Zare, N. Chiesa, Y. Moroz, X. Chen, M. Martinez-Duro, C. M. Arturi, E. P. Dick, A. Narang, R. A. Walling, J. Mahseredjian, J. A. Martinez, and F. de León (Chair of the IEEE Taskforce), "Duality Derived Transformer Models for Low-Frequency Electromagnetic Transients – Part II: Complementary Modeling Guidelines", IEEE Transactions on Power Delivery, Vol. 31, No. 5, October 2016, pp. 2420-2430.
S. Jazebi, S. E. Zirka, M. Lambert, A. Rezaei-Zare, N. Chiesa, Y. Moroz, X. Chen, M. Martinez-Duro, C. M. Arturi, E. P. Dick, A. Narang, R. A. Walling, J. Mahseredjian, J. A. Martinez, and F. de León (Chair of the IEEE Taskforce), "Duality Derived Transformer Models for Low-Frequency Electromagnetic Transients – Part I: Topological Models", IEEE Transactions on Power Delivery, Vol. 31, No. 5, October 2016, pp. 2410-241

5. Magnetizing Current Chopping

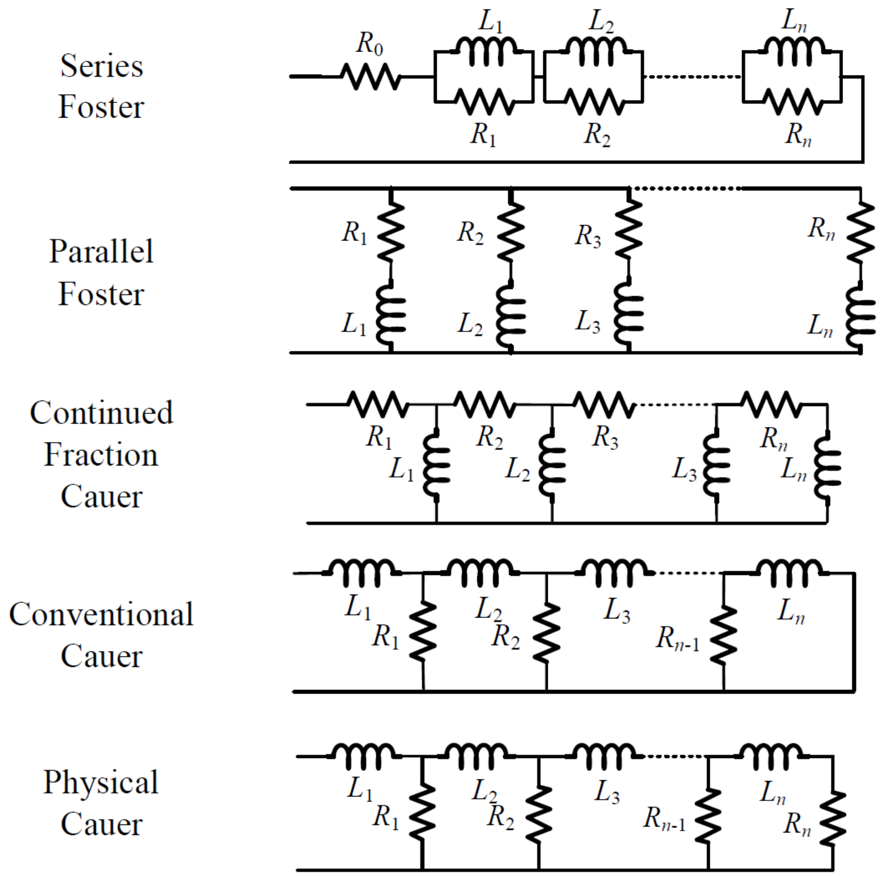


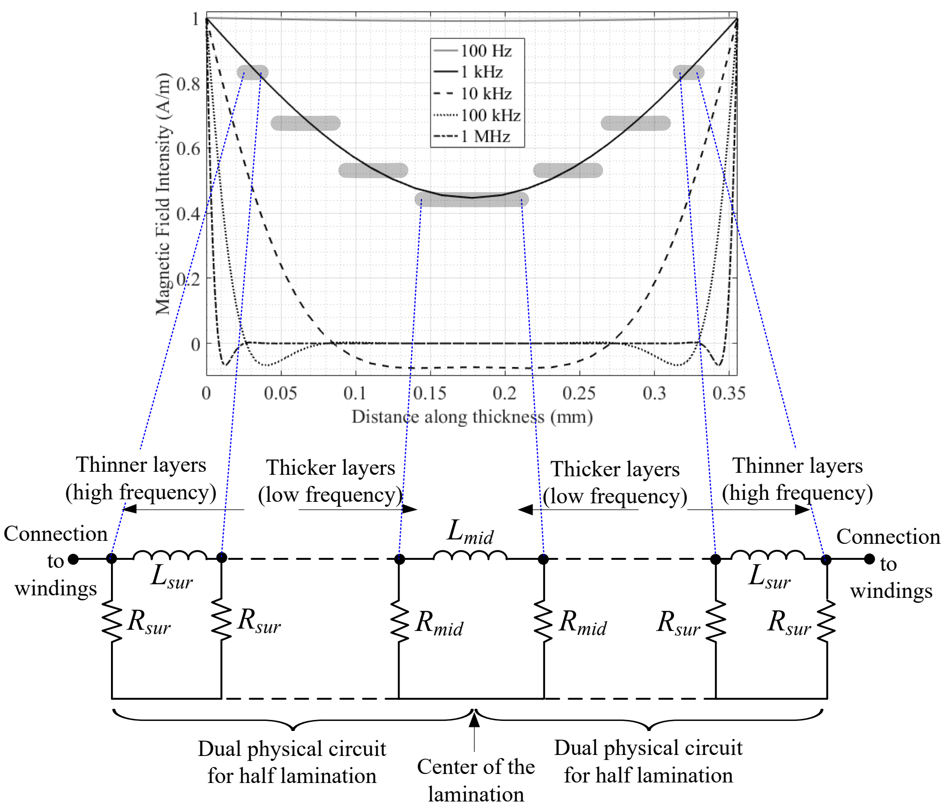
High overvoltages caused by the circuit breaker's ability to stop short circuit currents at zero crossing that chops the small magnetizing currents



The problem is more dangerous in distribution than in transmission transformers

5. Iron-Core (high frequency) Models

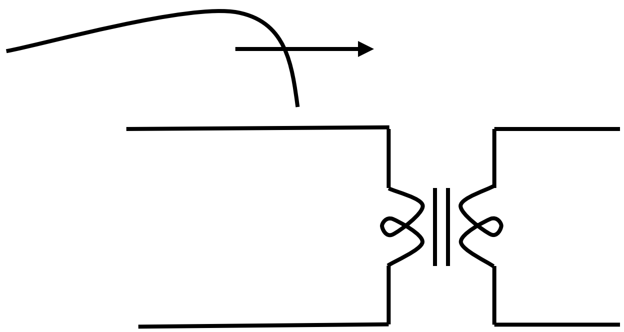


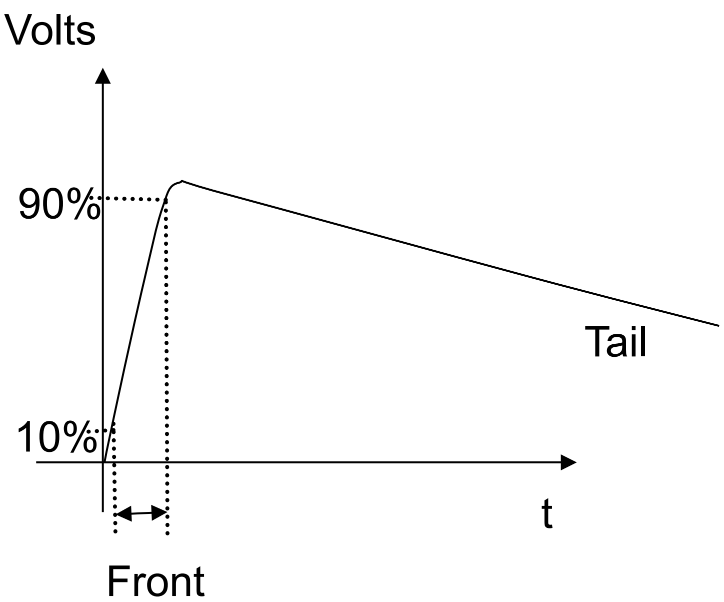


S. Jazebi and F. de León, "*Duality-Based Transformer Model Including Eddy Current Effects in the Windings*", IEEE Transactions on Power Delivery, Vol. 30, No. 5, October 2015, pp. 2312-2320.

D. Deswal and F. de León, "*Generalized Circuit Model for Eddy Current Effects in Multi-Winding Transformers*", IEEE Transactions on Power Delivery, vol. 34, no. 2, March 2019, pp. 638-650

6. Switching and Lightning Waves





Basic Insulation Level (BIL)

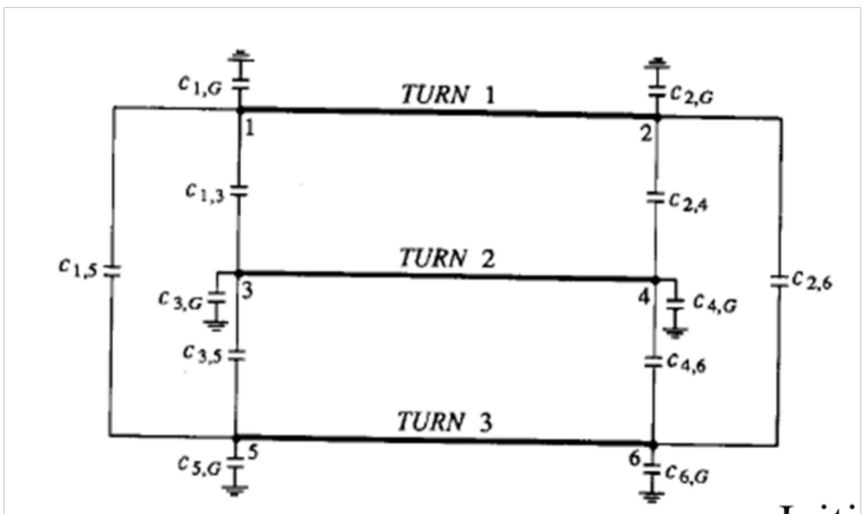
The price of the transformer depends on the BIL

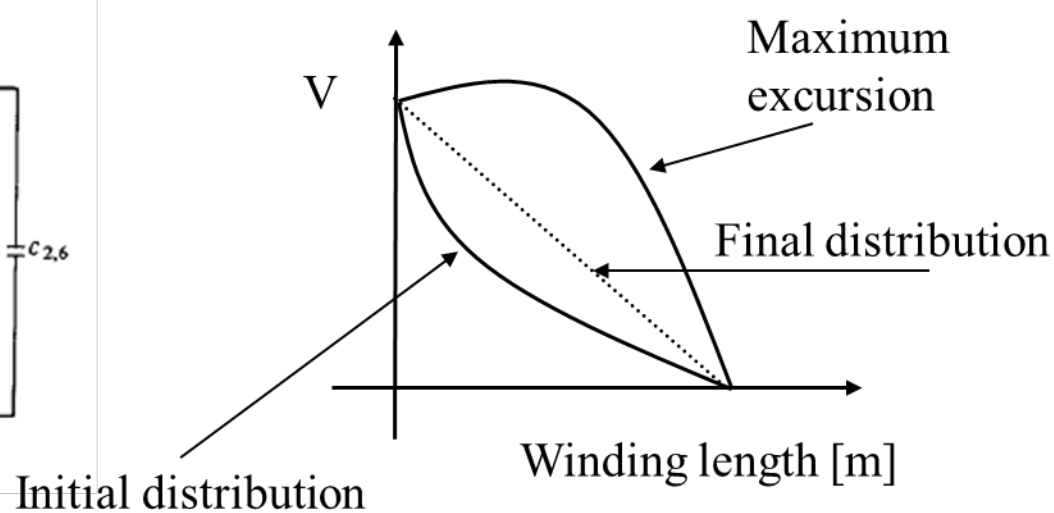
Lightning 1.2 / 50 μs
Switching 250 / 2500μs

6. Switching and Lightning Waves

- Transformer designers “worry” about the impulse tests

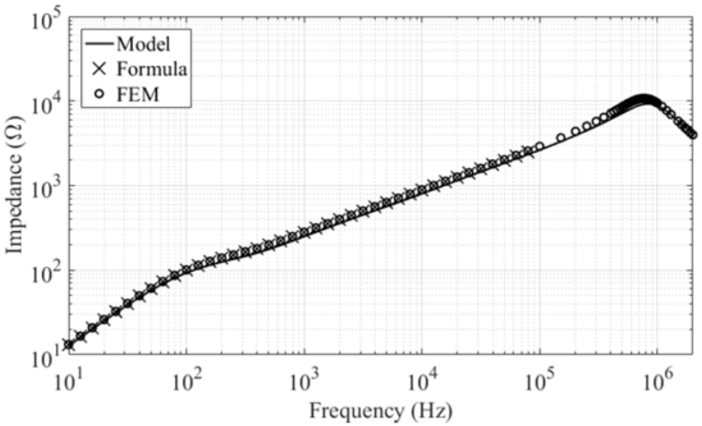
- Transient voltage distribution
  (Initial distribution and final distribution)

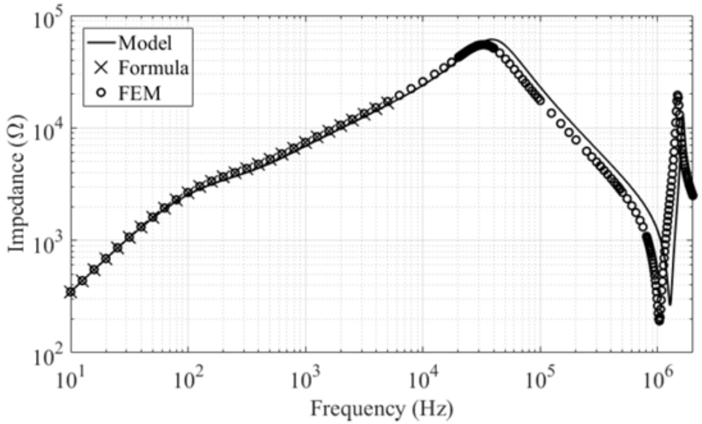




6. Switching and Lightning Waves

- Most manufacturers use the “capacitive model”
- Few use an inductive-capacitive model
- We need to get the proper damping
- Switching waves are more difficult to model than lightning waves



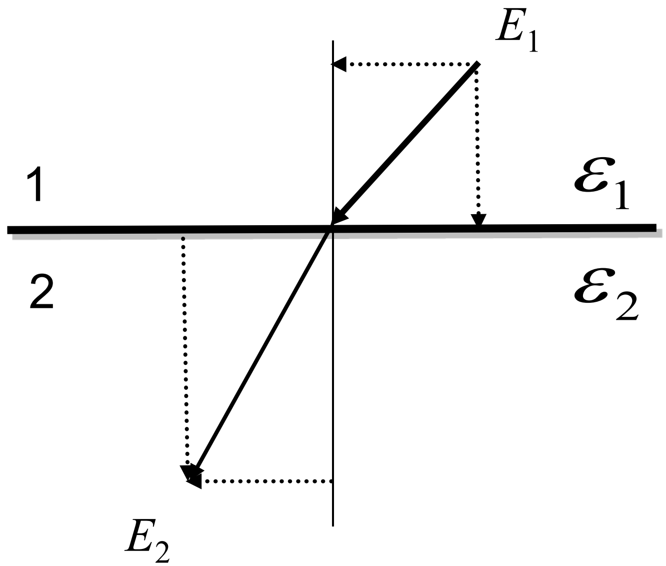


Design and Control

- Increase of insulation
  - It may not work if one is not conscious of the surface field interfaces

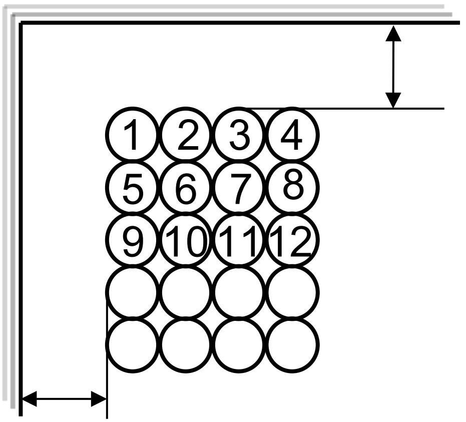
$$E_{n2} = \frac{\varepsilon_1}{\varepsilon_2} E_{n1}$$

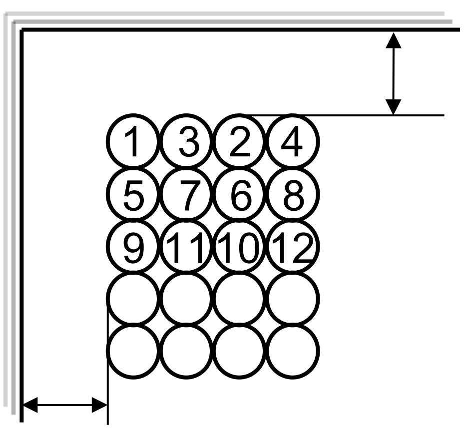
$$E_{t2} = E_{t2}$$

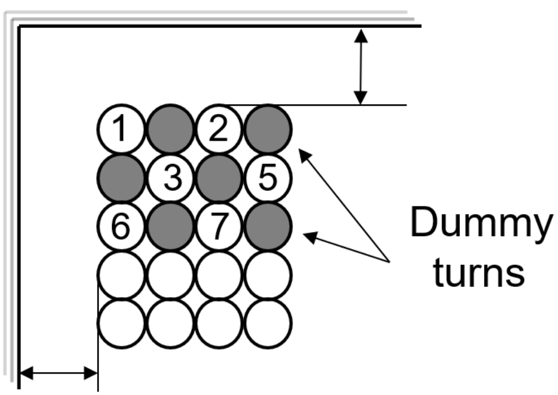


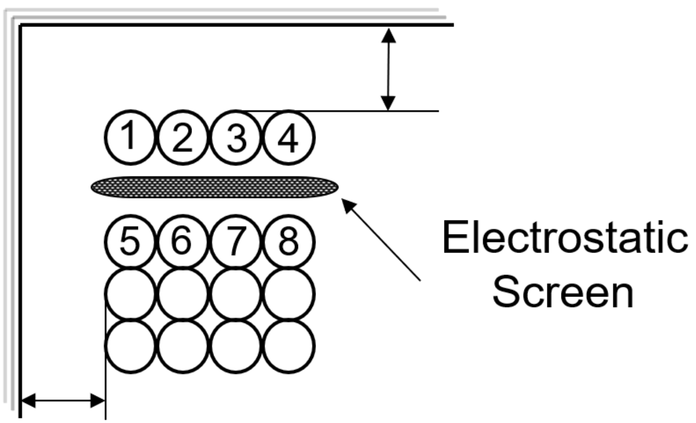
6. Switching and Lightning Waves

- Increase of Series Capacitance
- Reduction of Capacitance to Ground
    - Distances
    - Turns interleaving
    - Dummy turns
    - Electrostatic screen

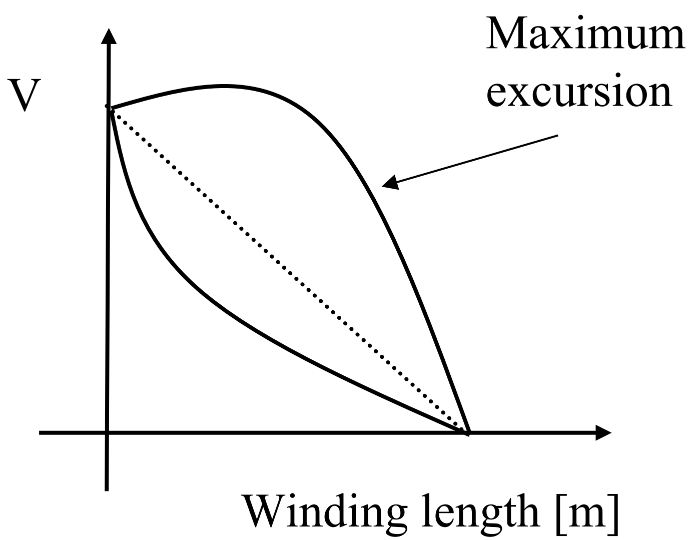








7. Internal (partial) Resonances



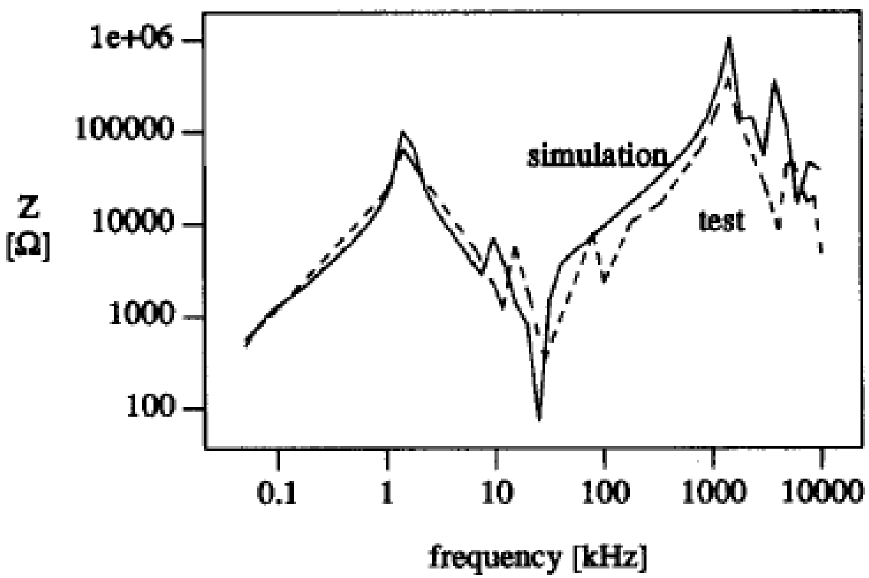


Figure 7. Input impedance for the 75 kVA transformer in open circuit

- The maximum excursion is due to internal (or partial) resonances
- Because there are no good reliable models, insulation design is still very much an art and less a science

8. Ferroresonance

- It is a series resonance caused by unsymmetrical operation of circuit breakers or fuses and the saturation of the iron-core

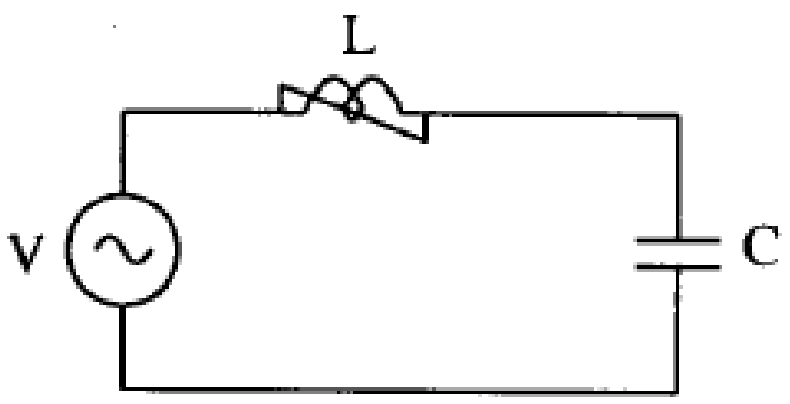


Figure 12. Circuit for the study of ferroresonance

8. Ferroresonance

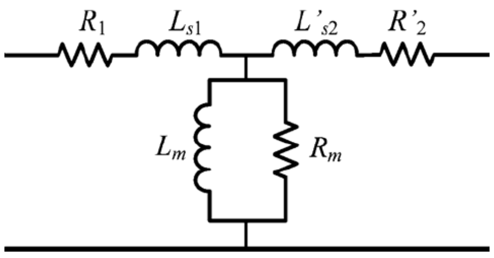


Fig. 1. T equivalent circuit.

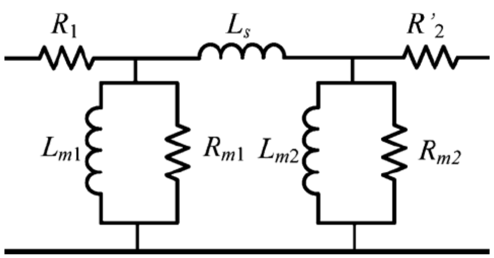


Fig. 2. π equivalent circuit.

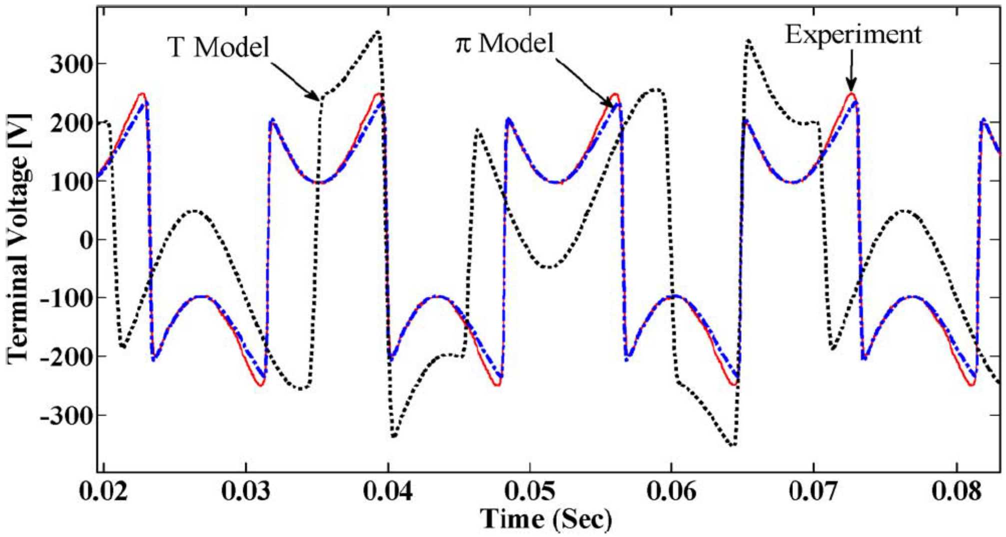


Fig. 2. Terminal voltage of T2 with 20-μF series capacitance.

S. Jazebi, A. Farazmand, B. Murali*, F. de León, "A Comparative Study on PI and T Equivalent Circuits for the Analysis of Transformer Ferroresonance", IEEE Transactions on Power Delivery, Vol. 28, No. 1, January 2013, pp. 526-528.

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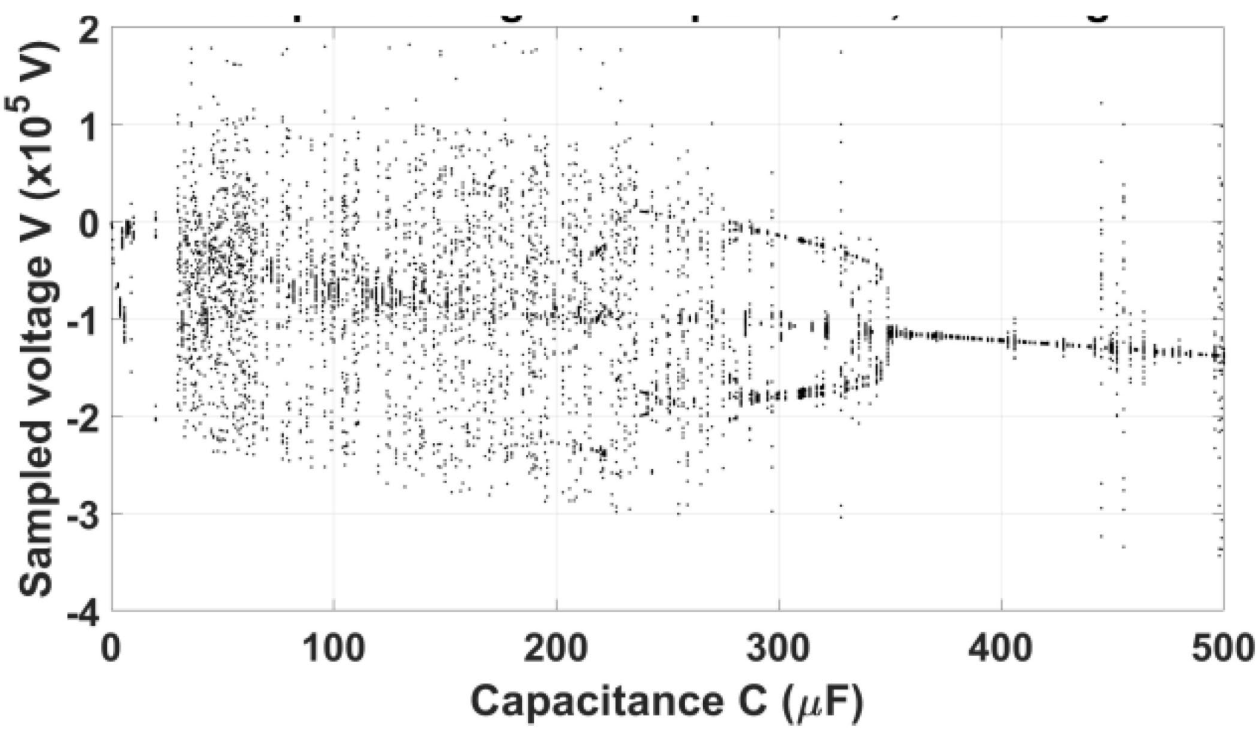
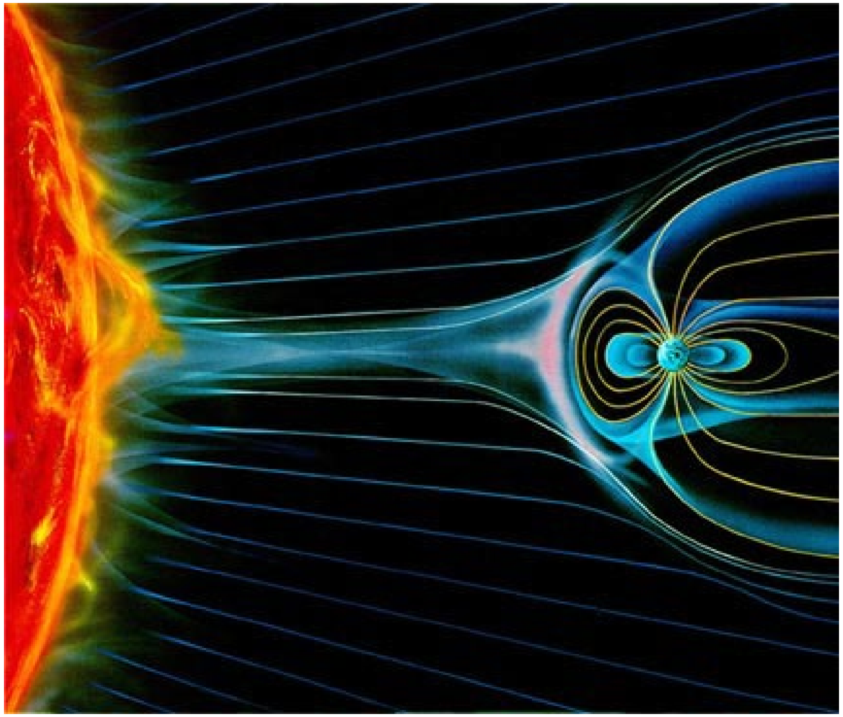
8. Ferroresonance

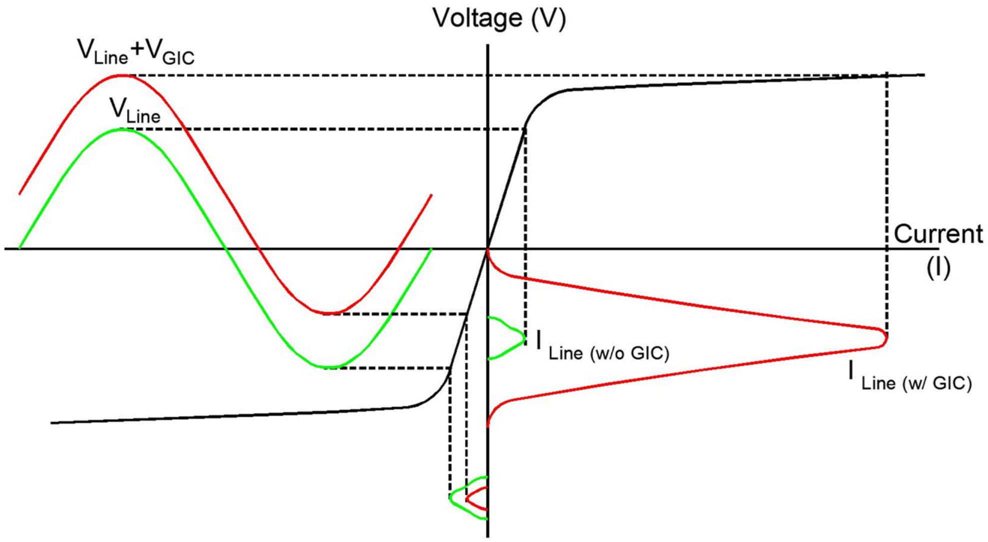
- Can be avoided by symmetrical switching
  (It is not always the economical choice)
- It is a highly nonlinear phenomenon (it is chaotic, with bifurcations)
- Ferroresonance produces violent transformer failures

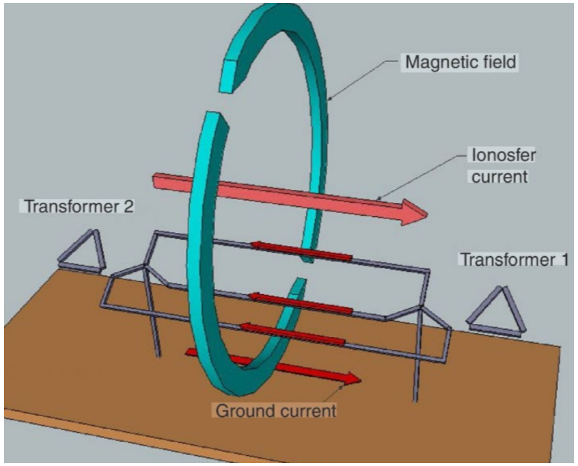


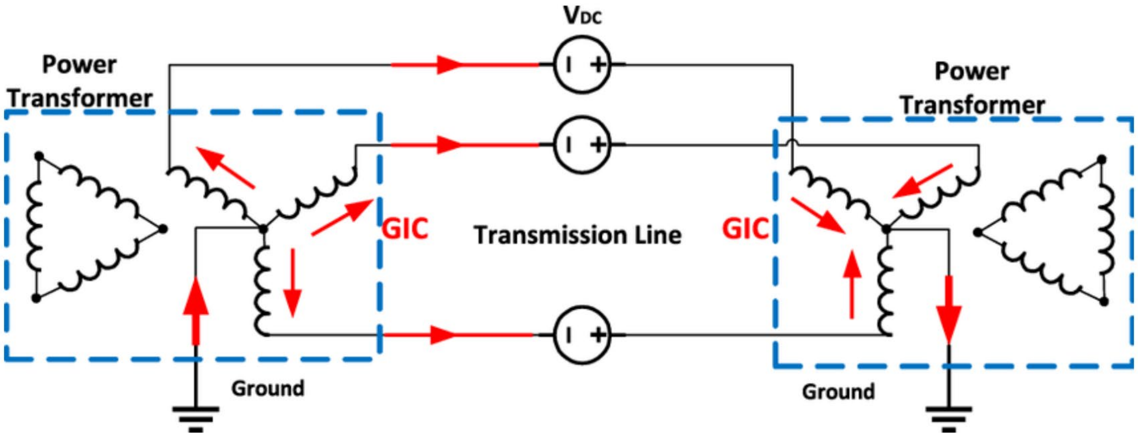
Bifurcation diagram: Poincaré-sampled voltage

9. Geomagnetically Induced Currents

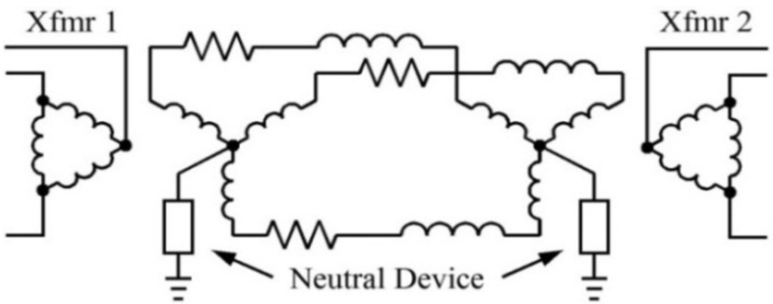




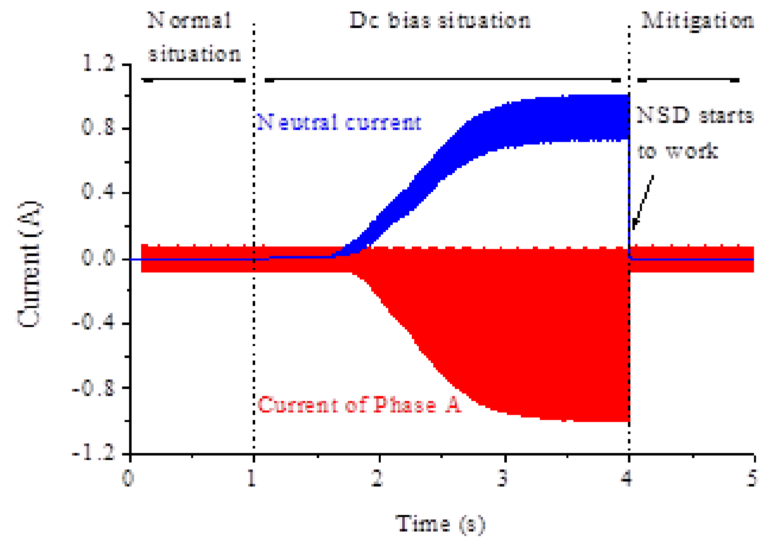




9. Geomagnetically Induced Currents



1.		Disconnect at Neutral
2.		Inductor at Neutral
3.		Resistor at Neutral
4.		Capacitor at Neutral
5.		Capacitor with by-pass at Neutral



B. Kovan and F. de León, "*Mitigation of Geomagnetically Induced Currents by Neutral Switching*", IEEE Transactions on Power Delivery, Vol. 30, No. 4, August 2015, pp. 1999-2006.

M. Yang*, D. Deswal*, and F. de León, "*Mitigation of Half-Cycle Saturation of Adjacent Transformers during HVDC Monopolar Operation – Part I: Mitigation Principle and Device Design*", IEEE Transactions on Power Delivery, vol. 34, no. 6, December 2019, pp. 2232-2239.

M. Yang*, D. Deswal*, and F. de León, "*Mitigation of Half-Cycle Saturation of Adjacent Transformers during HVDC Monopole Operation – Part II: Detecting Zero-Sequence Fault Currents*", IEEE Transactions on Power Delivery, vol. 35, no. 1, February 2020, pp. 16-24.

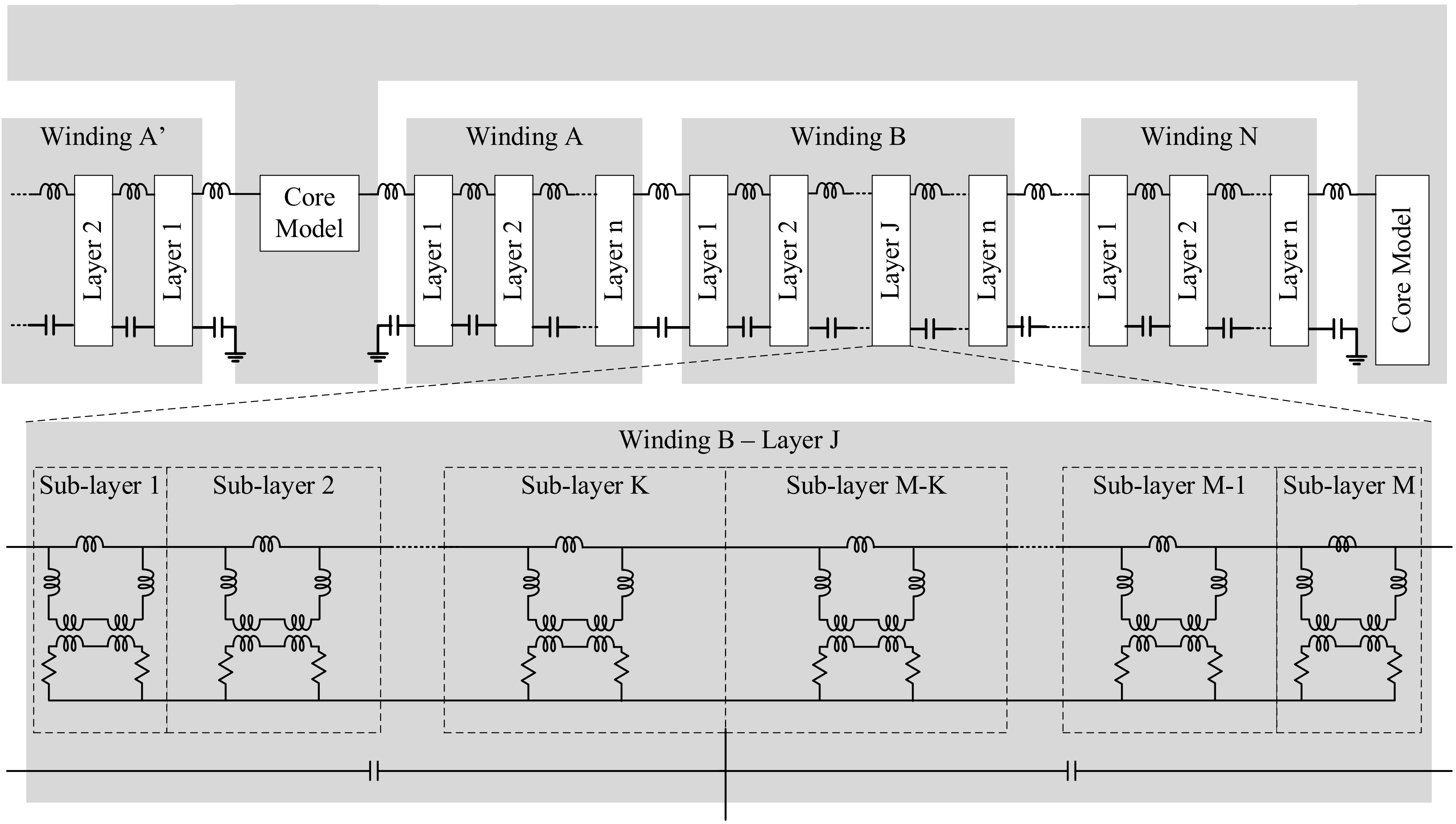
10. Simulation and Experimentation

- Analysis tools:
  - Scale Physical Models (TNA)
  - EMT Simulators (EMTP, PSCAD, ATP, …)
  - Field Experiments
  - History and Engineering Experience

- The preferred (modern) modeling tool is the Digital Computer. However …

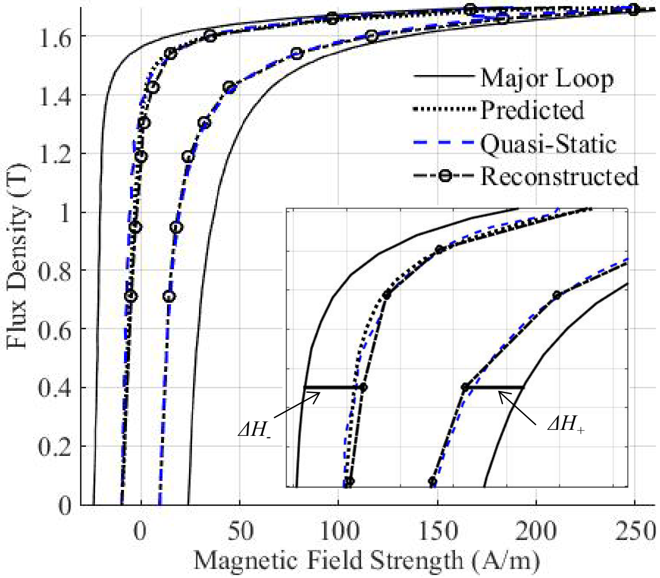
  - Reliable models for transformers do not exist in EMT-type programs
  - EMT can include saturation, but data is almost never readily available
  - For multi-winding transformers, the core models in EMT software is physically wrong
  - EMT programs do not have high frequency models for core or windings
  - A design change brings uncertainty to manufacturers because of lack of good models
  - There is no reliable data (except for the CIGRE "Fictitious Transformer")

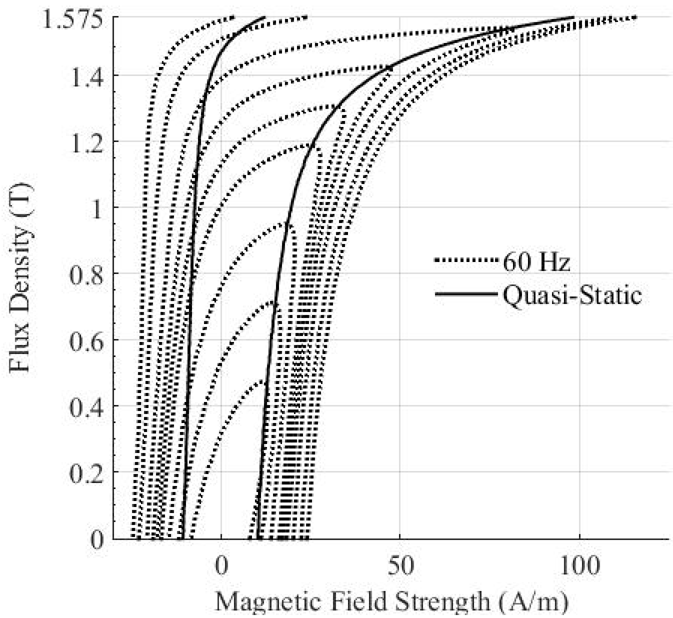
10. Simulation and Experimentation



10. Simulation and Experimentation

Core model: Inverse hysteresis model





S. E. Zirka, Y. I. Moroz, R. G. Harrison, and N. Chiesa, "*Inverse hysteresis models for transient simulation*," IEEE Trans. Power Delivery, vol. 29, no. 2, pp. 552-559, Apr. 2014.

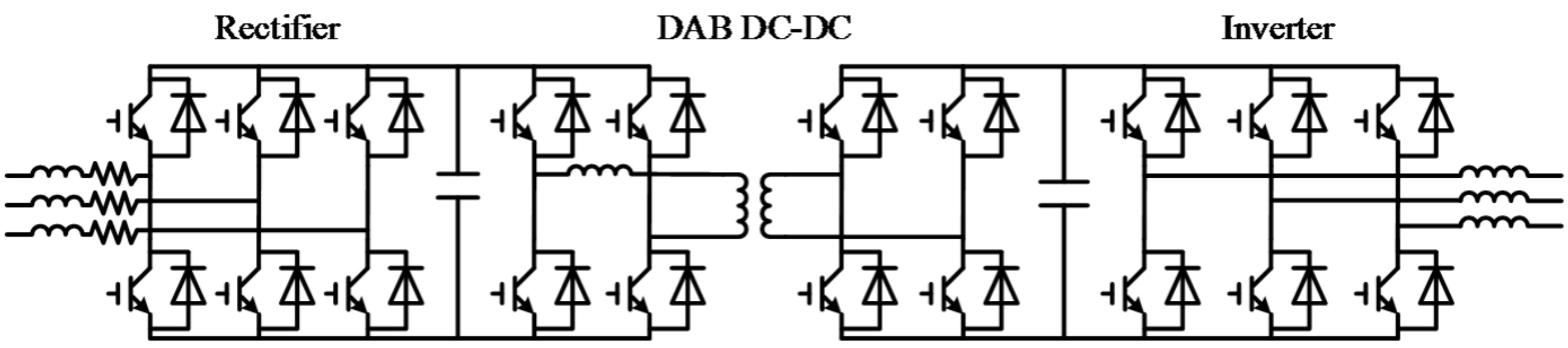
C. Alonso and F. de León, "*Experimental Parameter Determination and Laboratory Verification of the Inverse Hysteresis Model for Single-Phase Toroidal Transformers*", IEEE Transactions on Magnetics, Vol. 52, No. 11, November 2016.

11. High Frequency Transformers & Solid State Transformers

- To reduce the size of transformers we can increase the frequency. Faraday's Law:

$$V \uparrow = N\,B\,A\,\omega \uparrow = N\,B\,A\,2\pi\, f \uparrow$$

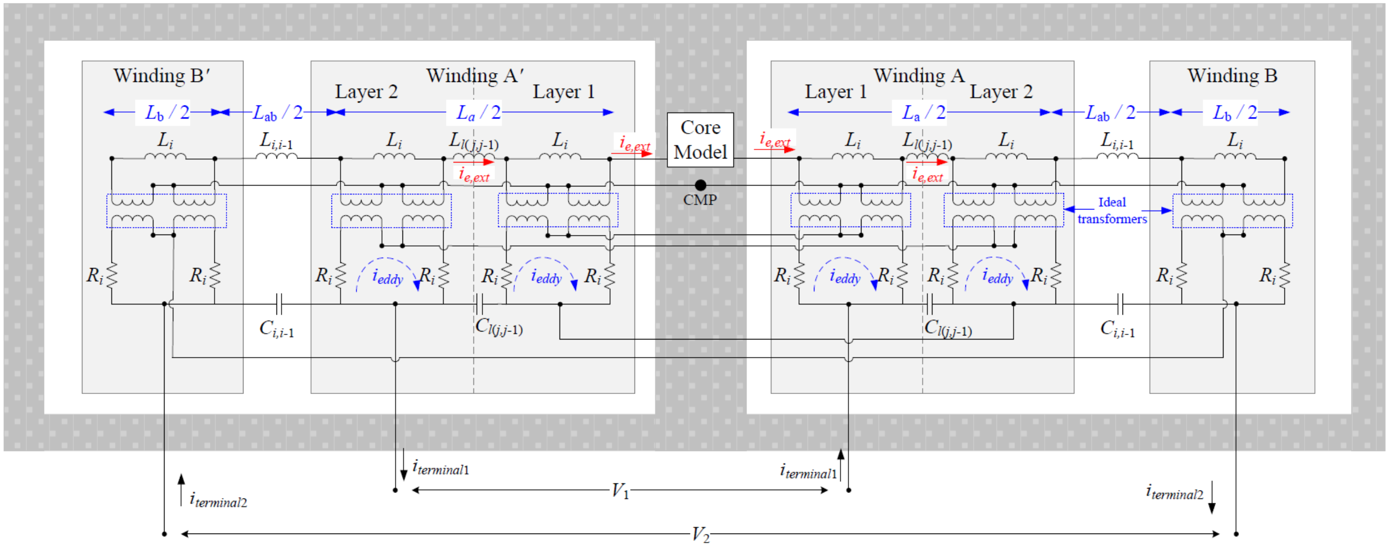
- We can reduce *N* and *A* to induce the same voltage

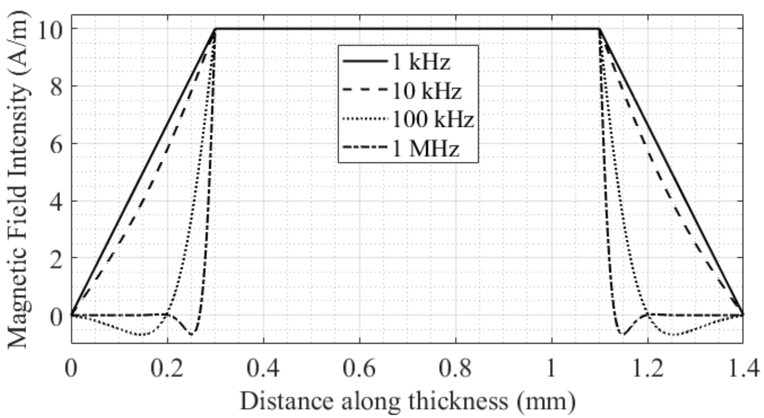


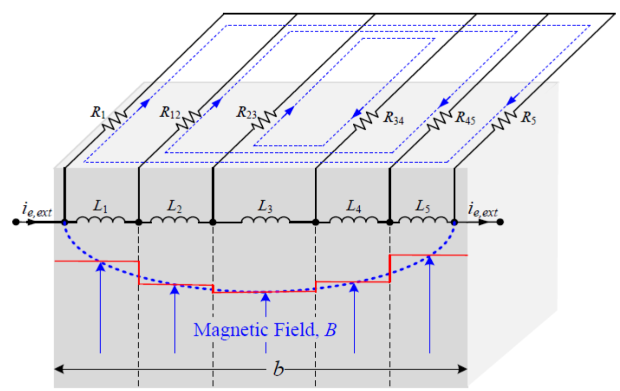
- We need a high frequency models mainly for windings. Eddy currents (skin and proximity effects).

D. Deswal and F. de León, "*Distributed Dual Model for High-Frequency Transformer Windings: Electromagnetic Transients and Solid State Transformers*", IEEE Open Access Journal of Power and Energy, vol. 9, pp. 549-559, doi: 10.1109/OAJPE.2022.3208251.

11. High Frequency Transformers & Solid State Transformers

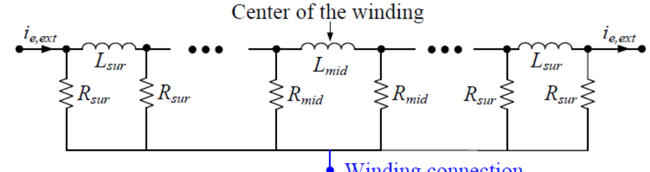






(b)

Center of the winding



12. Digital Twins

- A buzzword or a real solution?
- Definition: A digital twin is a digital model that faithfully reconstructs an object, an operation process, or a system comprising multiple objects.
- Can a "true digital twin" exist? I think "not"
- Digital twins to solve engineering problems already exist
- Applying the digital twin buzzword is deemed an abuse of language.
- I think that a "true digital twin" will never exist
- I will continue using "model" and not "digital twin"

Innocent Kamwa, Editor's voice, "*From buzzword to solutions digital twins in power systems*", IEEE Power and Energy Magazine, Jan/Feb 2024, pp. 4-11

13. Conclusions

- Electromagnetic Transients in Transformers include:
  - ➢ Inrush Currents
  - ➢ Magnetizing Current Chopping
  - ➢ Lightning and Switching waves
  - ➢ Internal (partial) resonances
  - ➢ Ferroresonance
  - ➢ GIC
- The design and price of transformers depends very much on the transients
- Transient design and control is still not as scientific as it could be
- There is considerable amount of work to be done – Let us go ahead and do it!

➡ Go and build that digital twin! 😀