Countering Threats from Transients in Magnetics

Victor W. Quinn
Director of Engineering & Technology
Exxelia US Magnetics Design Center
vquinn@exxelia.com
585-230-4368

www.exxelia.com

Agenda

"Failures are often caused by latent microscopic instabilities."

- Threats
- Causes
- Natural Transient Response
- Susceptibilities
- Dynamic Effects
- Product Development Plan
- Threat Prevention Examples
- Summary Checklist
- References

Threats from Transients

- Unexpected operating waveforms from transients
  - Concentrated stress densities
  - EMI
  - Circuit malfunction
  - Protective shutdown
  - Breakdown of insulation
  - System failure

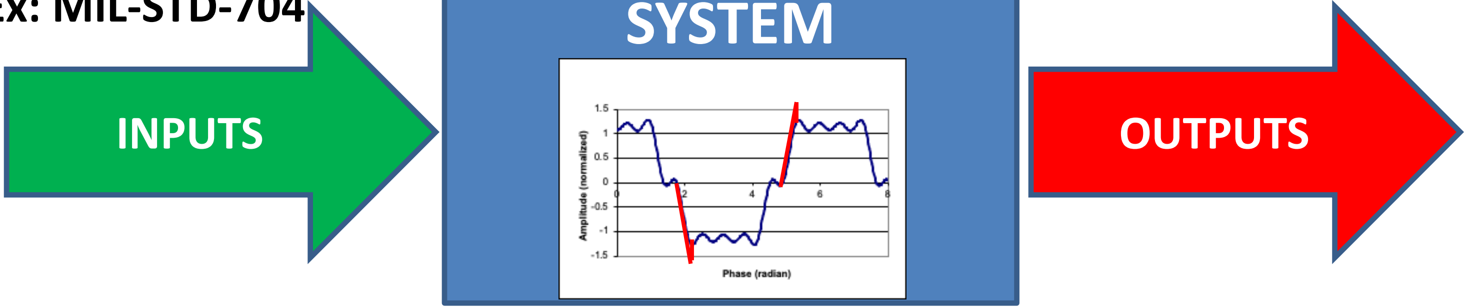
Collapse of newly opened Tacoma Narrows Bridge on November 7, 1940

Causes of Electrical Transients

- Dynamic inputs or outputs for system in final application
- Dynamic environmental conditions

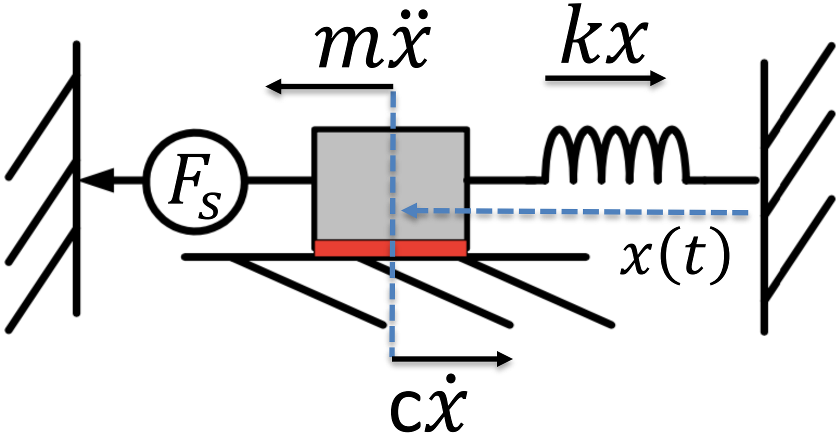
Ex: MIL-STD-704

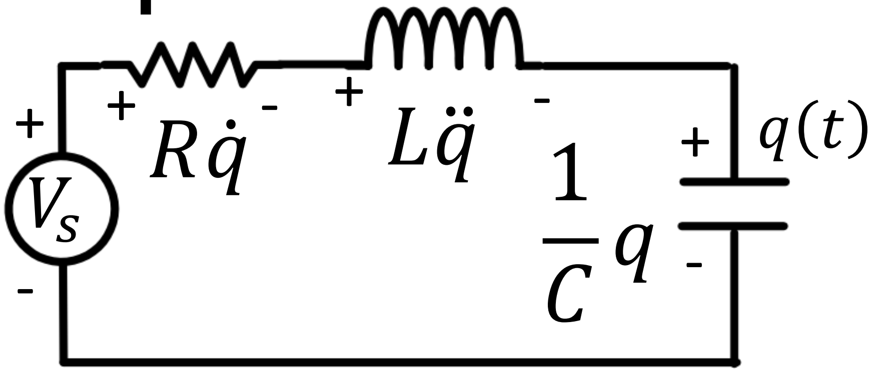
Ex: MIL-STD-461



- **<u>Inherent</u>** signal variations within system's circuits (dependent on RLC dynamics, transfer functions and component nonlinearities)

Natural Response





$$F_s = c\dot{x} + m\ddot{x} + kx$$

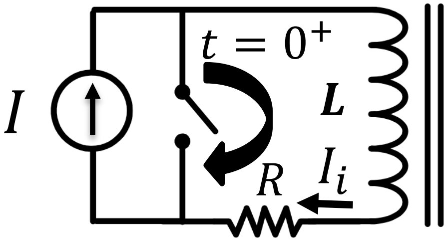
$$V_s = R\dot{q} + L\ddot{q} + \frac{1}{C}q$$

- Natural systems described by differential equations
- Transient condition disrupts normal forcing function

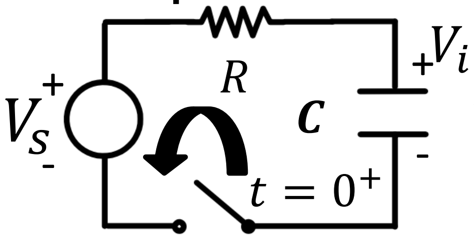
- Reactive components
  - Amplification
  - Oscillation
  - Decay

Passive Components

- Resistor dissipates energy to bleed power from a circuit.

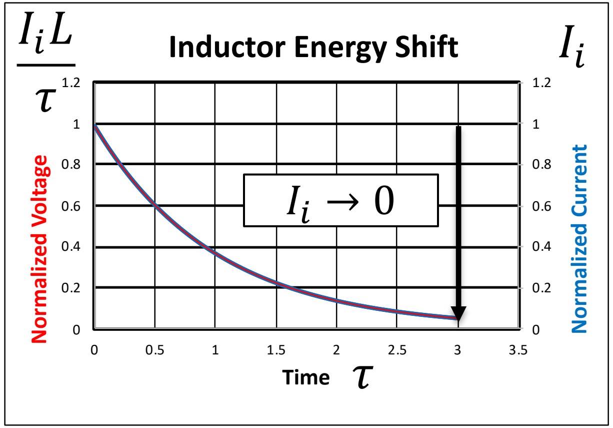


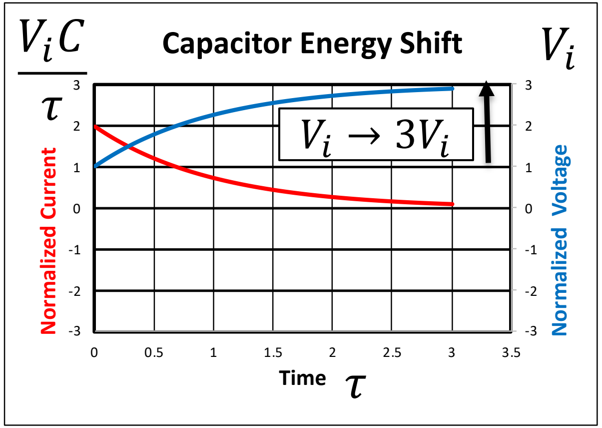
$\tau = \frac{L}{R}$

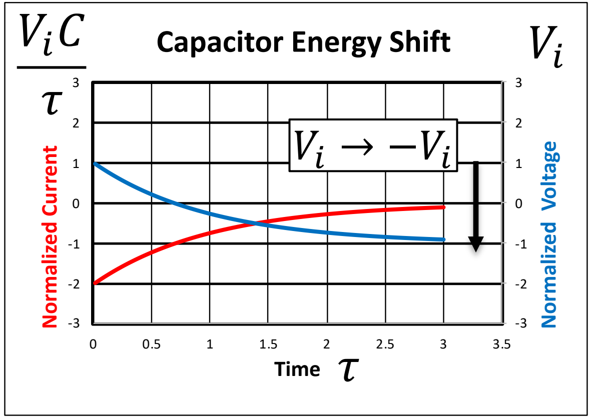


$\tau = RC$

- Inductor generates voltage to slow the change in its current.
- Capacitor absorbs or releases charge to slow the change in its voltage.

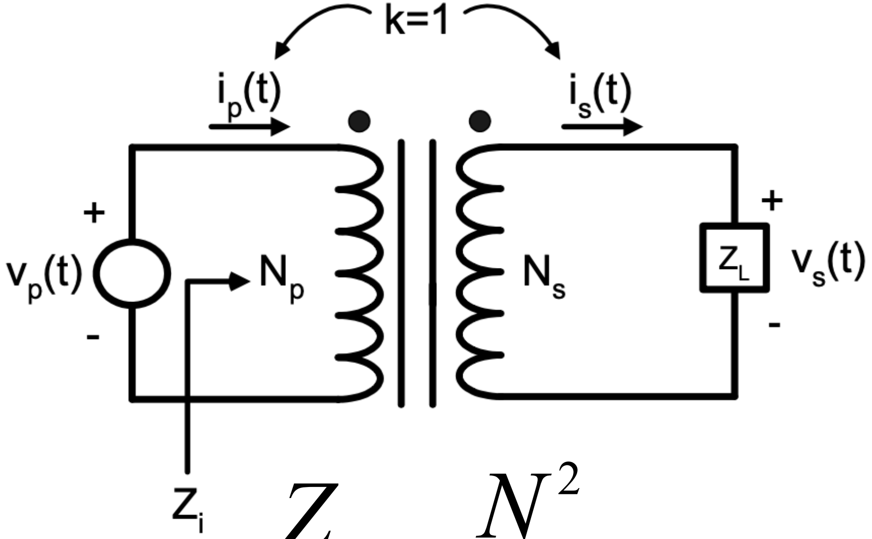






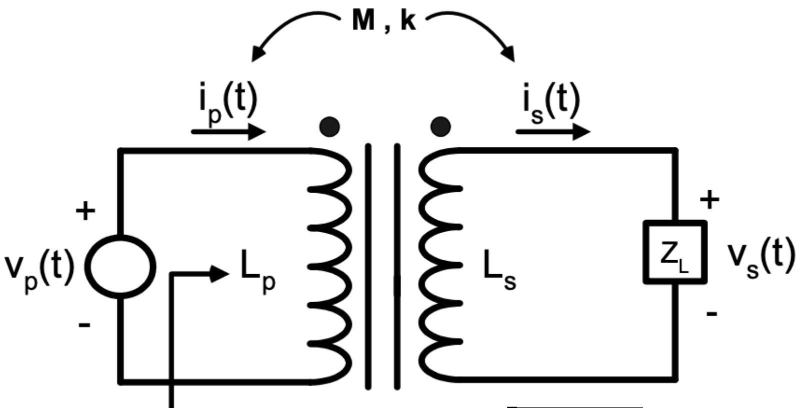
Ideal Transformers

- Transform impedance
  - Increase or decrease dynamic voltage
  - Decrease or increase dynamic current
- Transmit power between Isolated Circuits

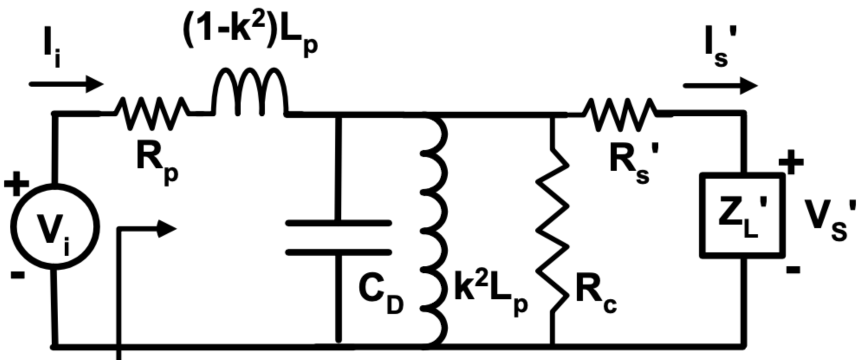


$$\frac{Z_i}{Z_L} = \frac{N_p^2}{N_s^2}$$

Transformer Equivalent Circuit



$$M = k\sqrt{L_p L_s}$$



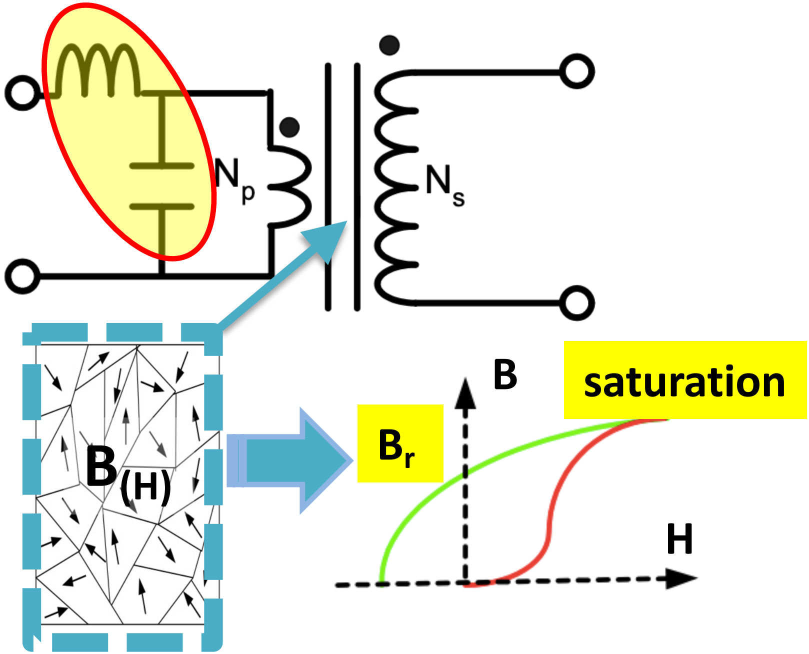
$$\frac{Z_L'}{Z_L} = k^2 \frac{L_p}{L_s}$$

- Inherently loaded with other passive components
- Transient effects

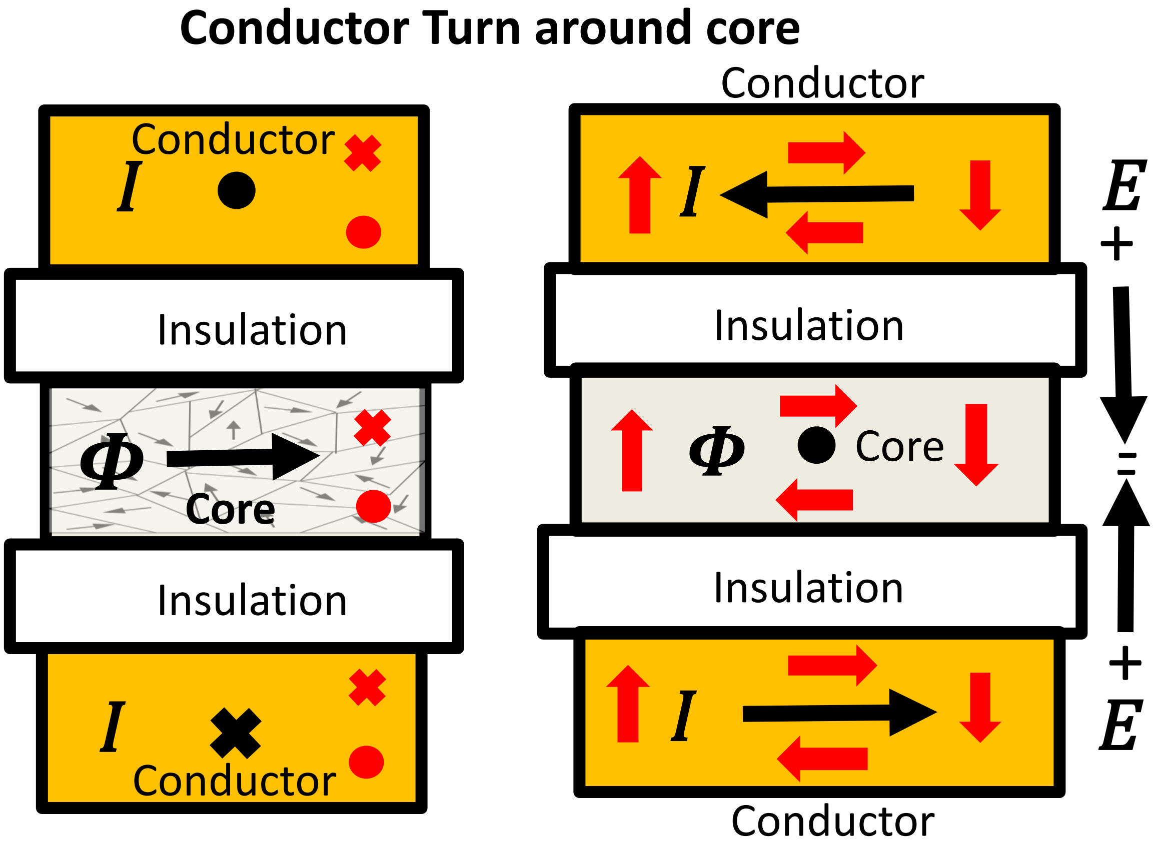
  - ***Amplification***
  - ***Oscillation***
  - ***Saturation***
  - ***Breakdown***

Susceptibilities

- Inherent capacitive loading from high voltage windings
- Nonlinearities
  - Magnetization dynamics
    - Hysteresis
    - Nonlinear permeability
    - Saturation
- Saturation risks
    - Turn on phase dependency
    - Volt – Second unbalance
- Flux Remanence Risks
  - Reduced flux headroom for start up or residual magnetic moment



Dynamic Stress Densities



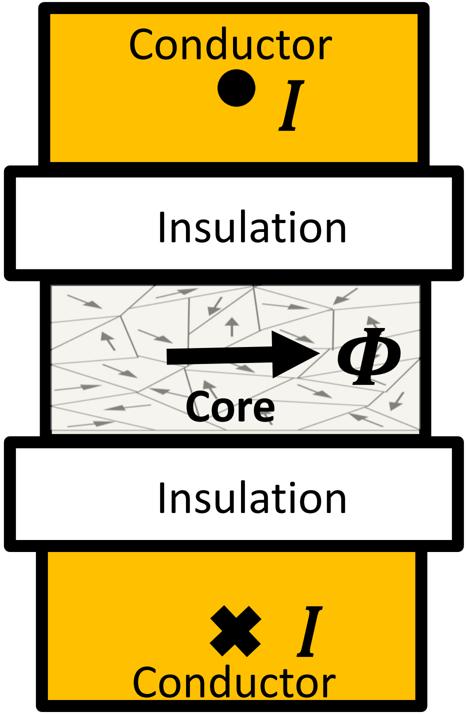
Induced eddy currents cause

- attenuation (& delay) of stress densities within volumes
- increased peak stress densities near surface for given net flux

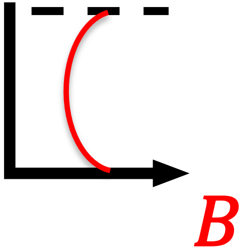
Eddy Currents Increase Stress

B flux density
J current density

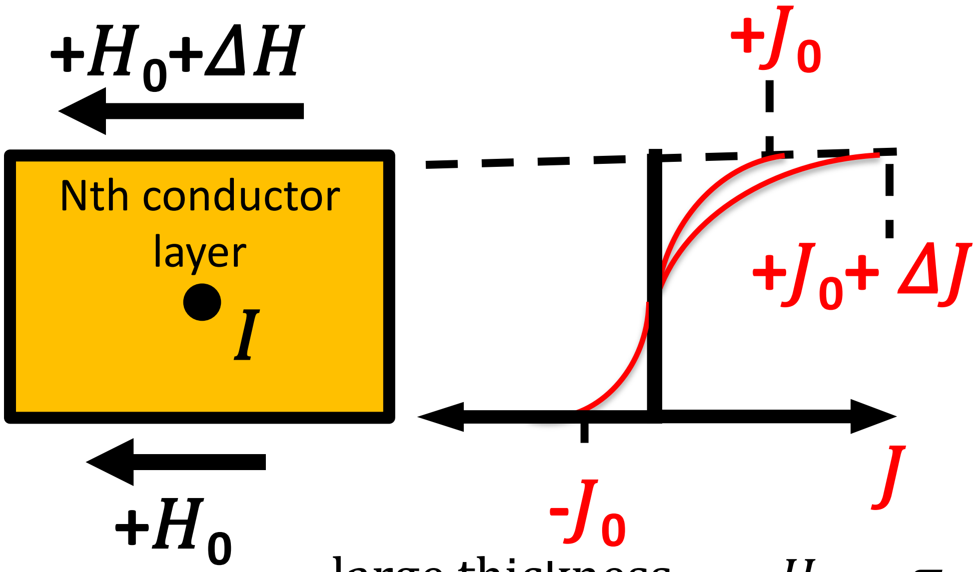
Conductor Turn around core



Flux crowding increases peak flux density and increases loss



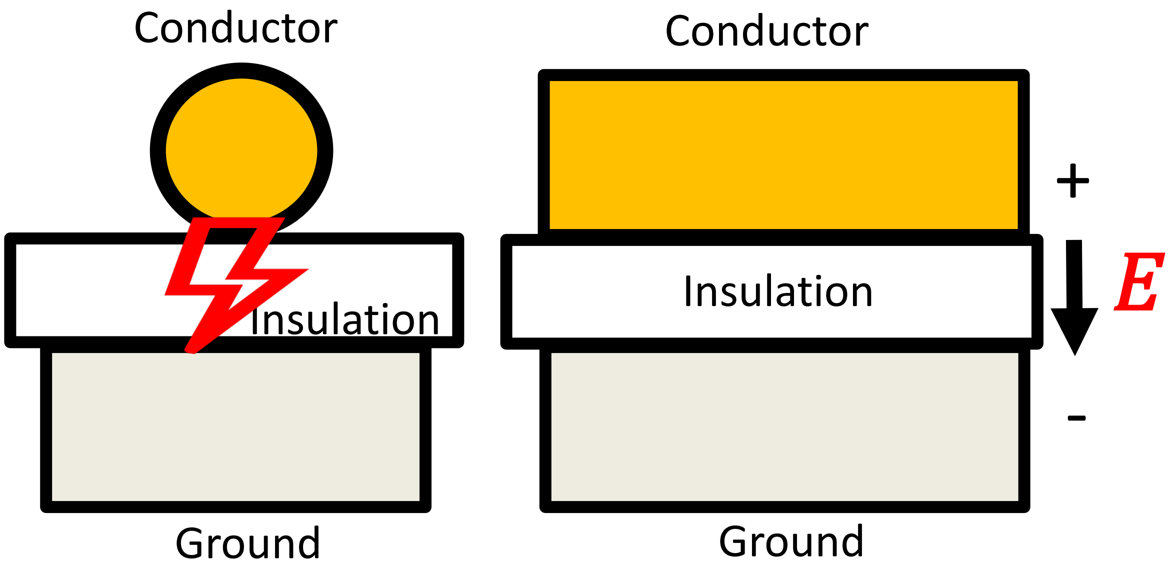
Nth conductor layer in proximity field of N-1 layers



$$J_0 \xrightarrow{\text{large thickness}} \sqrt{2}\,\frac{H_0}{\delta}, \angle\frac{\pi}{4}$$

Nth layer loss may be $2N^2$ x the loss from skin depth assumption.

Conductor Shapes Increase *E* **field intensity**



edge radius mils	5
clearance mils	50
Approximate Field Enhancement Factors:	
sphere & plane	9.90
cylinder & plane	3.76
adjacent cylinders	2.51

Thin conductors increase electric field intensity at edge, > **3 x average voltage stress**.

New Product Development Mitigations

DFMEA

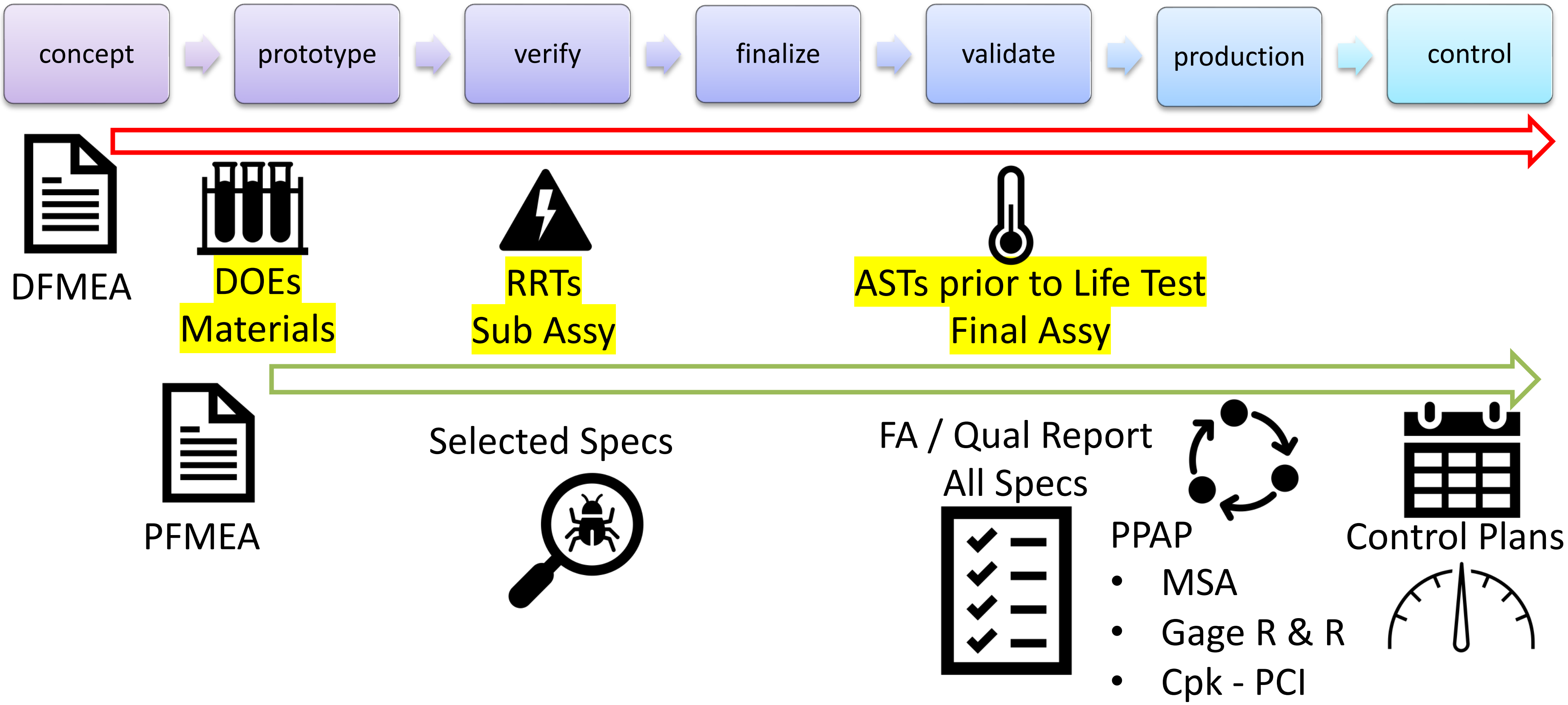
DOEs
Materials

RRTs
Sub Assy

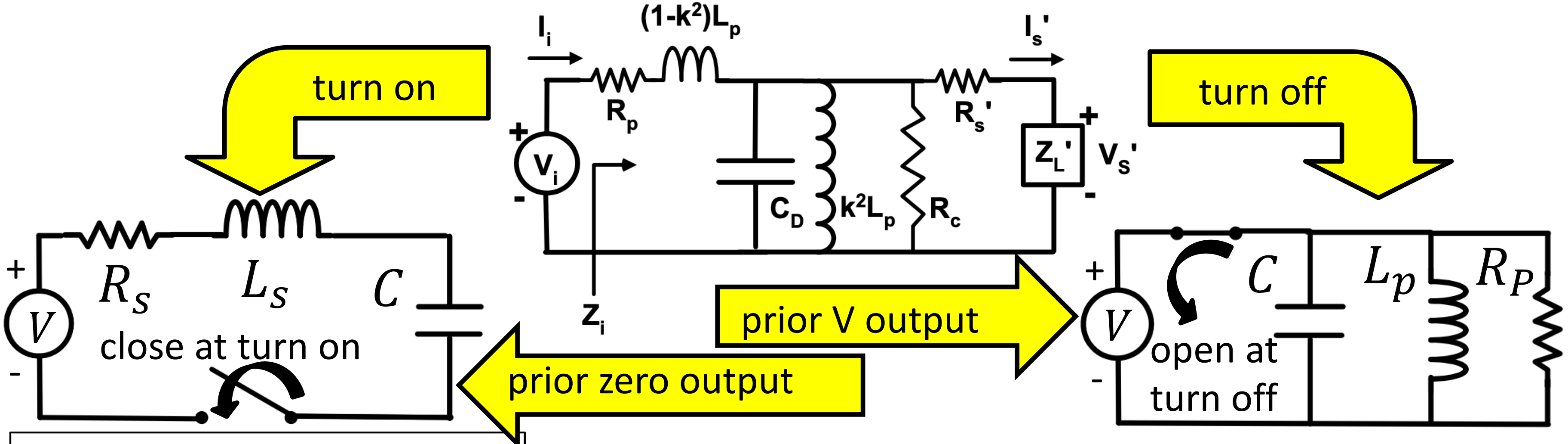
ASTs
Final Assy

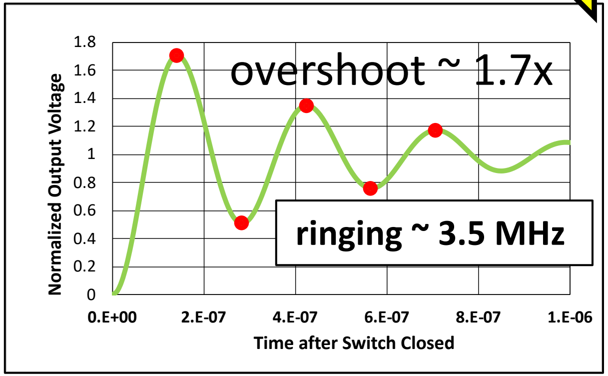
- Map transient stress and loss densities for review at Design Stages.
- Use DFMEA to identify and reduce risks of transients.
- Perform DOEs (Design of Experiments) on selected materials used for unprecedented stress density, physical size, operating level or environmental condition.
- Build selected subassemblies to perform RRTs (Risk Reduction Tests) of noted high risk regions before final assembly.
- Use ASTs (Accelerated Stress Tests) to verify design margins by probing induced failure modes.

New Product Development for Risk Reduction

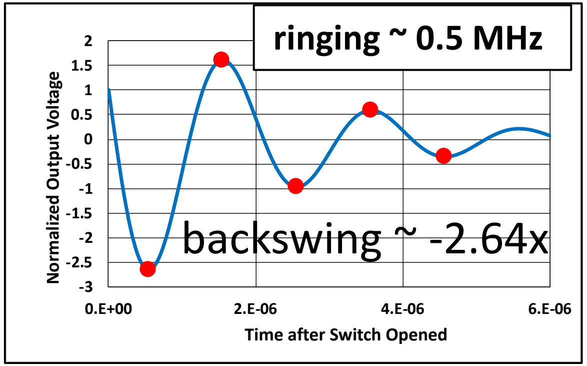


Step Up Transformer: Ringing and Overshoot

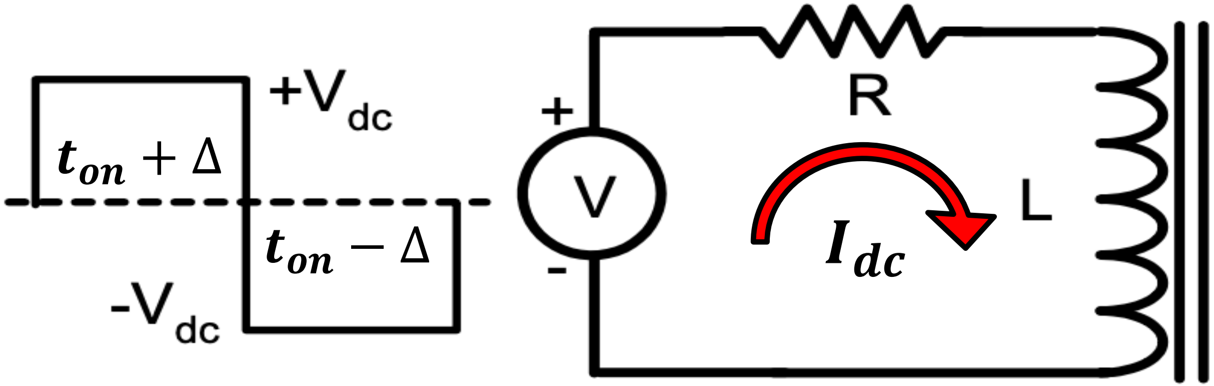




- Ringing frequency changes largely with interval.
- Overshoot ≠ Backswing.
- Identify and control transformer parameters that impact ringing in each interval.



Volt – Second Unbalance: Bias Current Risk

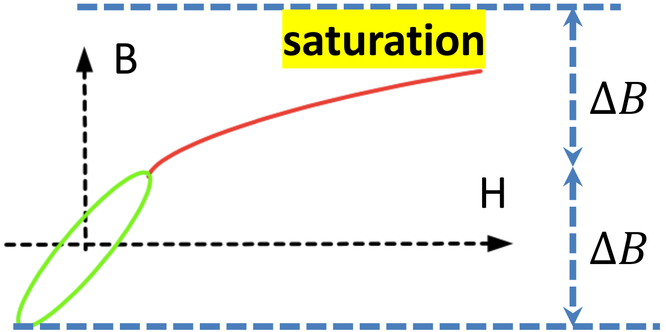


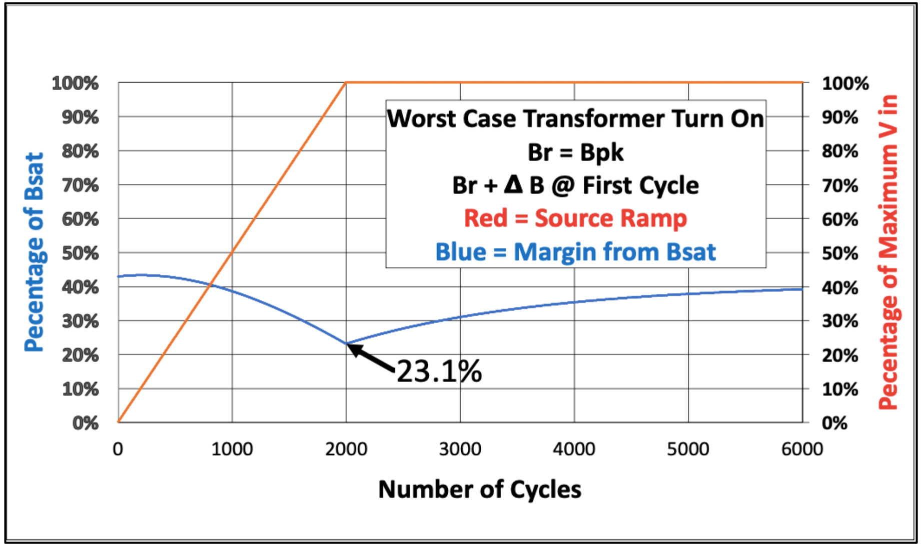
$$I_{dc} = \frac{V_{dc}}{R} \cdot \frac{\Delta}{t_{on}}$$

- Evaluate maximum bias current in transformers as generated by transient net Volt Second unbalance in drive or load circuits without capacitor blocks.

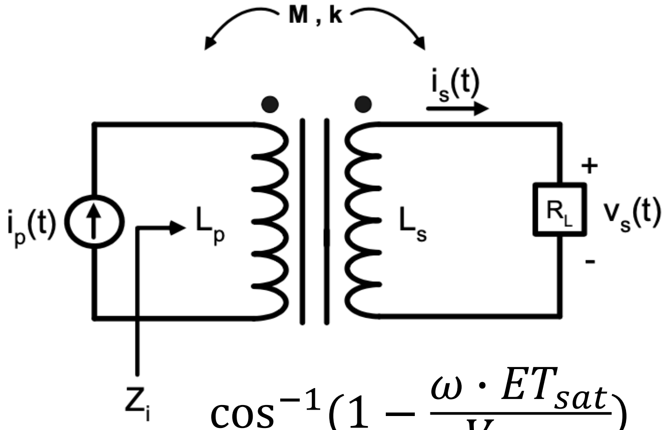
Transformer Soft Start: Prevent Saturation

- Design magnetics to withstand worst case phasing of turn on waveshape transients at minimum operating frequency and maximum voltage and temperature.

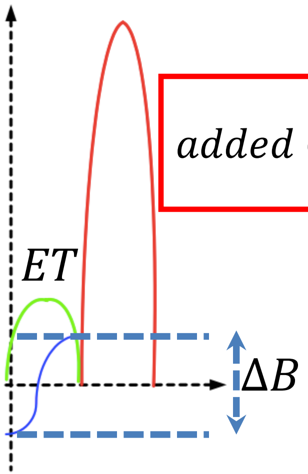




Current Transformer : Fault Current Detection

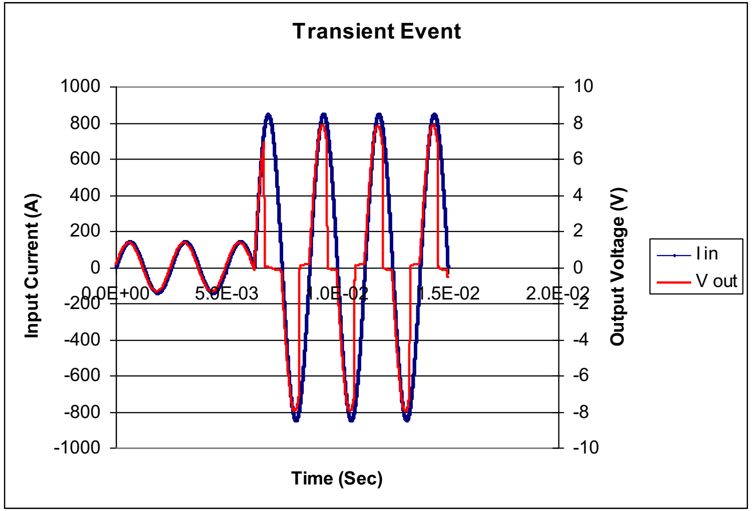


$$T_{saturate} \sim \frac{\cos^{-1}\left(1 - \frac{\omega \cdot ET_{sat}}{V_{peak}}\right)}{\omega}$$



$$added\ 6\ ET \xrightarrow{\text{yields}} +6\ \Delta B$$

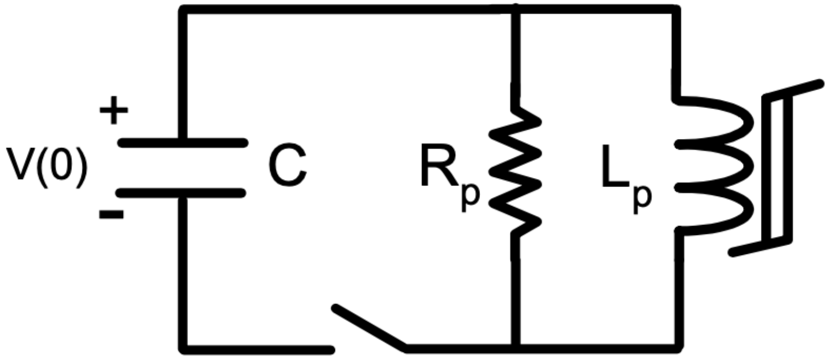
13x steady state flux density



- Aircraft frequency $\omega\ \sim 2\pi f\ with\ f\ \sim$400 Hz
- 100 ARMS Steady State
- Ex: 600 ARMS fault (849 Apk Transient)
- Use DOE to model magnetization curve.

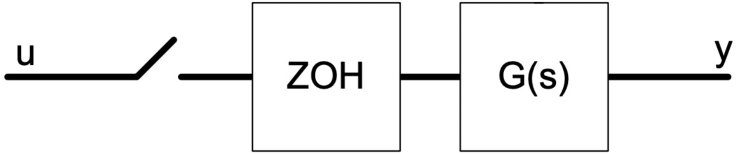
State Space Simulation: PFN Saturating Current

High energy pulse

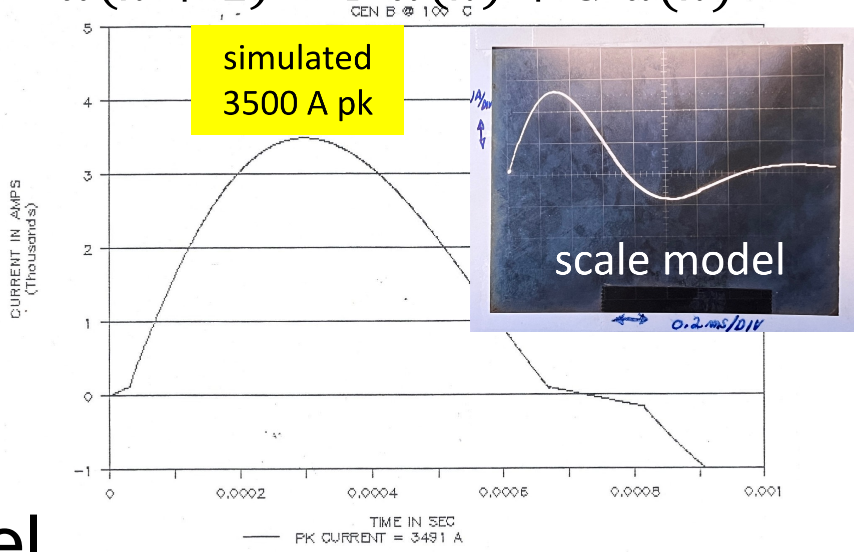


$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$
$$G(s) = C(sI - A)^{-1}B + D$$

- Verify computer simulation using empirical scale model.

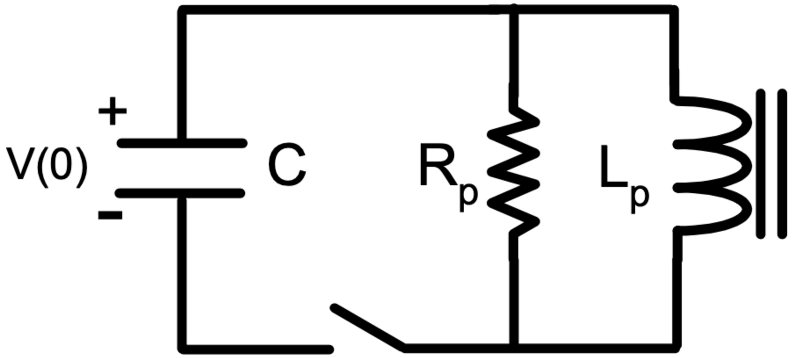


$$x(k+1) = F\,x(k) + G\,u(k)$$

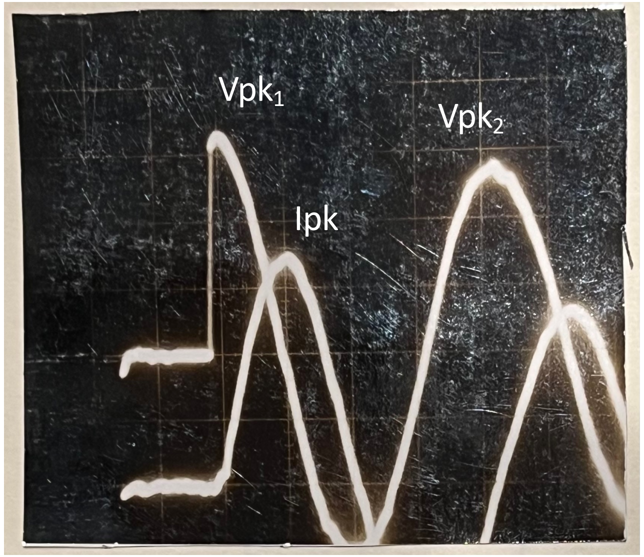


Inductor Verification: Transient Voltage Pulse

- Voltage pulse

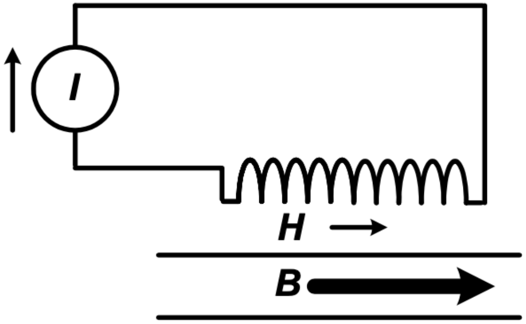


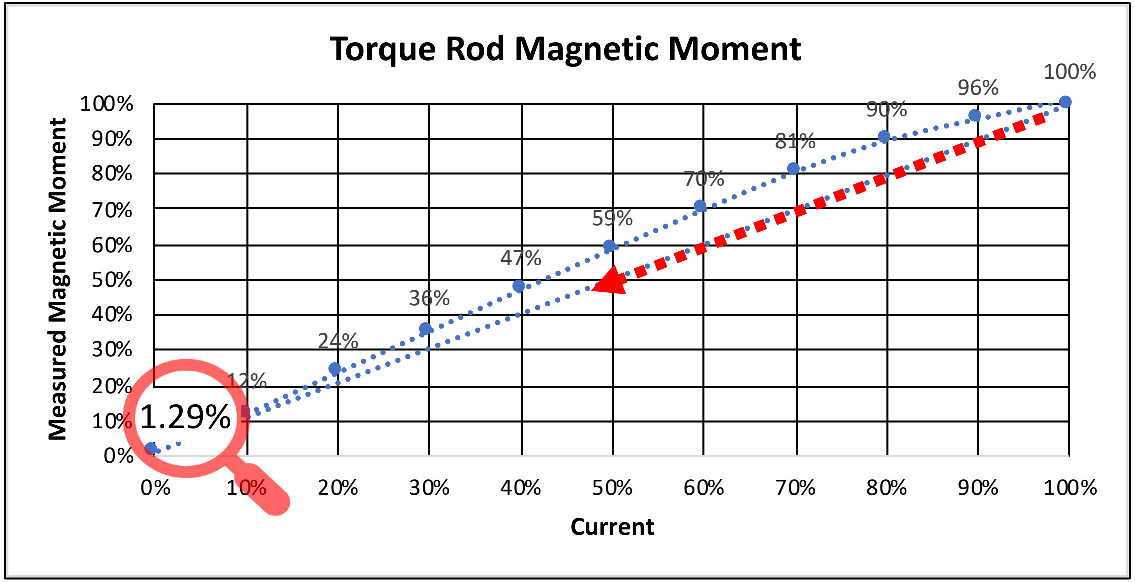
$$L = \frac{(Vpk_1)^{\frac{3}{4}} \, (Vpk_2)^{\frac{1}{4}}}{\omega \, Ipk}$$



- Measure component's effective inductance under extreme conditions throughout full scale production.

Magnetorquer Remanence: Residual Moment





- Verify residual magnetization does not cause excessive magnetic moment at turn off.

Counter Transient Threats in Magnetics

- Use high bandwidth instruments to detect latent transient amplification and persistent ringing at normal operating conditions.
- Evaluate worst case bias current for magnetics in switched mode circuits without capacitor blocks.
- Check flux density for worst case phasing of voltage turn on at minimum operating frequency and maximum voltage and temperature.
- Verify current transformers responsible for circuit protection can detect transient overcurrent despite saturation reduced output.
- Verify residual magnetization does not cause insufficient magnetization headroom or unacceptable radiated flux at turn off.
- Perform DOEs, RRTs and ASTs to mitigate risks through Design Stages.
- Employ CAPs, MOVs or similar to protect circuits susceptible to lightning.

References

- Hayt, William H., JR., Kemmerly, Jack E., ***Engineering Circuit Analysis*** (New York, McGraw-Hill, 1978).
- Grossner, Nathan R., ***Transformers for Electronic Circuits*** (New York, McGraw-Hill, 1983).