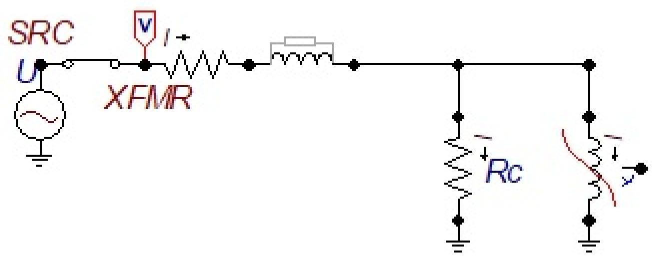
EE 5220 - Lecture 29 Wed Mar 20, 2024

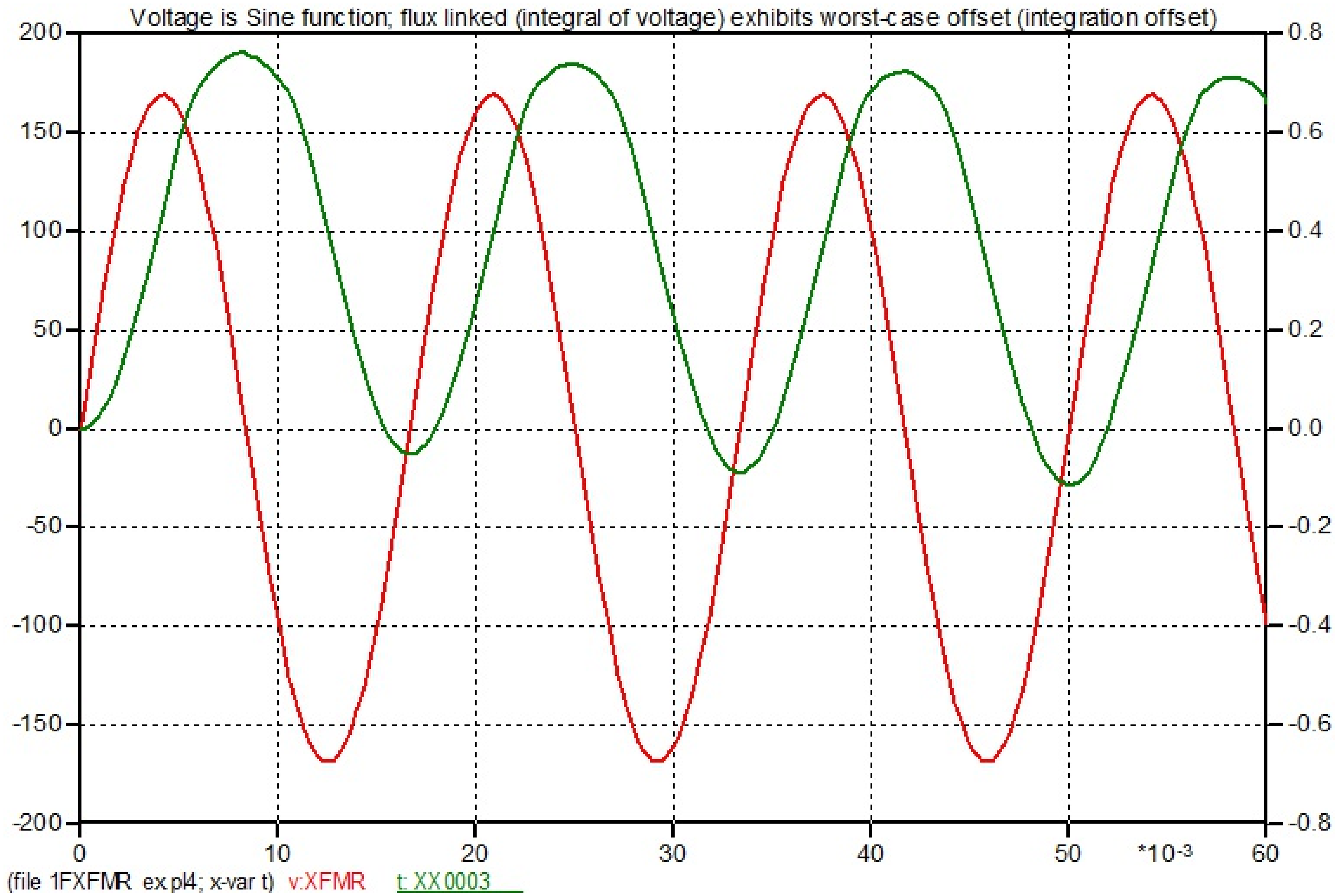
Topics for Today:

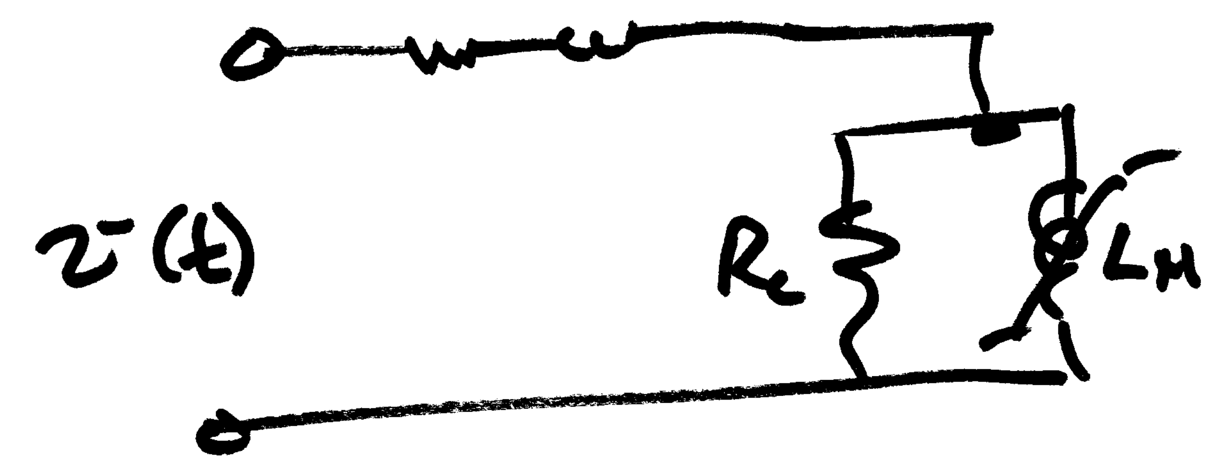
- Course Info:
  - Web page: https://pages.mtu.edu/~bamork/ee5220/
  - Book, references, syllabus, more are on web page.
  - Software - Matlab. ATP/EMTP [License - www.emtp.org] ATP tutorials posted on our course web page
  - EE5220-L@mtu.edu (participation = min half letter grade)

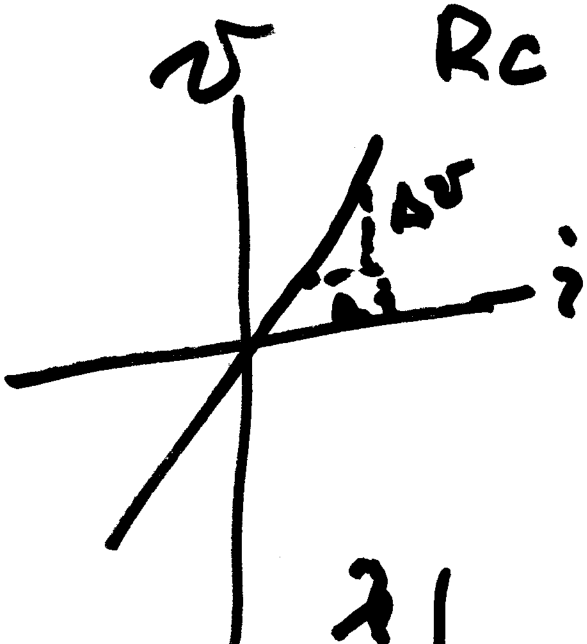
- HW#8 - Probs. 9.6, 9.12 now due.
- HW#9 - Probs. 9.2, 9.3, 9.4 due Tues Mar 26th, 9am.
- “Mid-term”: tentatively scheduled for Week 12 or 13. Comments?
- Transformer modeling - Section 11.1 of text, plus lecture notes
  - Nonlinear inductor models - Types 93, 98, 96
  - Magnetic materials: B-H characteristics
  - Transformer Inrush - initial conditions
    - Energization inrush
    - Recovery inrush
    - Sympathetic inrush
- Next - take stock of available ATP transformer models

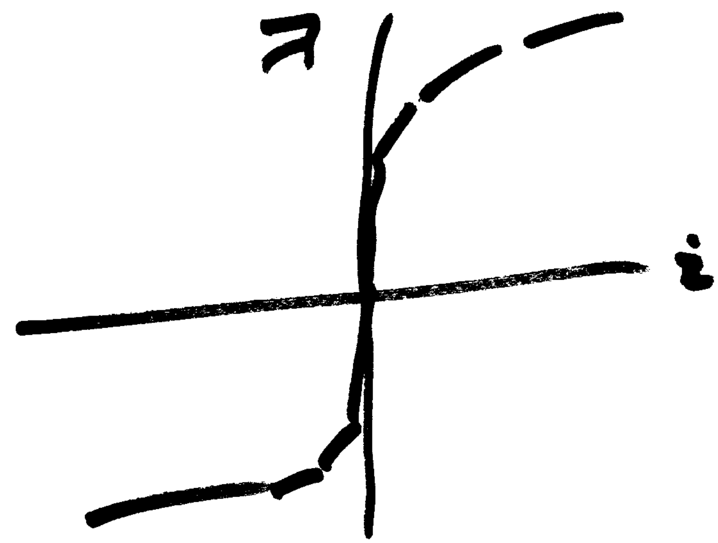


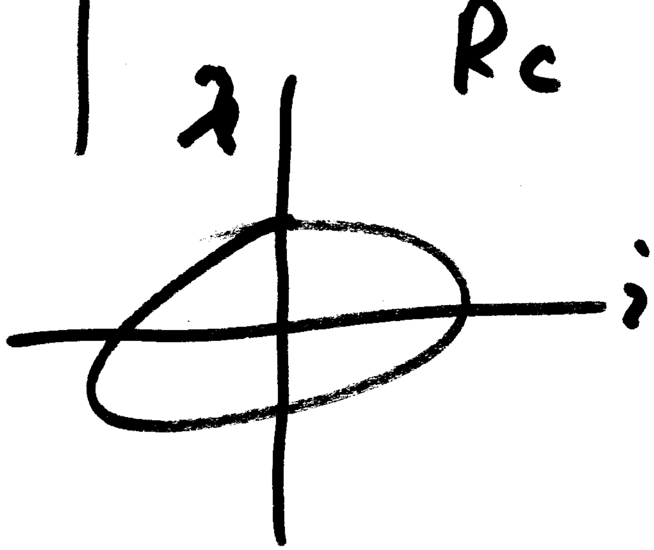
λ(0) = 0; voltage source (red) is Sine wave which turns on at t=0. Note worst-case integration offset in flux linked (green).



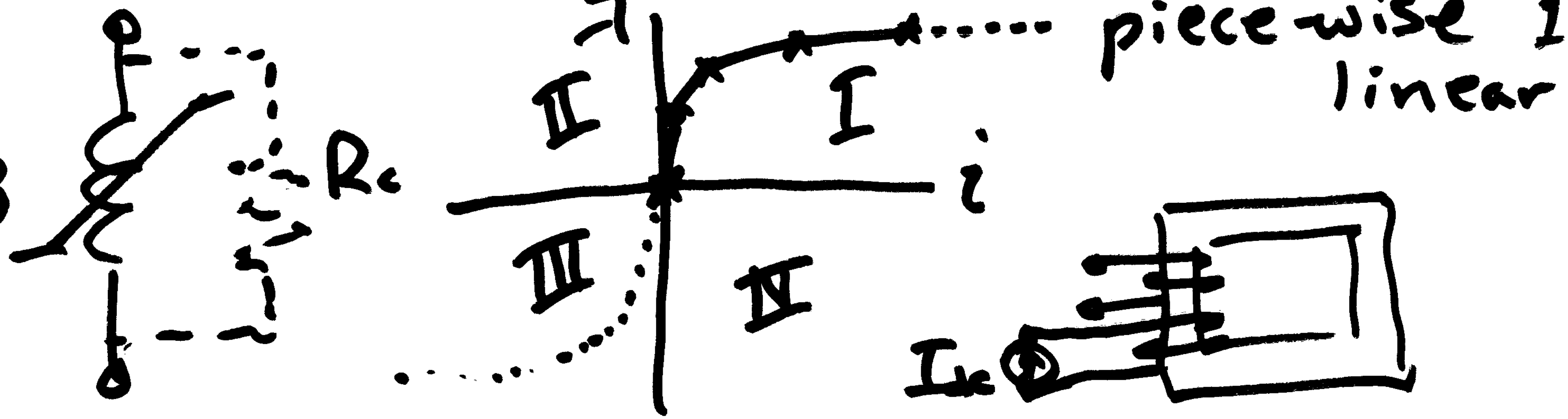

v(t)
Rc
LM


v
Rc
Δv
Δi
i

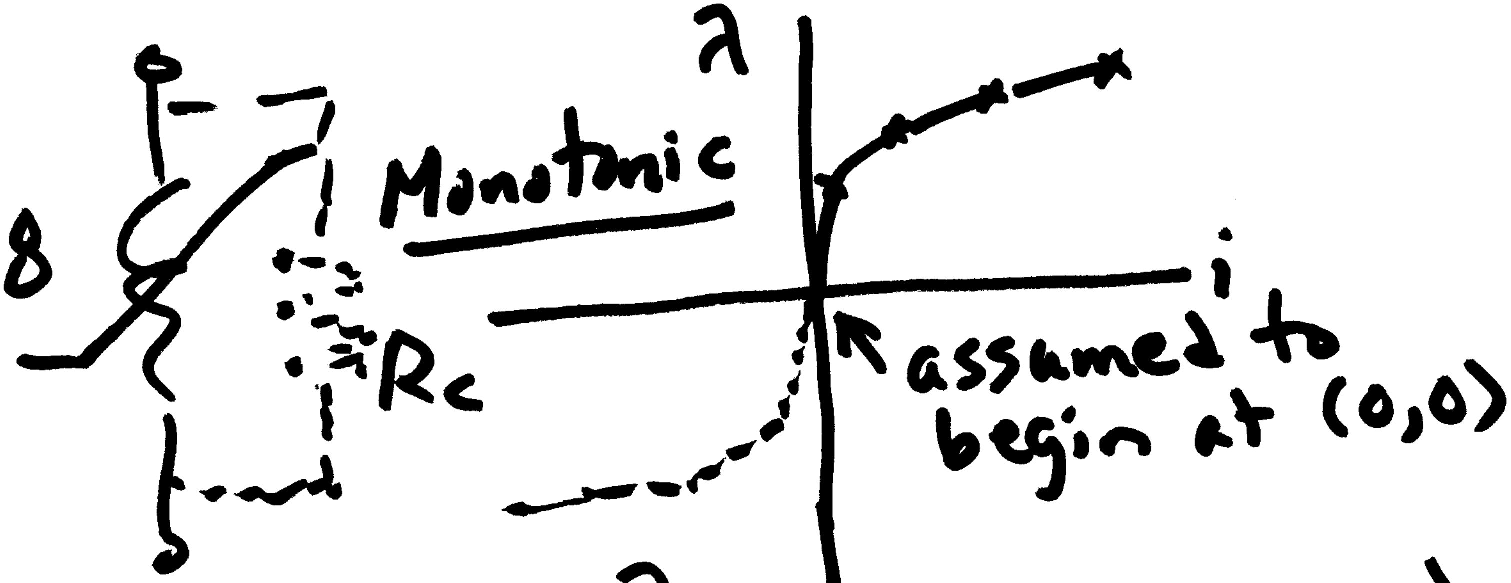

λ
i


λ
Rc
i

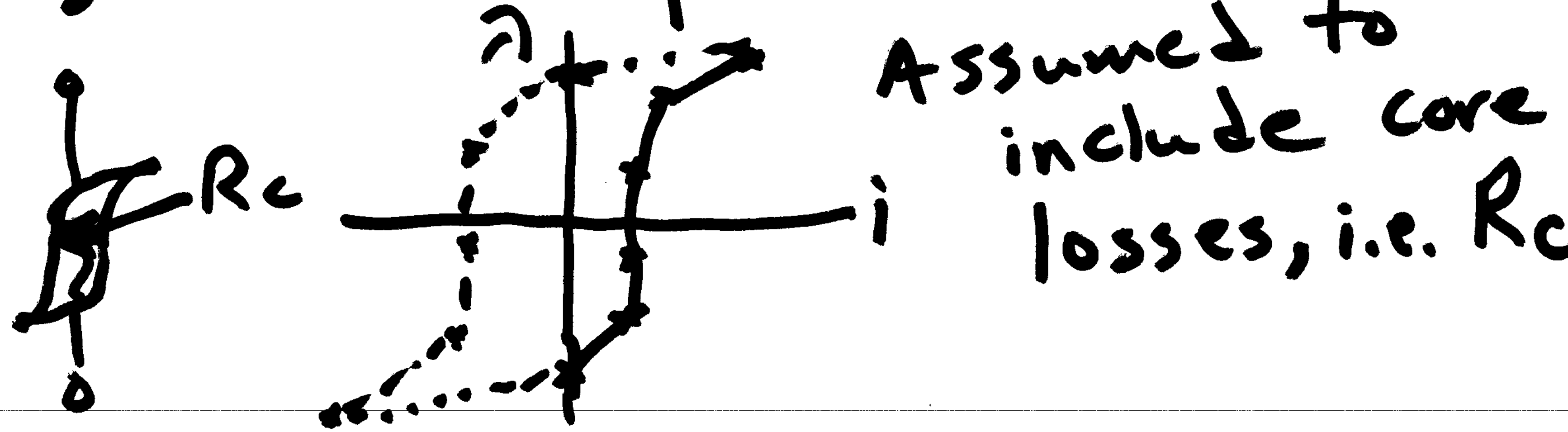
93


Rc
λ
i
I
II
III
IV
piece-wise linear
Ik

98


Rc
Monotonic
λ
i
assumed to begin at (0,0)

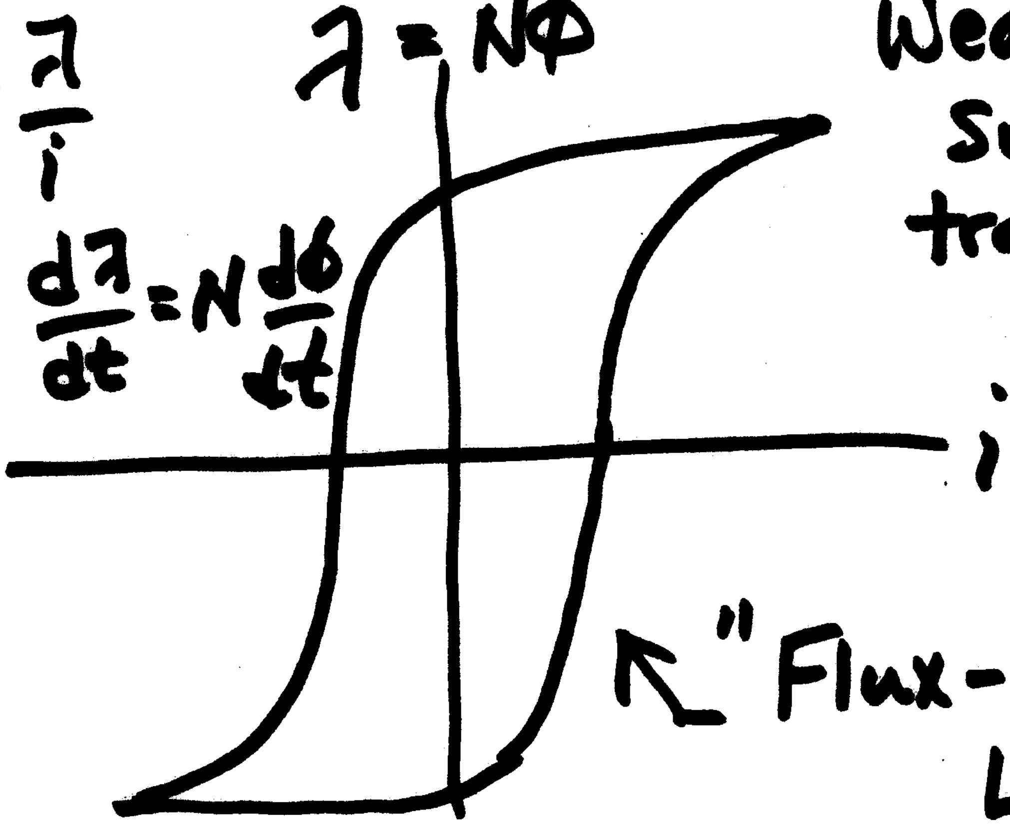
96


Rc
λ
i
Assumed to include core losses, i.e. Rc

"Type-96" - Hysteretic

$L = \frac{\lambda}{i}$

$e = \frac{d\lambda}{dt} = N\frac{d\phi}{dt}$

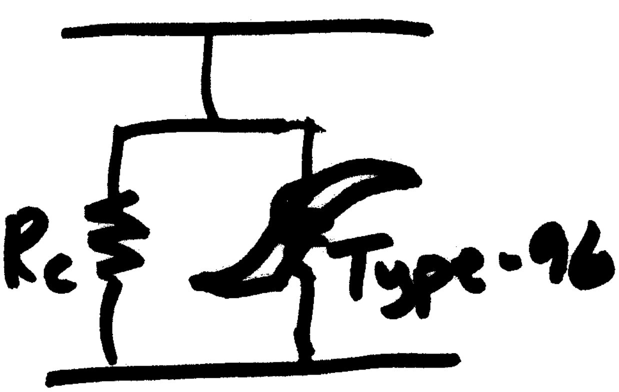


"Flux-Current Loop"

Weakness - Subloop trajectories.

Area ∝ Losses

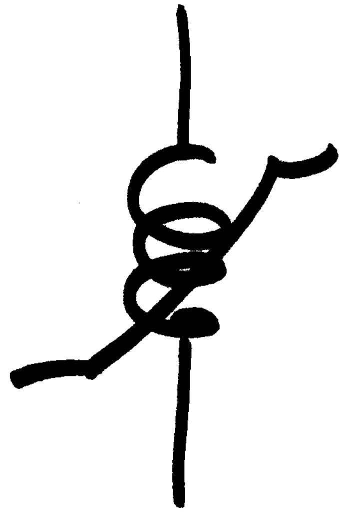
- Hystesis
- Eddy Current
- Anomalous
- Stray Losses



$R_c = \infty$ if all losses in Type-96

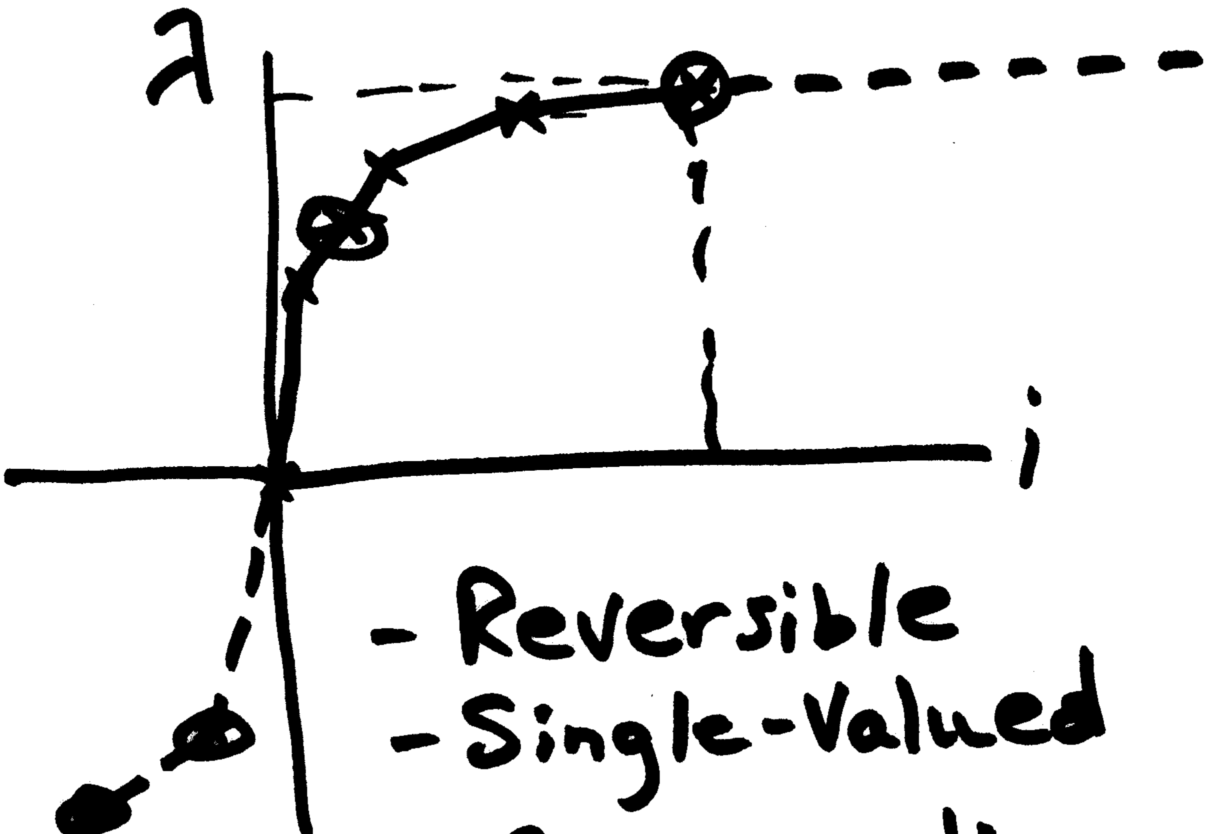
Type-93

"true nonlinear"

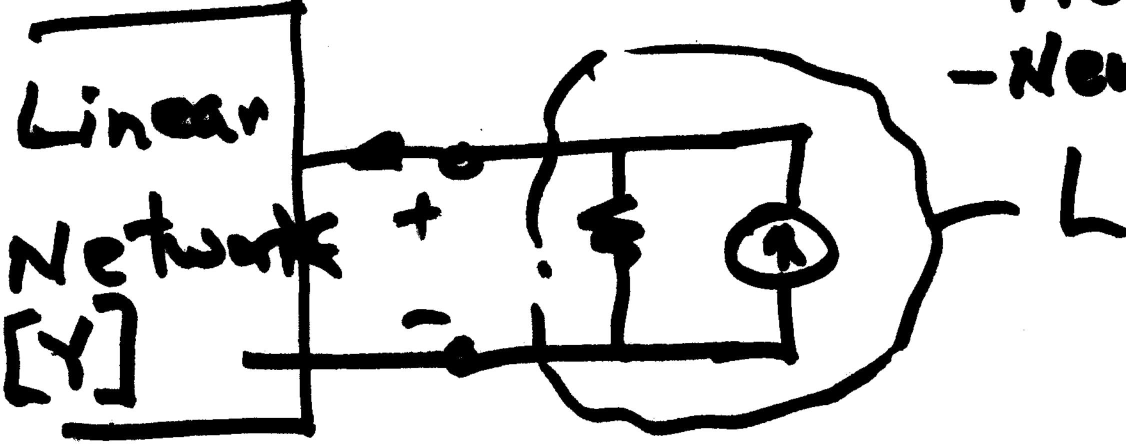


piece-wise Linear

4

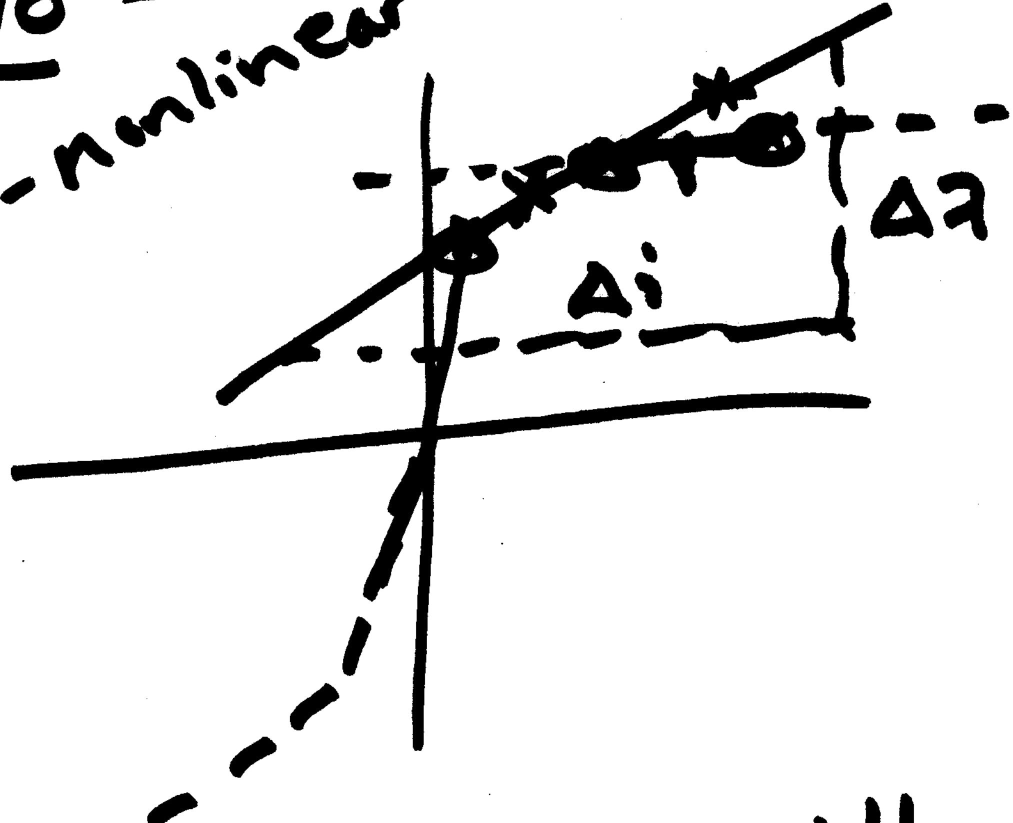


- Reversible
- Single-Valued
- Compensation Method
- Newton Iter.

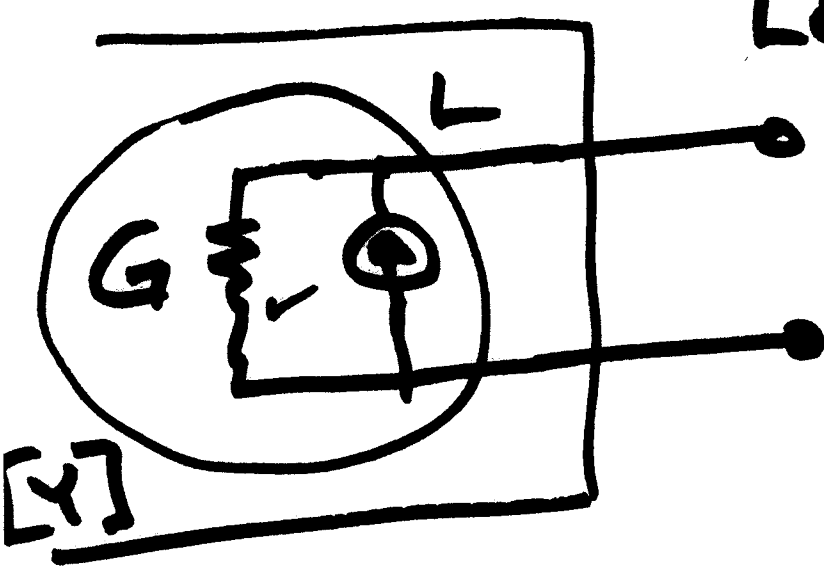


Type - 98 -

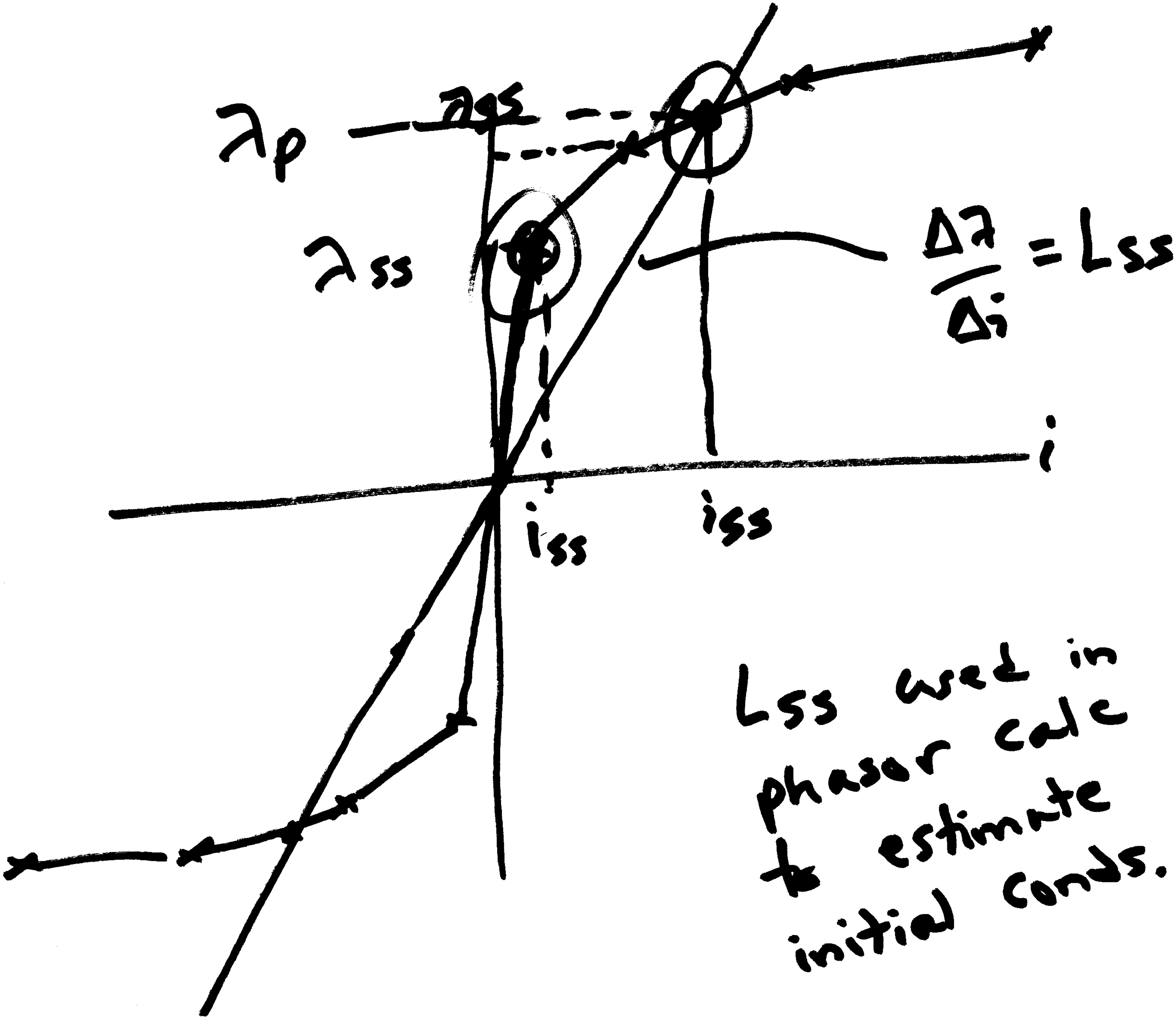
psuedo-nonlinear



- Approx with Linear L for Local operating point.



- Refactorize if segment change.



Lss used in phasor calc to estimate initial conds.

- Size of network
  - Big Network: Type-98 <u>BAD</u>

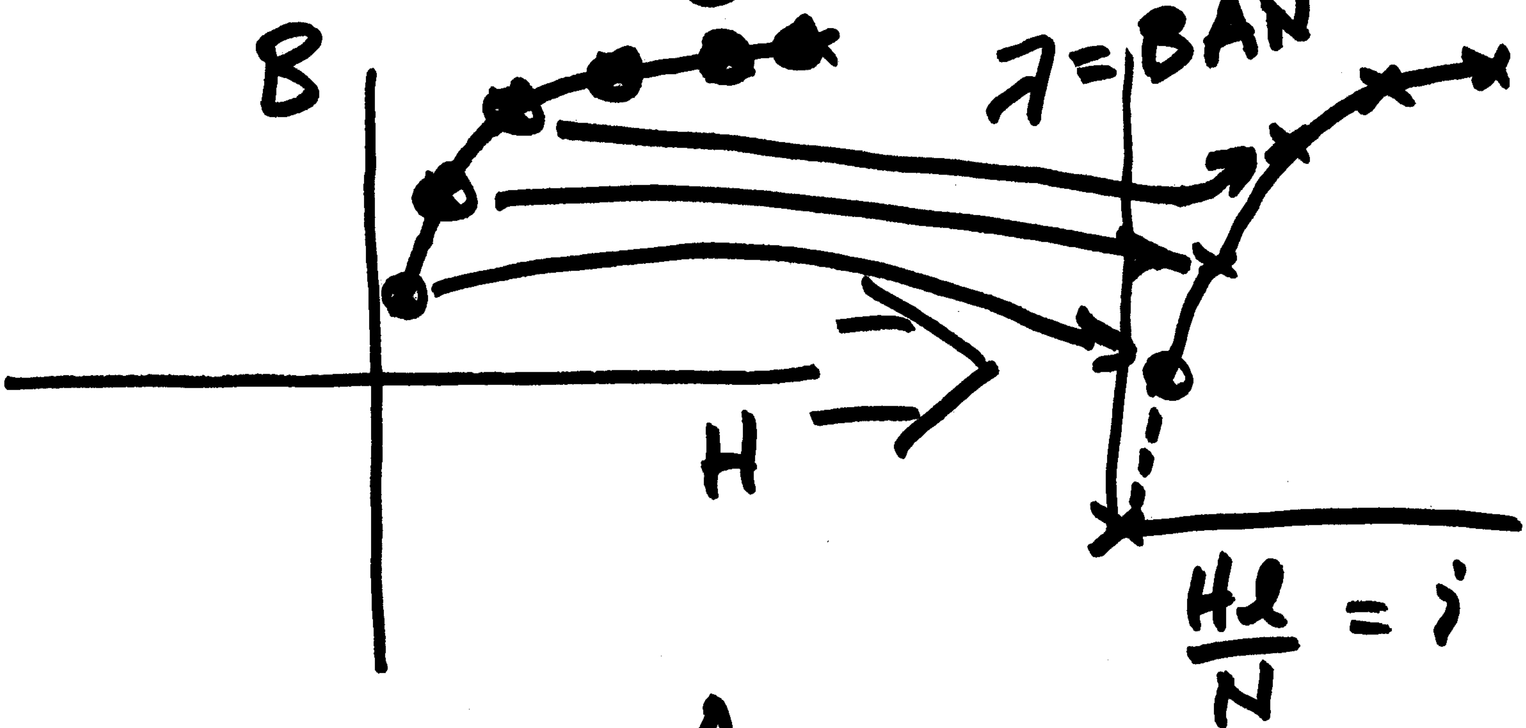
- No. of inductors
  98 - Bad if Lots
  93 - Better

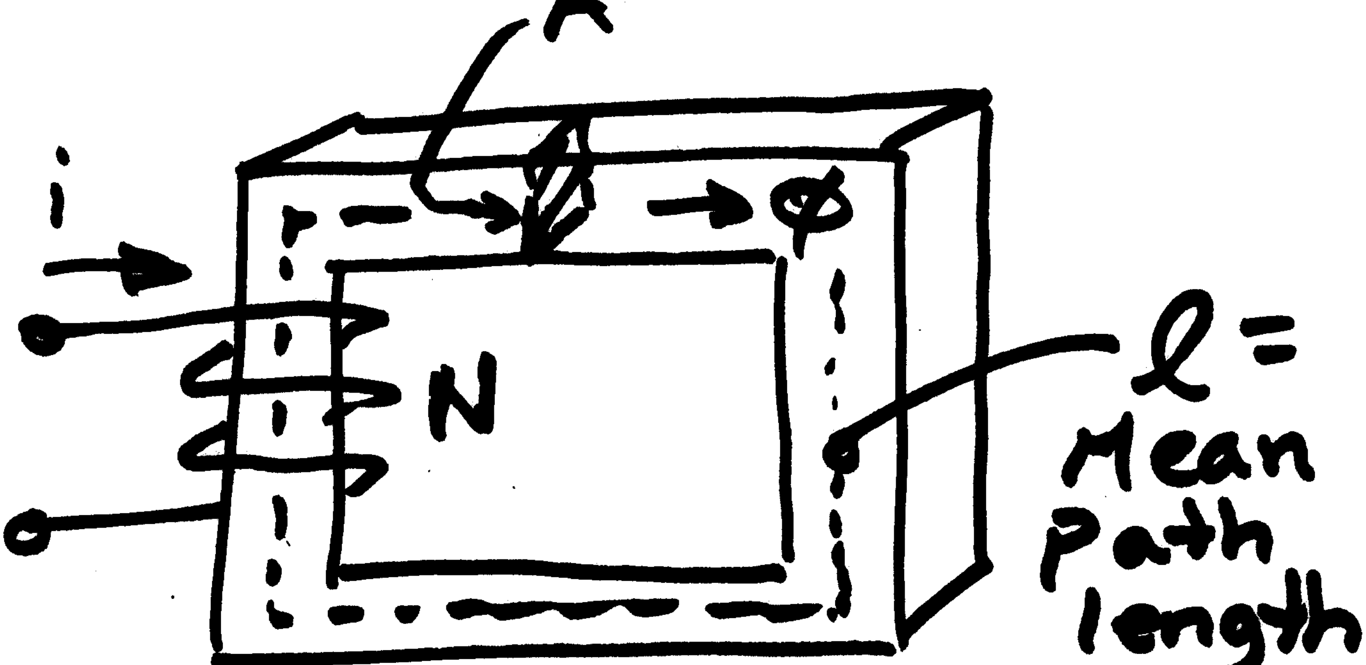
- No. of Segments
  Large: 98 - Bad
  93 - Good

Type-93 - More Stable.

Type-98 - Operates one timestep <u>outside</u> of proper segment.

B-H Scaling





B = Mag Flux Density $\frac{Wb}{m^2}$ or T

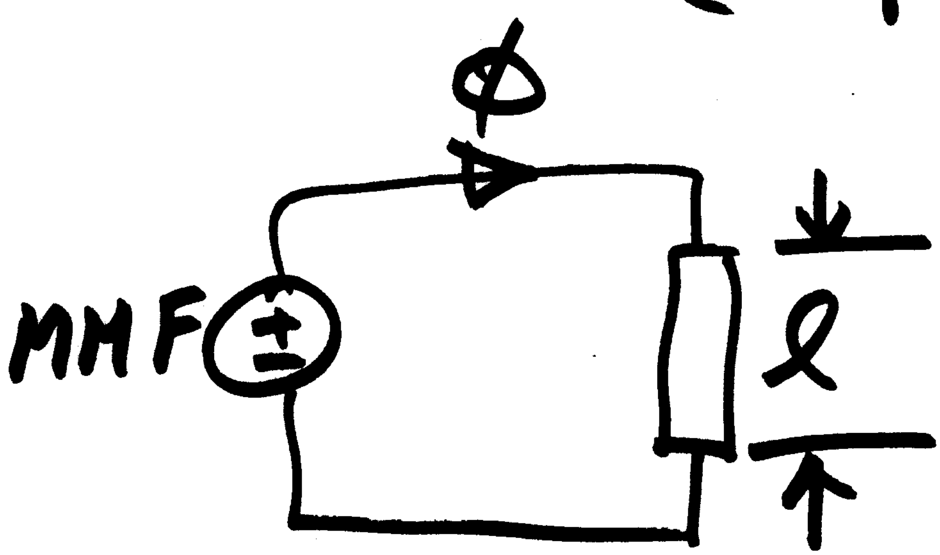
$$= \frac{\Phi}{A} = \frac{\lambda}{AN} \Rightarrow \lambda = BAN$$

$H \rightarrow i$?

H = Magnetic Field Intensity

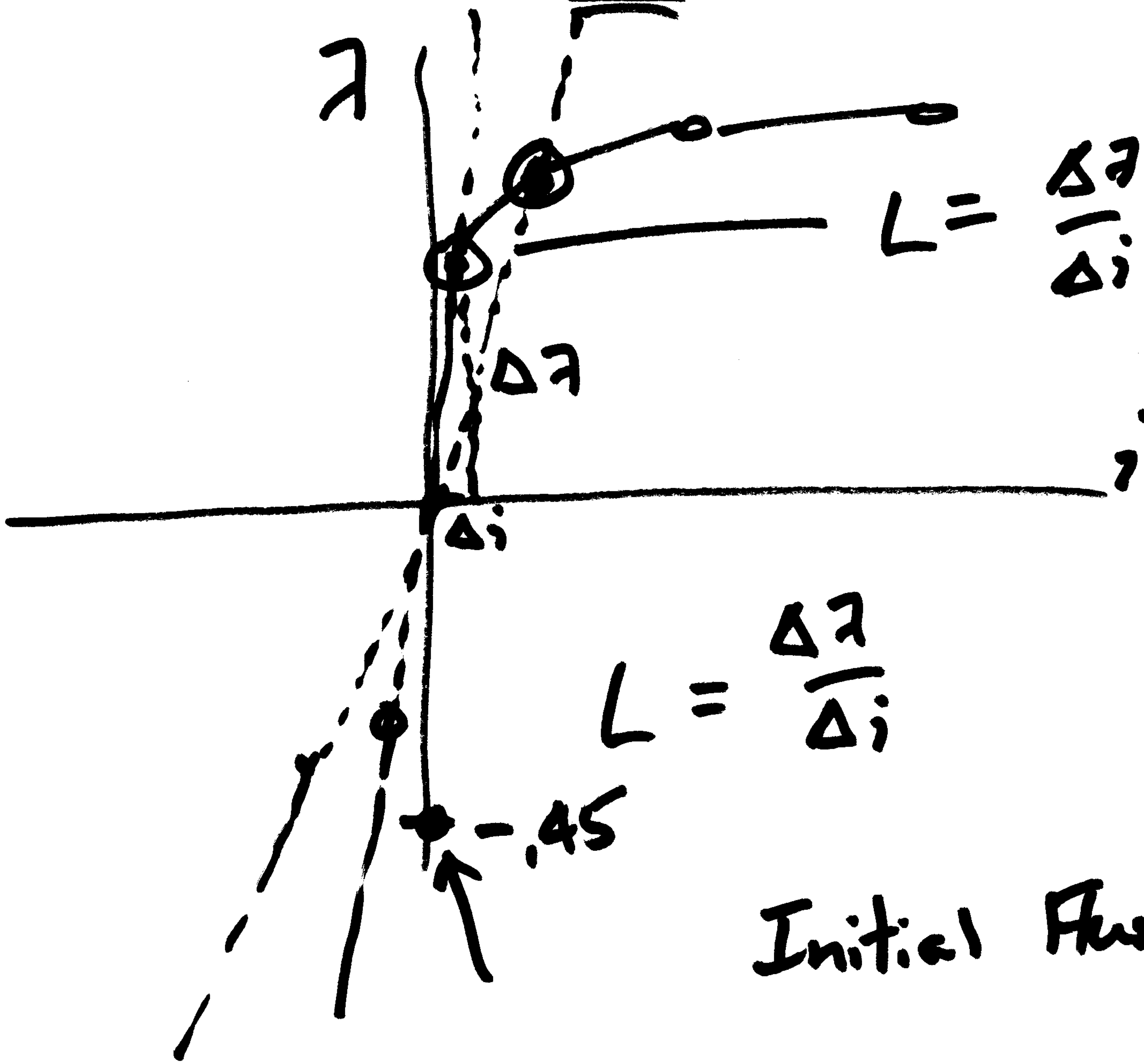
= MMF drop per unit length along mean path

MMF = $\mathcal{F}$ = Ni Ampere-turns (Amperes)



$$H = \frac{MMF}{l} = \frac{Ni}{l} \quad \frac{A\text{-}t}{m} \text{ or } \frac{A}{m}$$

Initialization (λ, i) point.



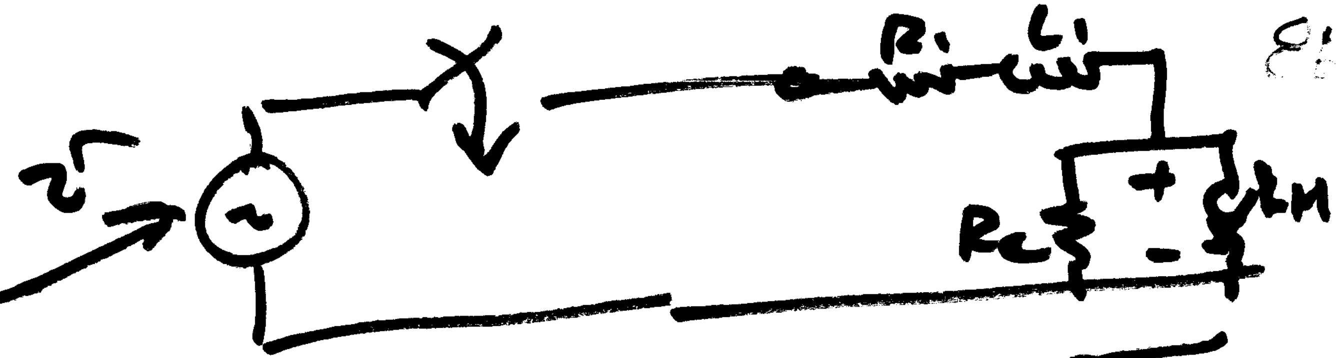
$$L = \frac{\Delta\lambda}{\Delta i} = \frac{\text{FLUX}}{\text{CURR}}$$

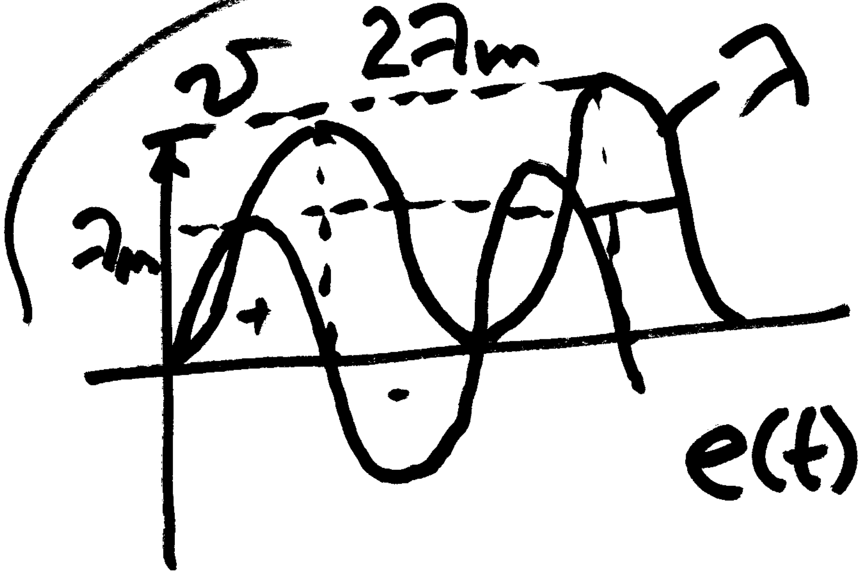
$$L = \frac{\Delta\lambda}{\Delta i}$$

Initial Flux = (I(0), FL(0))

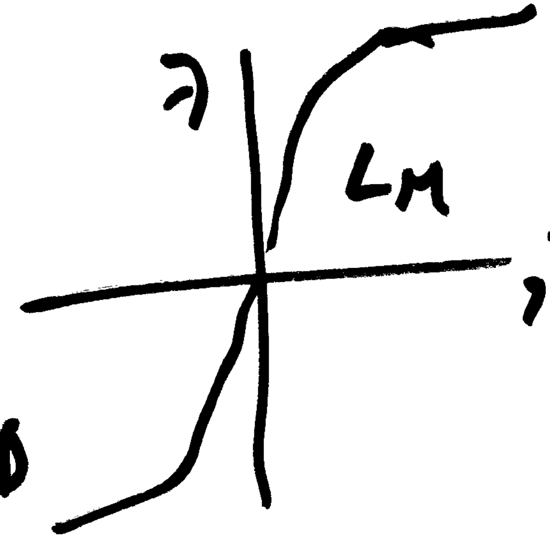
(0, -.45)

Inrush -





$$e(t) = V_m \sin \omega t + \phi$$



$$\lambda(t) = \lambda_m \sin(\omega t + \phi) + \lambda(0) - \underbrace{\lambda_m \sin \phi}_{\text{int. offset.}}$$

See next page for details of offsets!

if: $e(t) = V_m \cos(\omega t + \phi)$ ← $\phi = -90°$ for sin wave!

then:

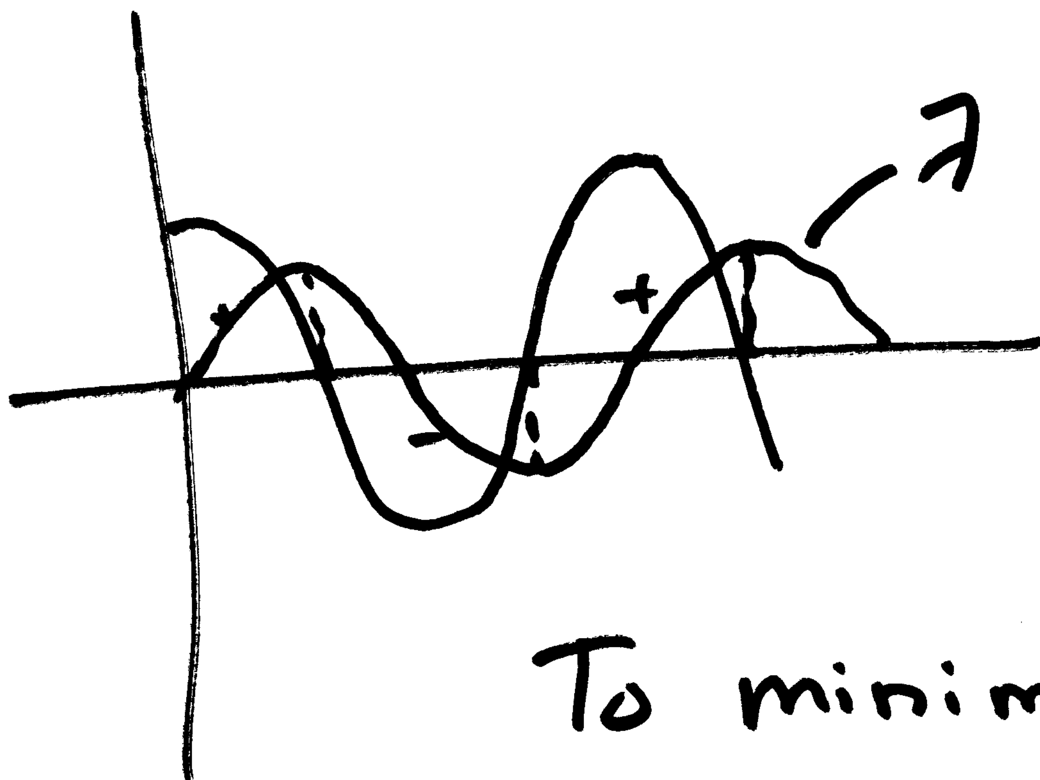
$$\lambda(t) = \int_0^t V_m \cos(\omega t + \phi) + \lambda(0)$$

$$= \frac{V_m}{\omega} \sin(\omega t + \phi) \underbrace{- \frac{V_m}{\omega} \sin\phi}_{= +\lambda_m \text{ if } \phi = -90°} + \lambda(0)$$

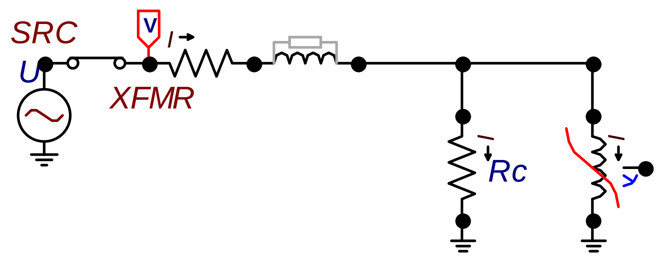
$$\boxed{\lambda(t) = \lambda_m \sin(\omega t + \phi) - \lambda_m \sin\phi + \lambda(0)}$$

$-\lambda_m \sin\phi$ ↑ "integration offset"

$\lambda(0)$ ↑ residual flux



To minimize inrush, switch on at V_p or $-V_p$!
(assumes $\lambda(0) = 0$).



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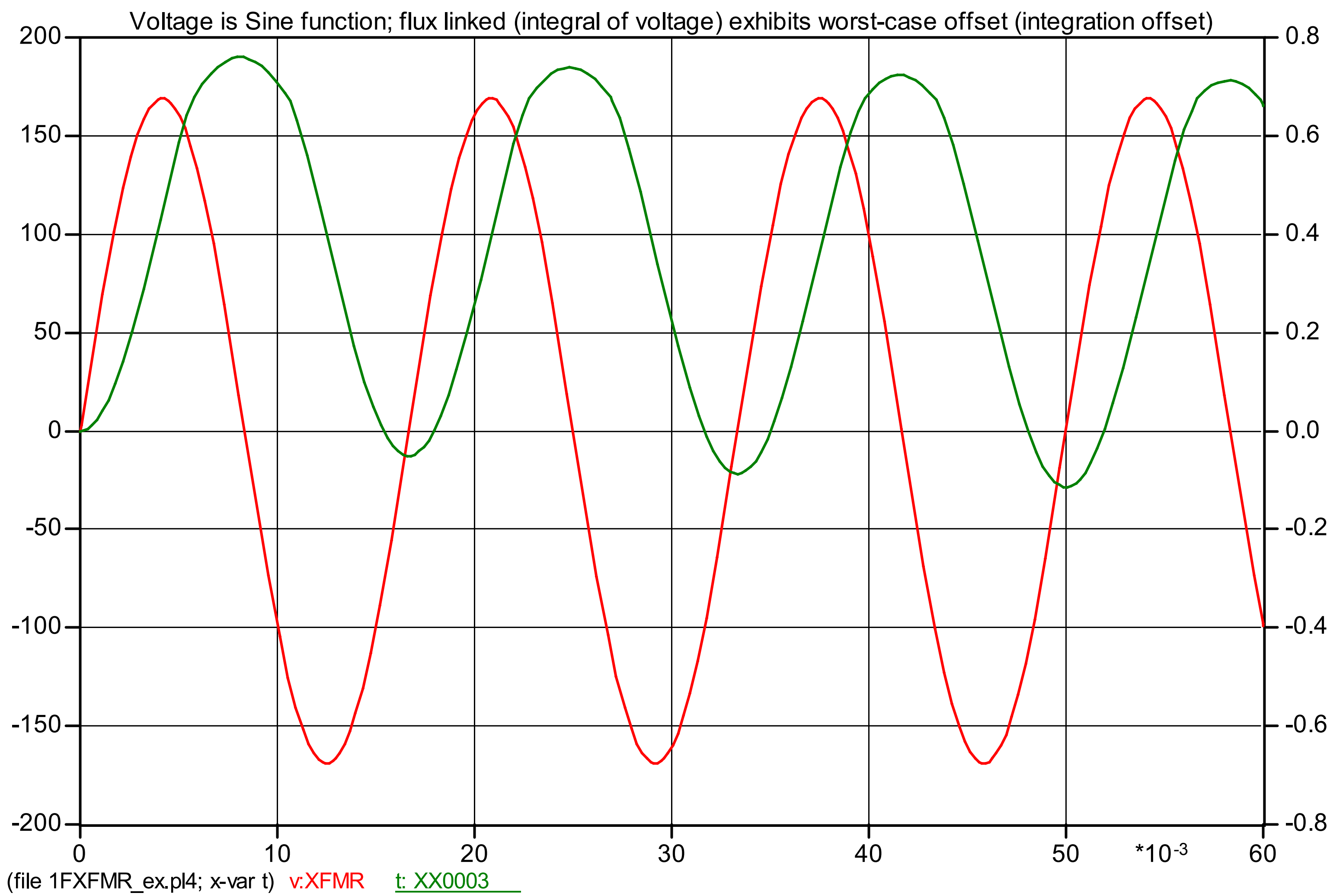
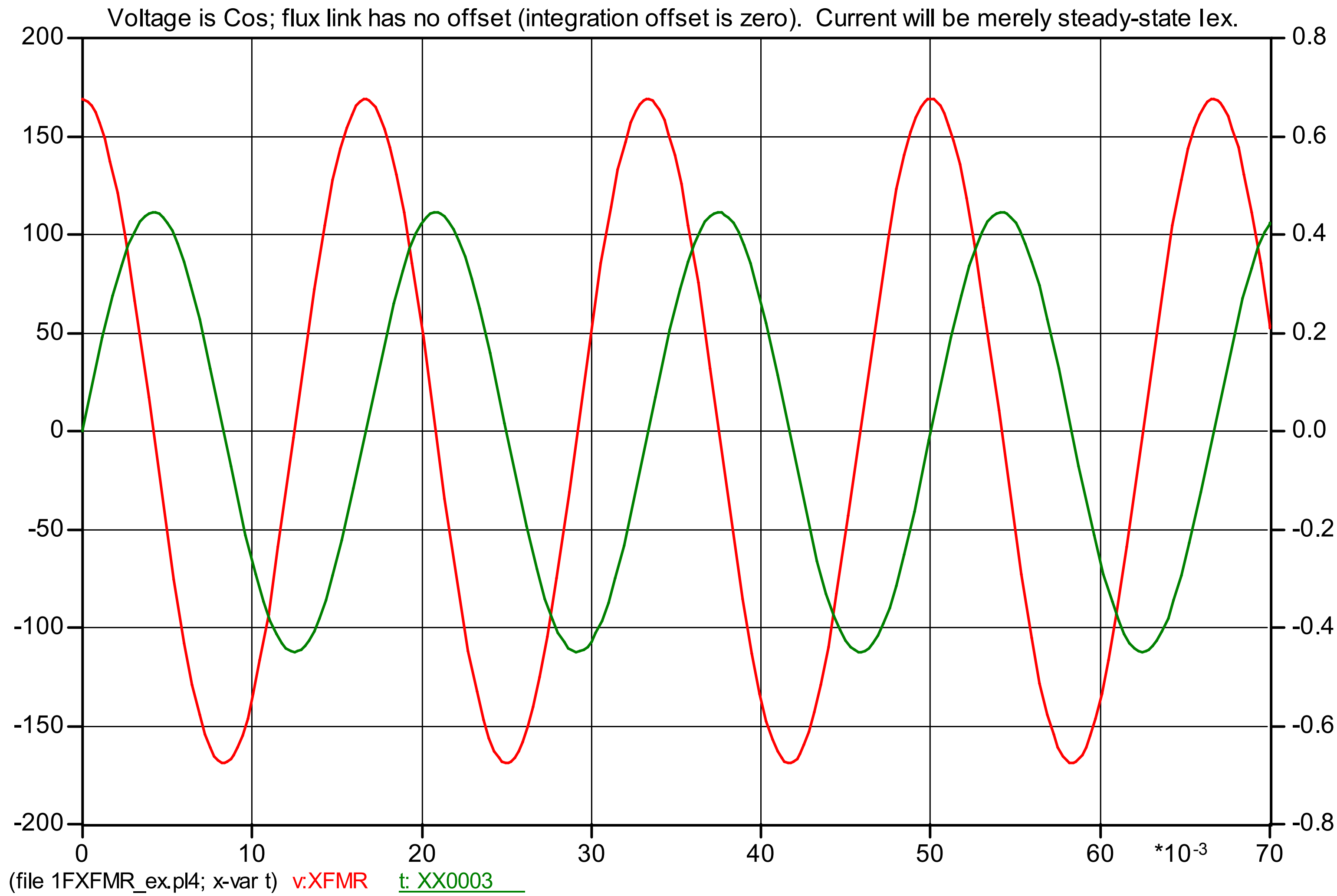
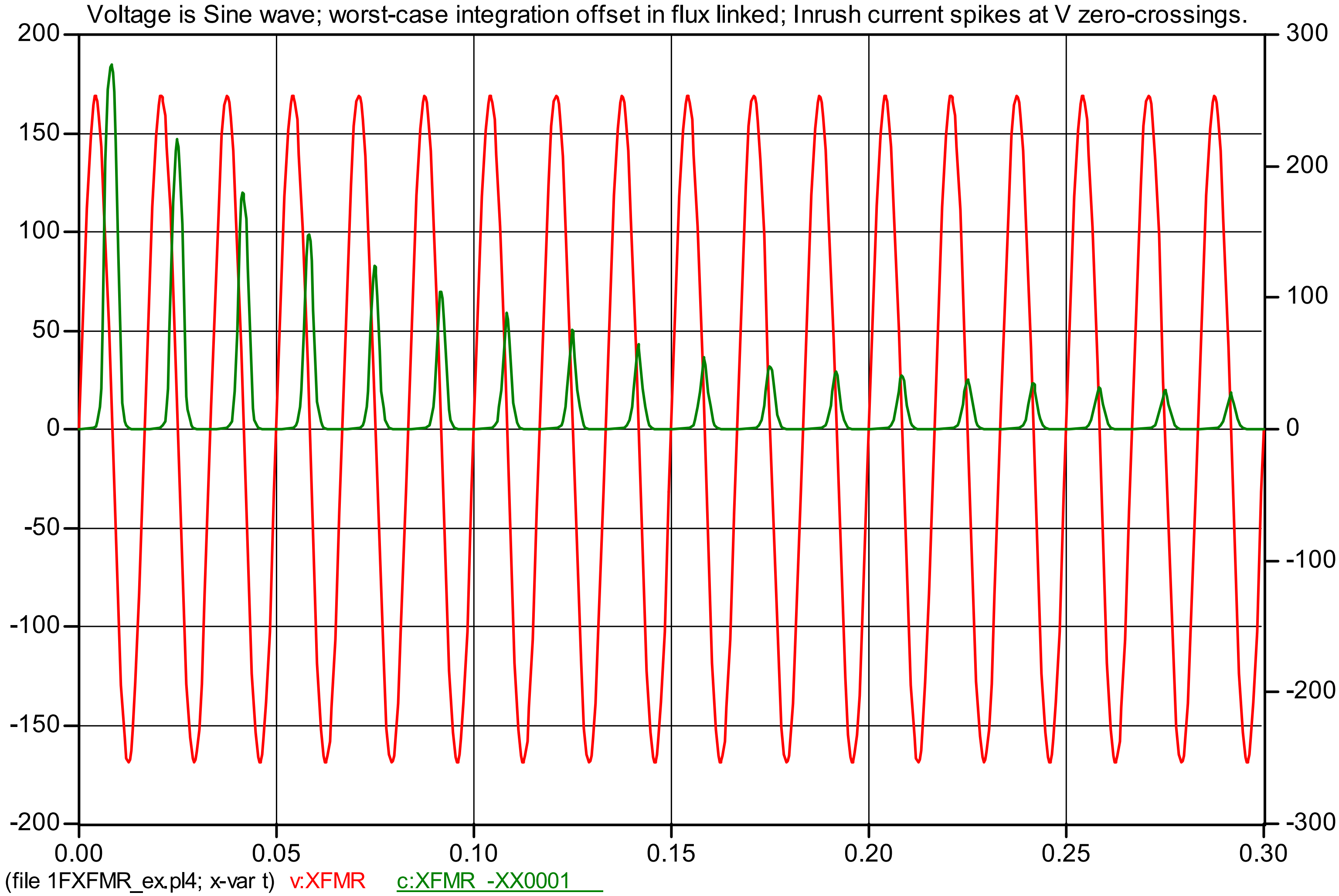




Special case to illustrate how to get rid of integration offset. Energize transformer at plus or minus peak voltage (Cos voltage function) and then the flux linked will have zero offset. (Again, this assumes that residual flux linked λ(0) in transformer core is zero. Unfortunately, λ(0) cannot be known or exactly predicted). Cases below go back to worst-case integration offset to illustrate the characteristics of inrush current. Inrush current spikes lag voltage by 90° as would be expected of an inductance L_M. Winding resistance R_1 provides damping.



Same case as above, inrush current is overplotted with flux linked. See how flux linked begins with full offset, but the offset decays due to the damping effect of R_1. Rate of decay is not exactly exponential like in a linear R-L circuit, due to nonlinear (saturable) L_M characteristic. Decay is initially quite rapid while L_M is in full saturation, but rate of decay is slower as it progresses (less saturation => smaller current spikes => less damping).