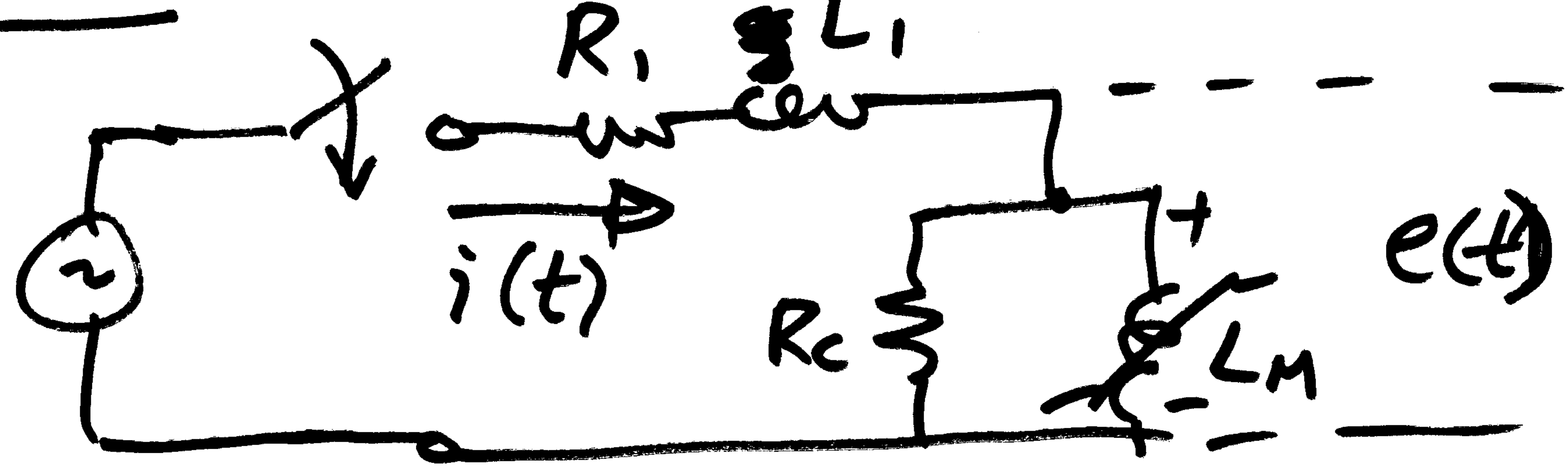
EE 5220 - Lecture 28 Mon Mar 18, 2024

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 due Tues. Partnered (term proj Team).
- HW#9 - Probs. 9.2, 9.3, 9.4 due Tues Mar 26th, 9am.
- “Mid-term” (homework + ATP): propose Week 12 or 13 time window.
- Term Project now due: a) complete reference list and b) fully-detailed table of contents according to format given in Term Project Guidelines.
- 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

Inrush:



Important to note:

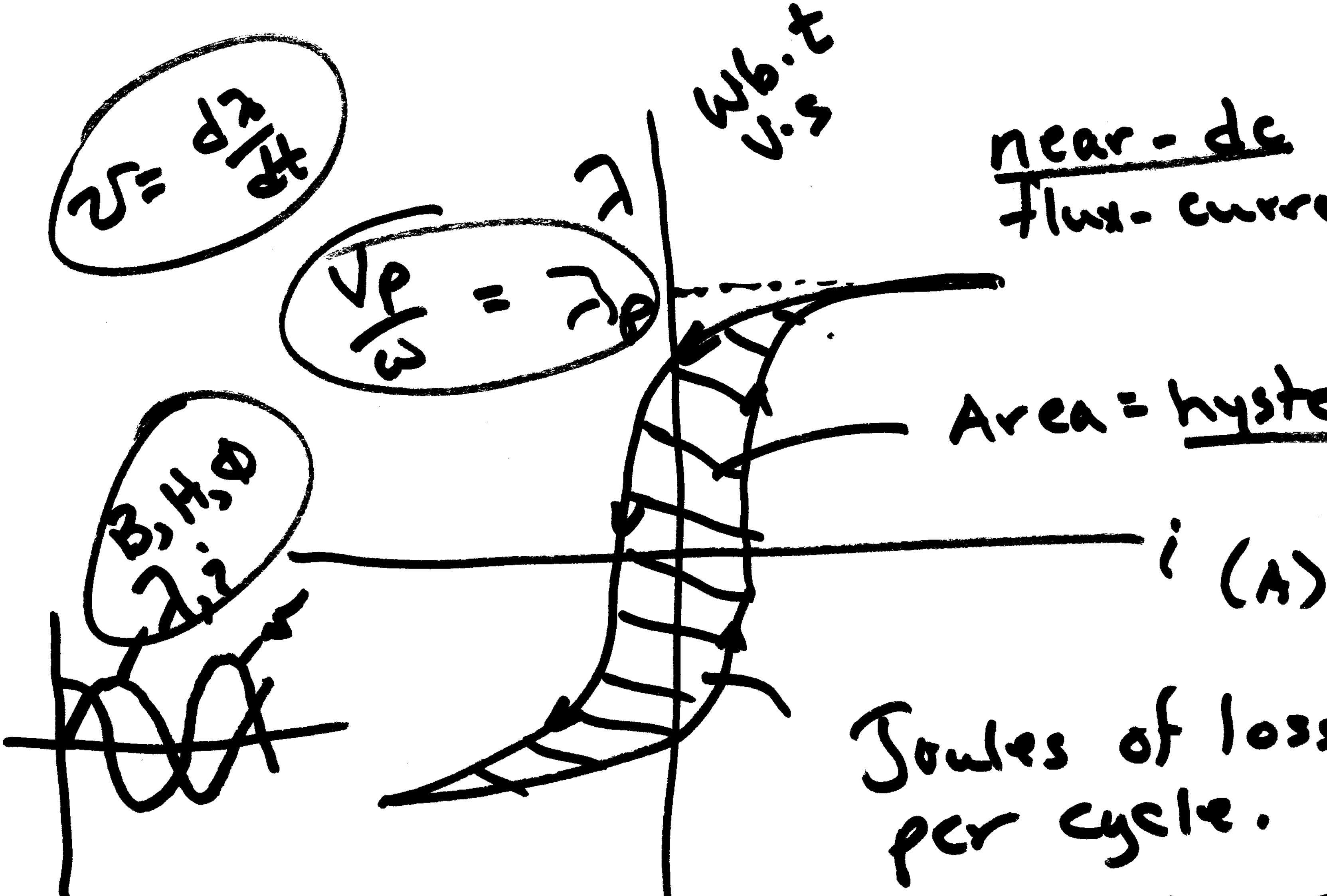
- $R_1, L_1 << R_c, L_M$
- R_1 is main source of damping for inrush.
- R_c no big effect.

The inrush current $i(t)$ depends on:

- switching time/angle
- Residual flux in L_M

$$v = \frac{d\lambda}{dt}$$

$$\frac{V_p}{\omega} = \lambda_p$$



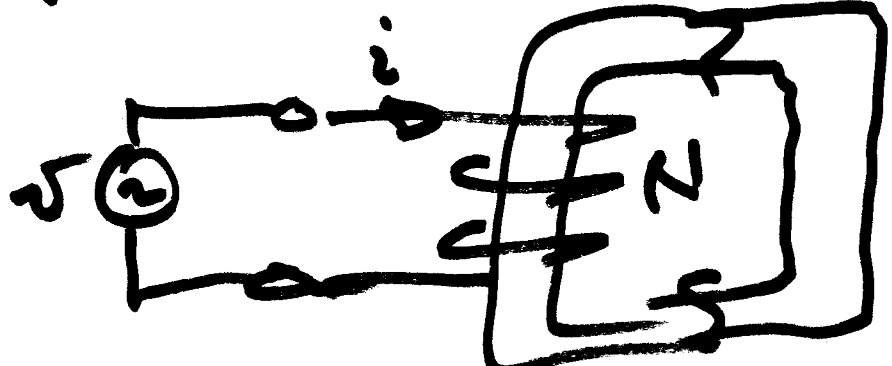
<u>near-dc</u>
flux-current loop.

Area = <u>hysteresis</u> losses

Joules of losses per cycle.

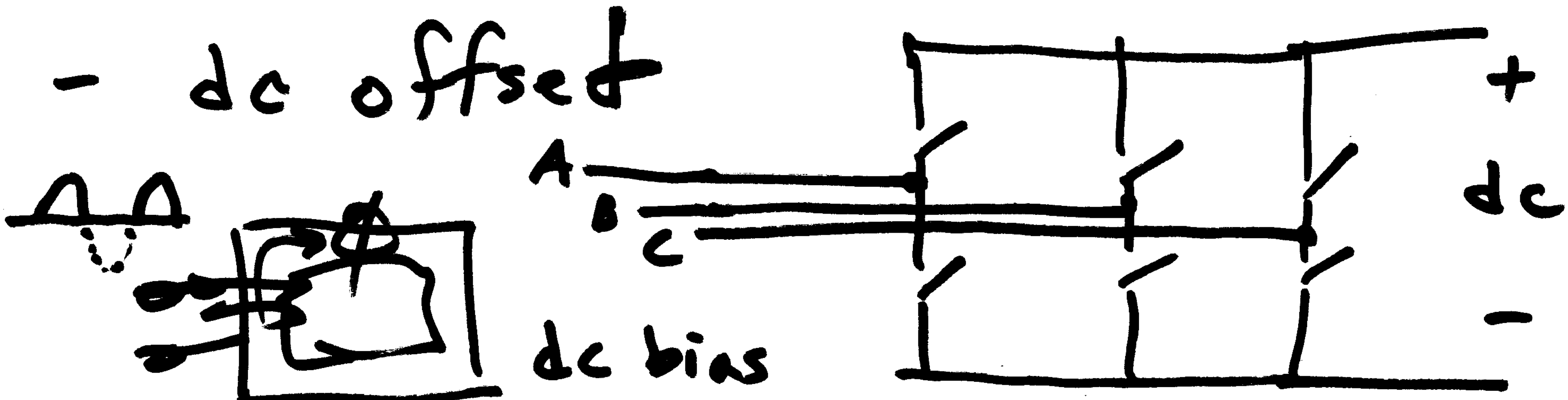
$\lambda =$ ~~[illegible]~~ $= \lambda_p \sin \underline{\omega} t$

$\Rightarrow v = \underline{\omega} \lambda_p \cos \omega t$



Transformer Behaviors

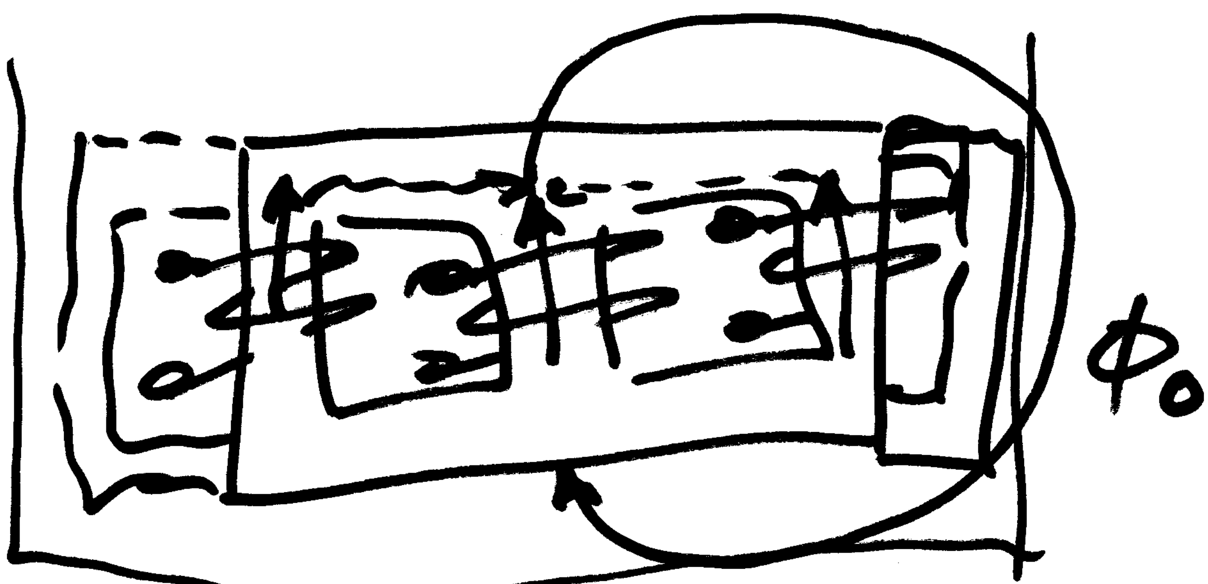
- S.S. Excitation (No-Load)
- Inrush
- Impulse / Lightning Surges — 500 kHz
- Switch Surges (Step response)
- Harmonics / harmonic deration
- dc offset

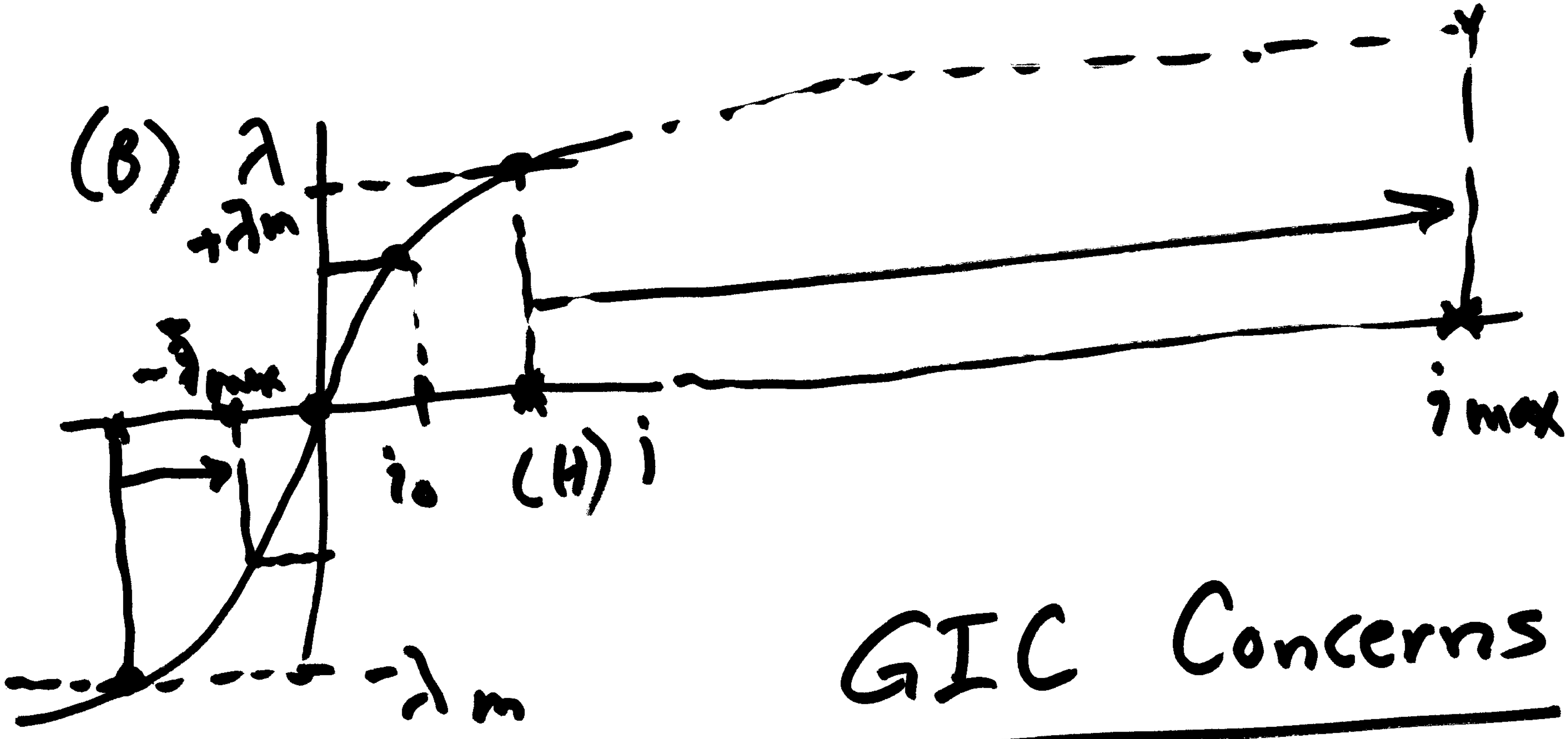


dc bias on my ckt.

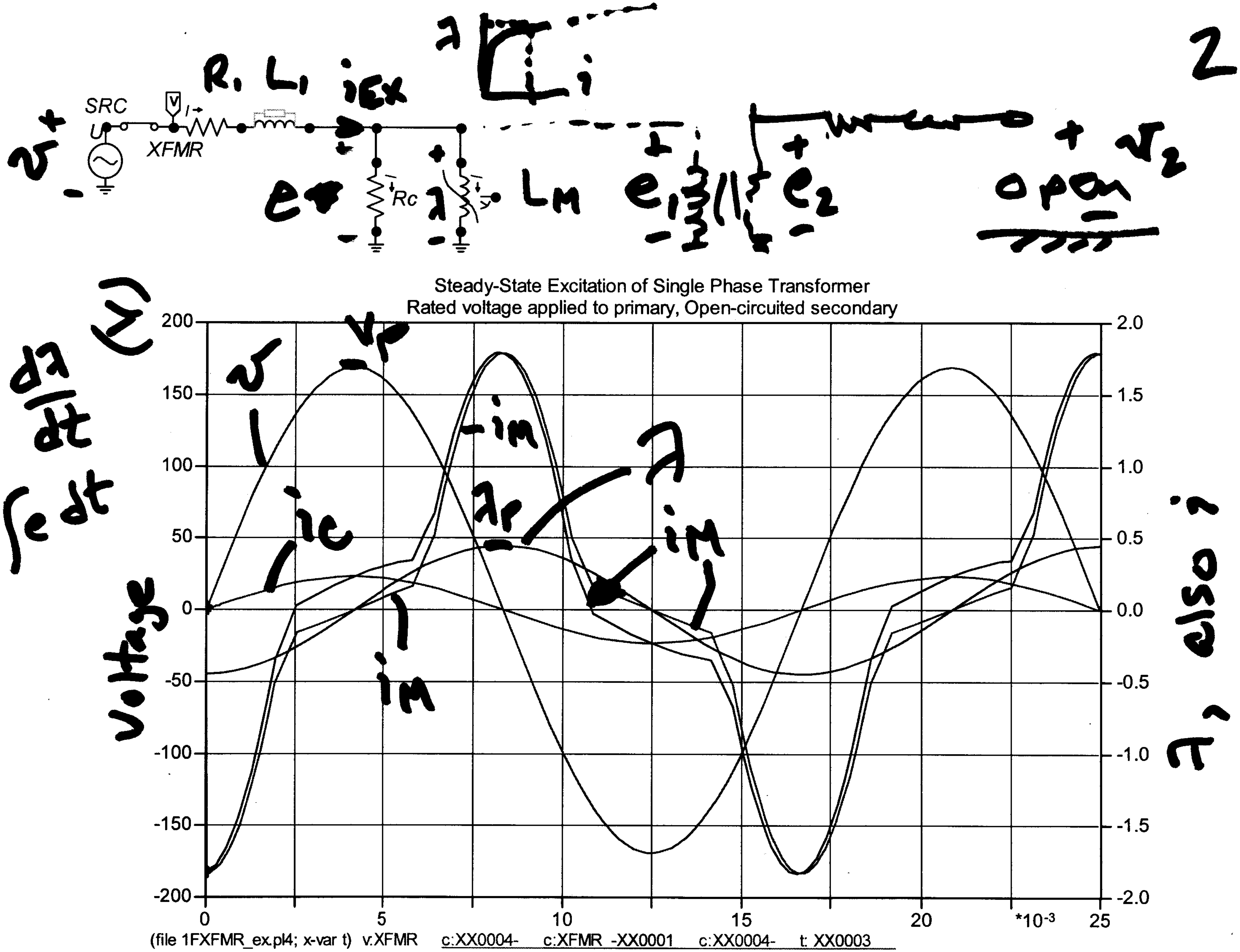
GIC - Geomagnetic Induced Currents
22-yr cycle

<u>0.01 Hz</u>





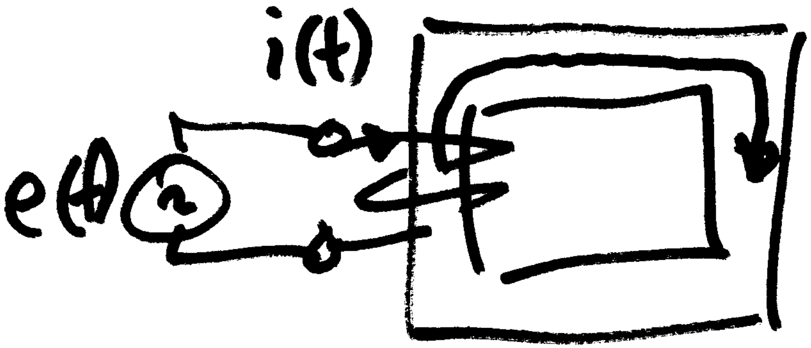
GIC Concerns



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

$\lambda = \int e\, dt$

$Ni = \Phi R$



$$\lambda(t) = \int_0^t e(t)\,dt + \lambda_0$$

In phase w/ $\lambda(t)$

$$\begin{cases} i_M \\ \Phi \\ B = \Phi/A \\ H = B/\mu \end{cases}$$

$$v(t) = V_p \sin(\underline{\underline{\omega}} t)$$

$$\lambda(t) = \int v(t)\, dt$$

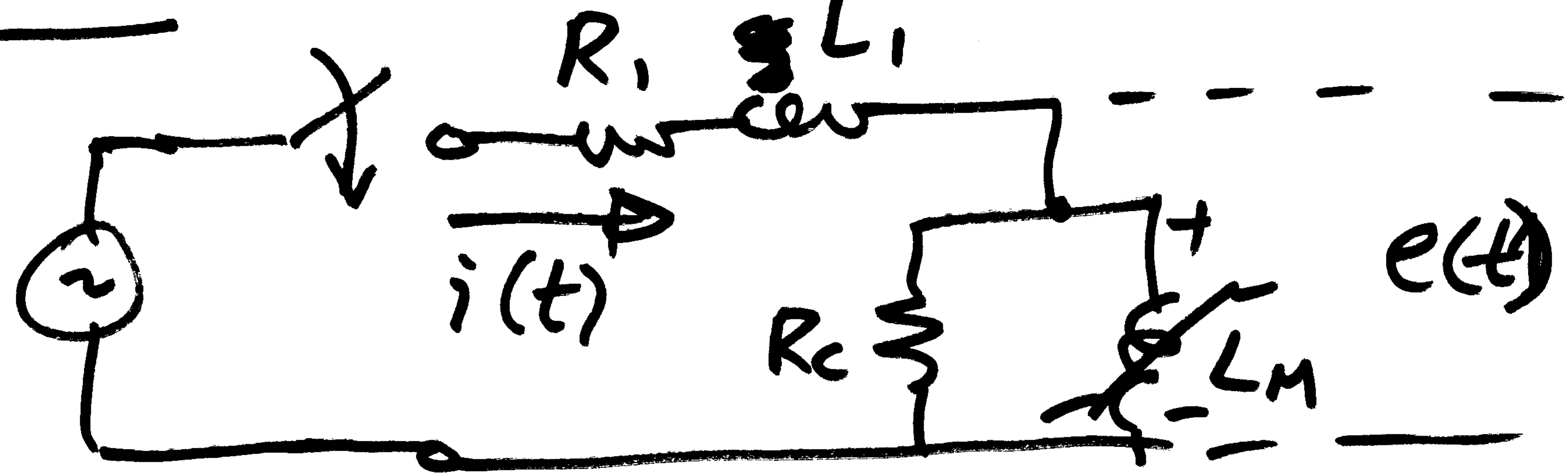
$$\lambda(t) = -\frac{V_p}{\omega} \cos(\underline{\underline{\omega}} t)$$

$$v(t) = \frac{d\lambda(t)}{dt} = V_p \sin(\omega t)$$

$$\therefore \; V_p = \omega \lambda_p \quad \text{or} \quad \lambda_p = \frac{V_p}{\omega}$$

$$\Rightarrow \frac{V_p}{\omega} = \frac{169\,V}{377\,s^{-1}} = \underline{\underline{0.45\,V\text{-}s}}$$

Inrush:



Important to note:

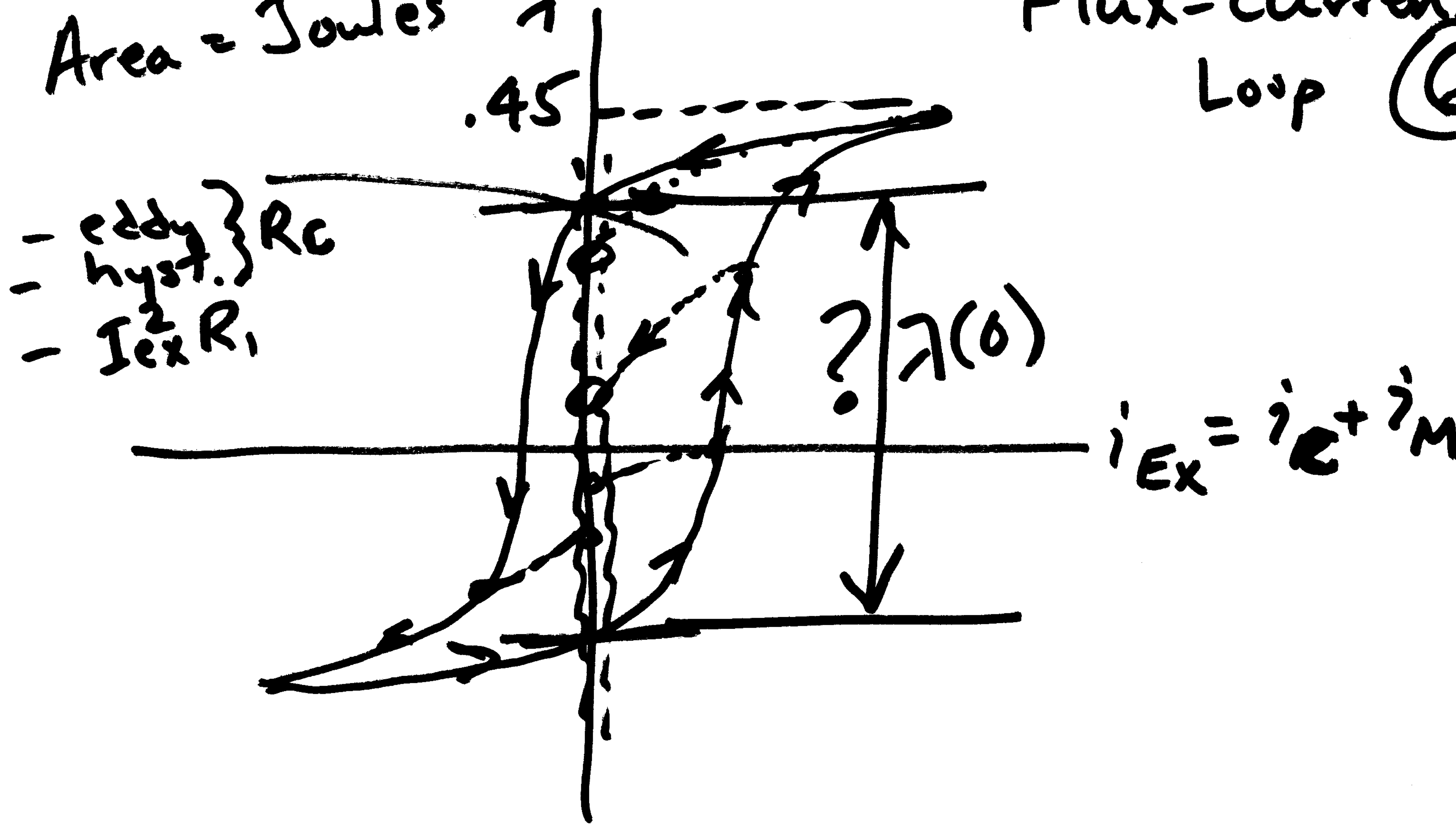
- $R_1, L_1 \ll R_c, L_M$
- R_1 is main source of damping for inrush.
- R_c no big effect.

The inrush current $i(t)$ depends on:

- switching time/angle
- Residual flux in L_M

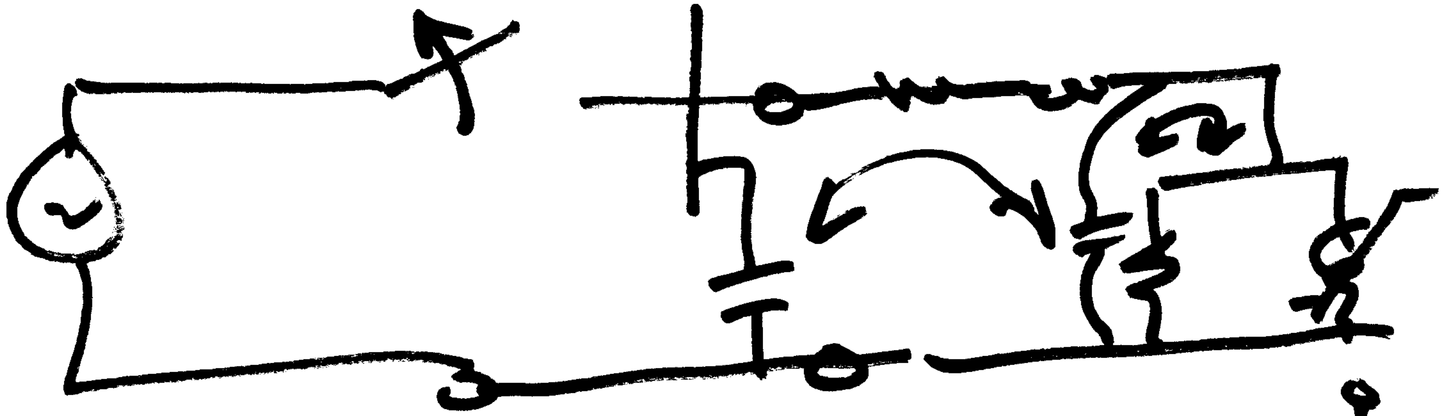
Flux-current Loop (6)

Area = Joules

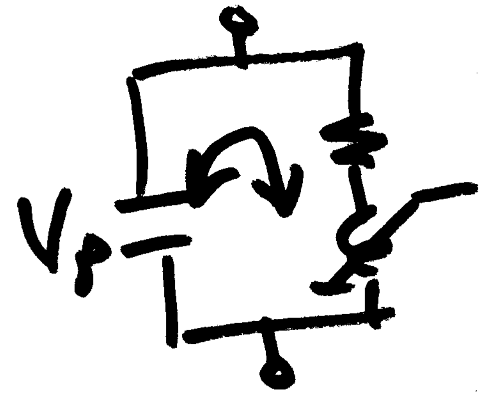


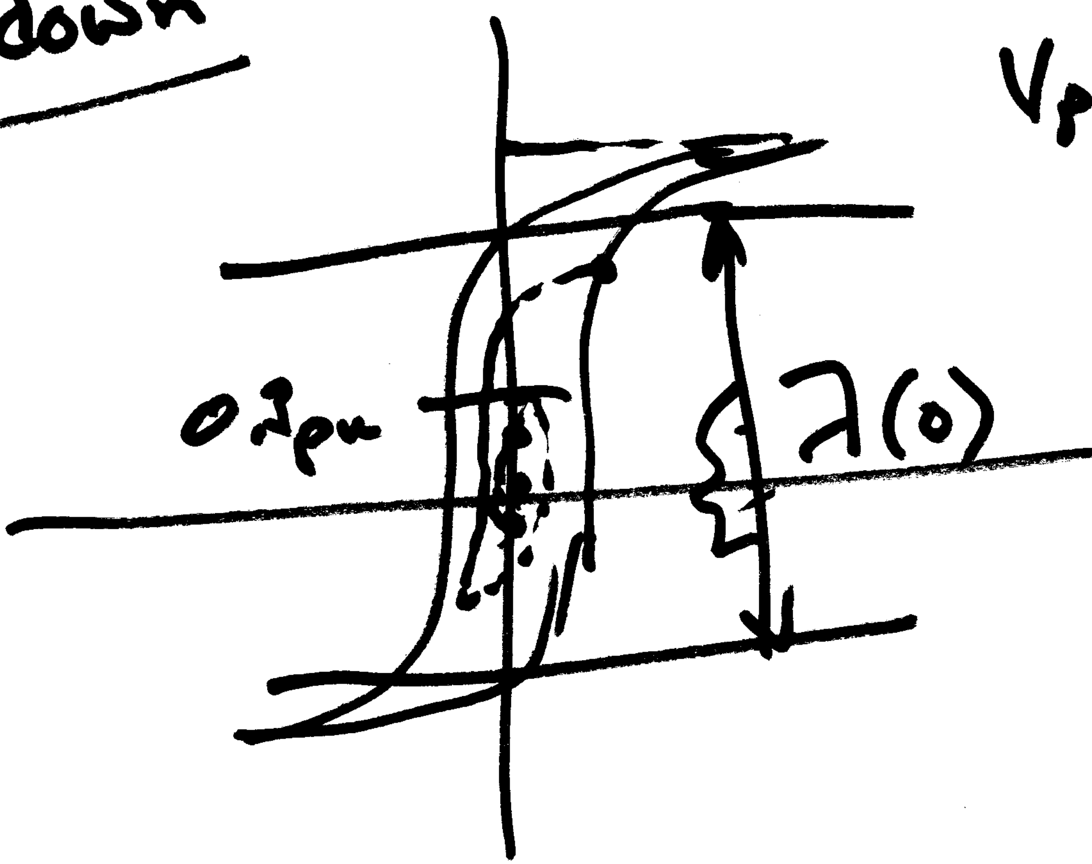
Residual flux in terms of λ.
λ_0 or λ(0)

⑦



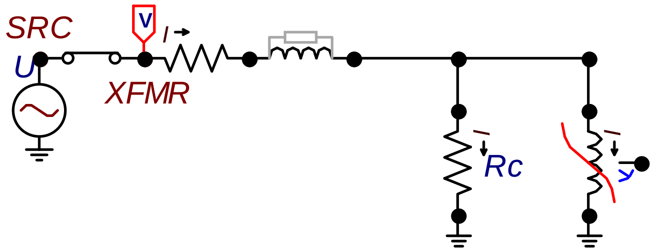
Ring-down

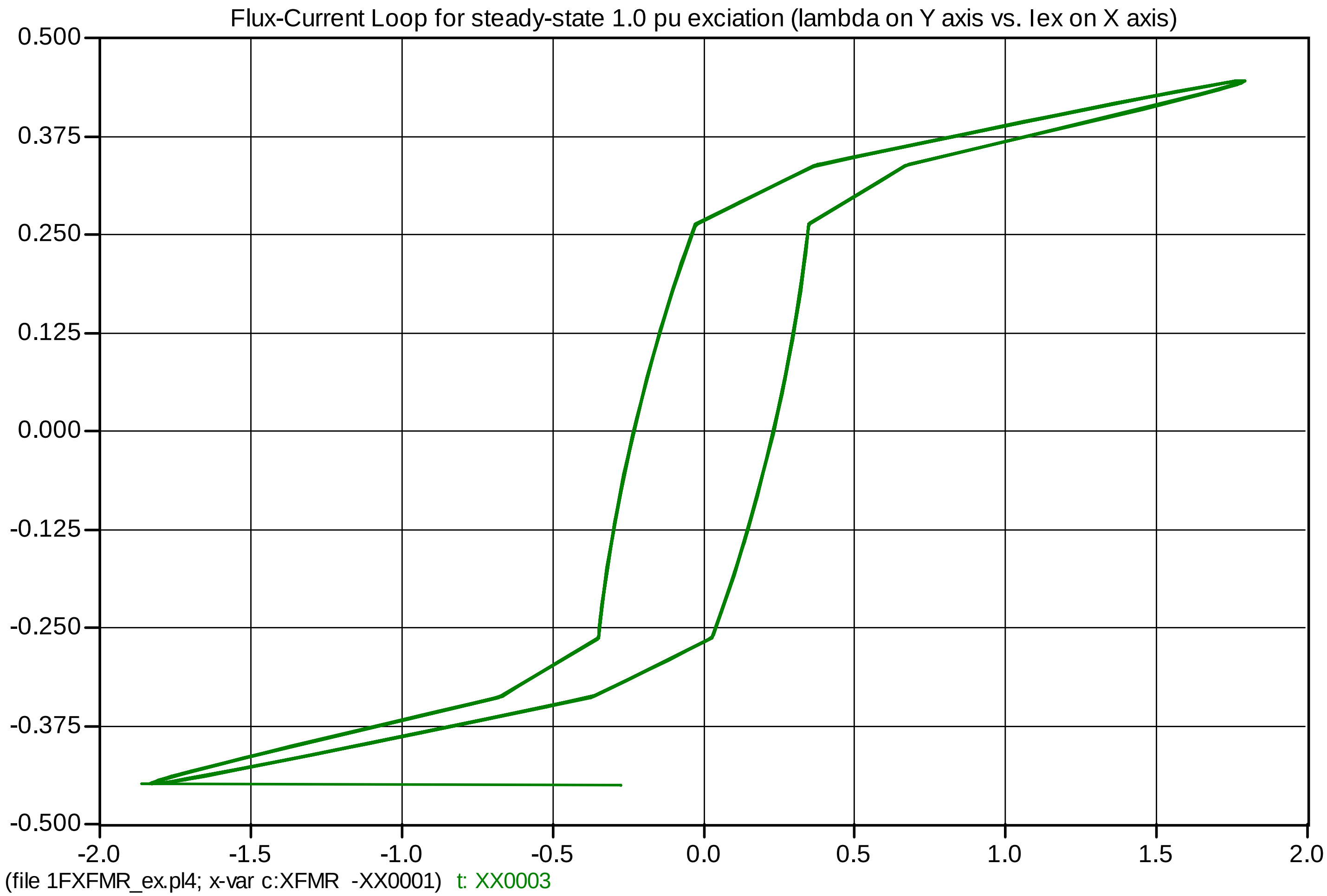


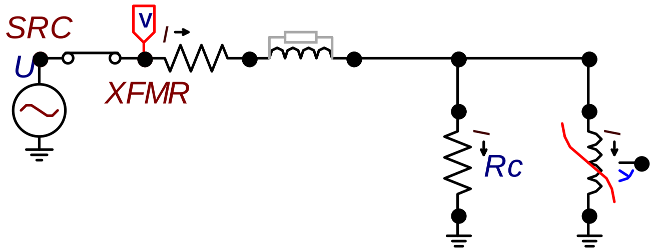


$$e(t) = \frac{d\lambda(t)}{dt} \quad \text{or} \quad \lambda(t) = \int_0^t e(t)\,dt + \underline{\underline{\lambda(0)}}$$

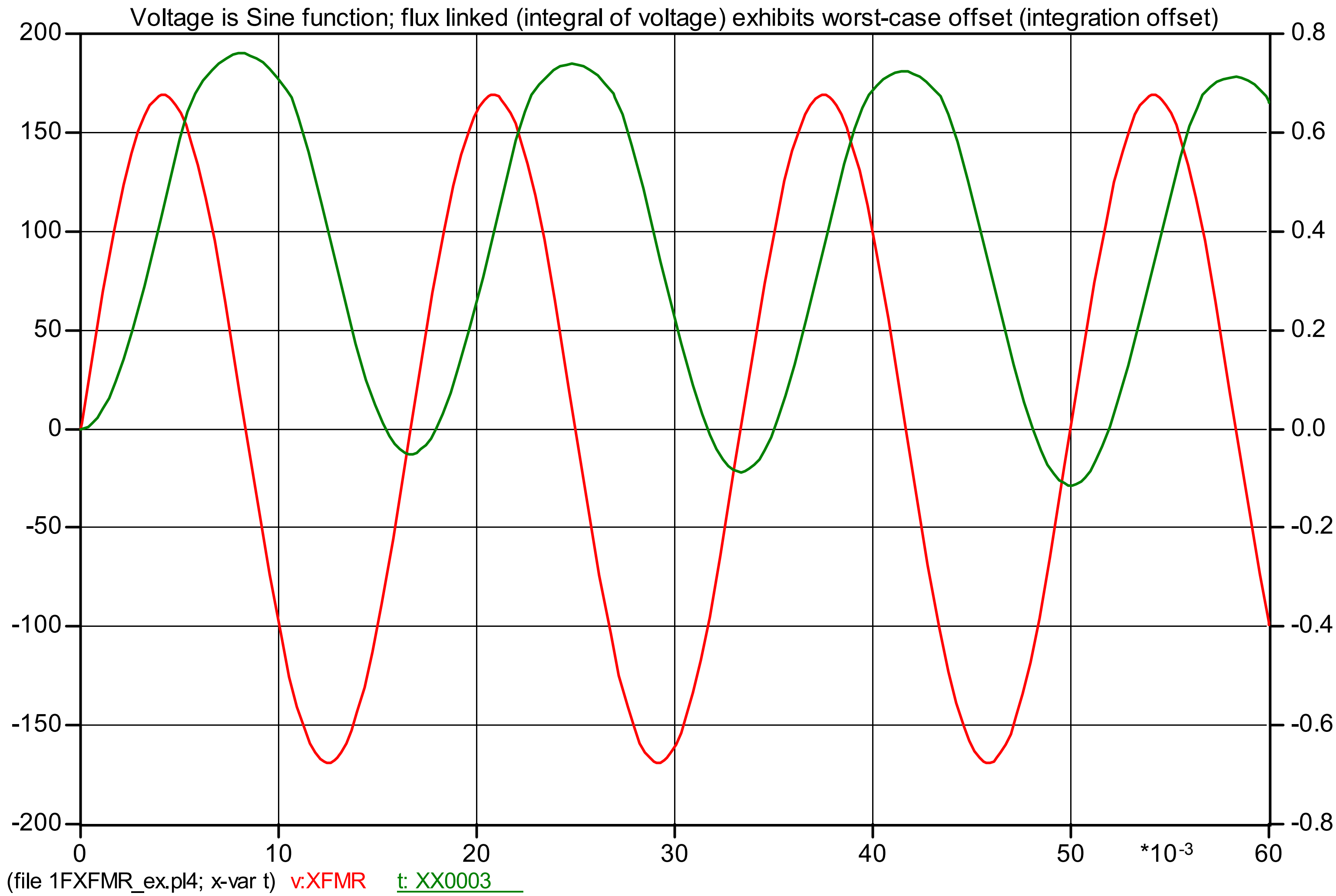
↑ inst. swith is closed!

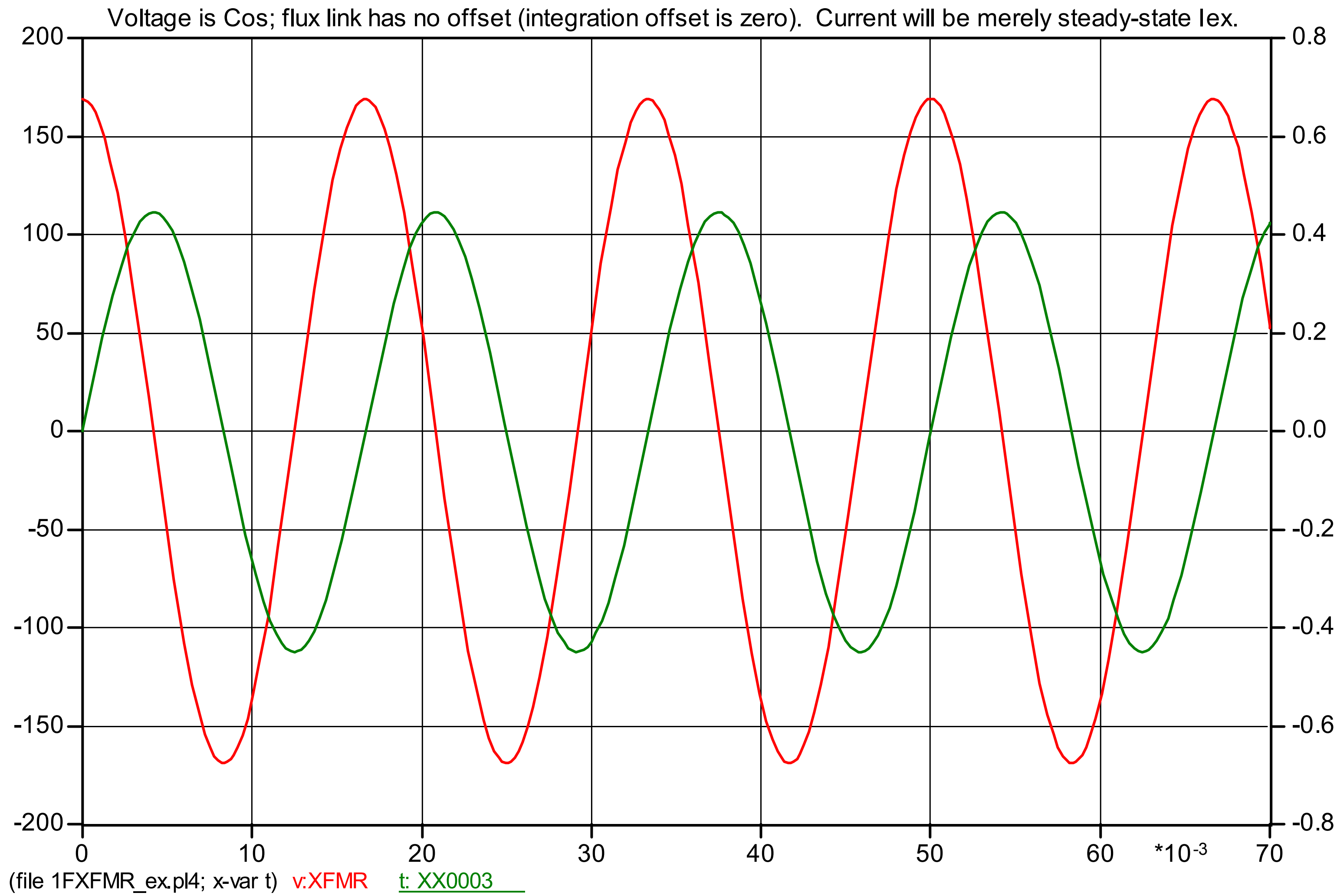

SRC
U
V
I
XFMR
Rc
I
I
V


Flux-Current Loop for steady-state 1.0 pu exciation (lambda on Y axis vs. Iex on X axis)
0.500
0.375
0.250
0.125
0.000
-0.125
-0.250
-0.375
-0.500
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
(file 1FXFMR_ex.pl4; x-var c:XFMR -XX0001) t: XX0003

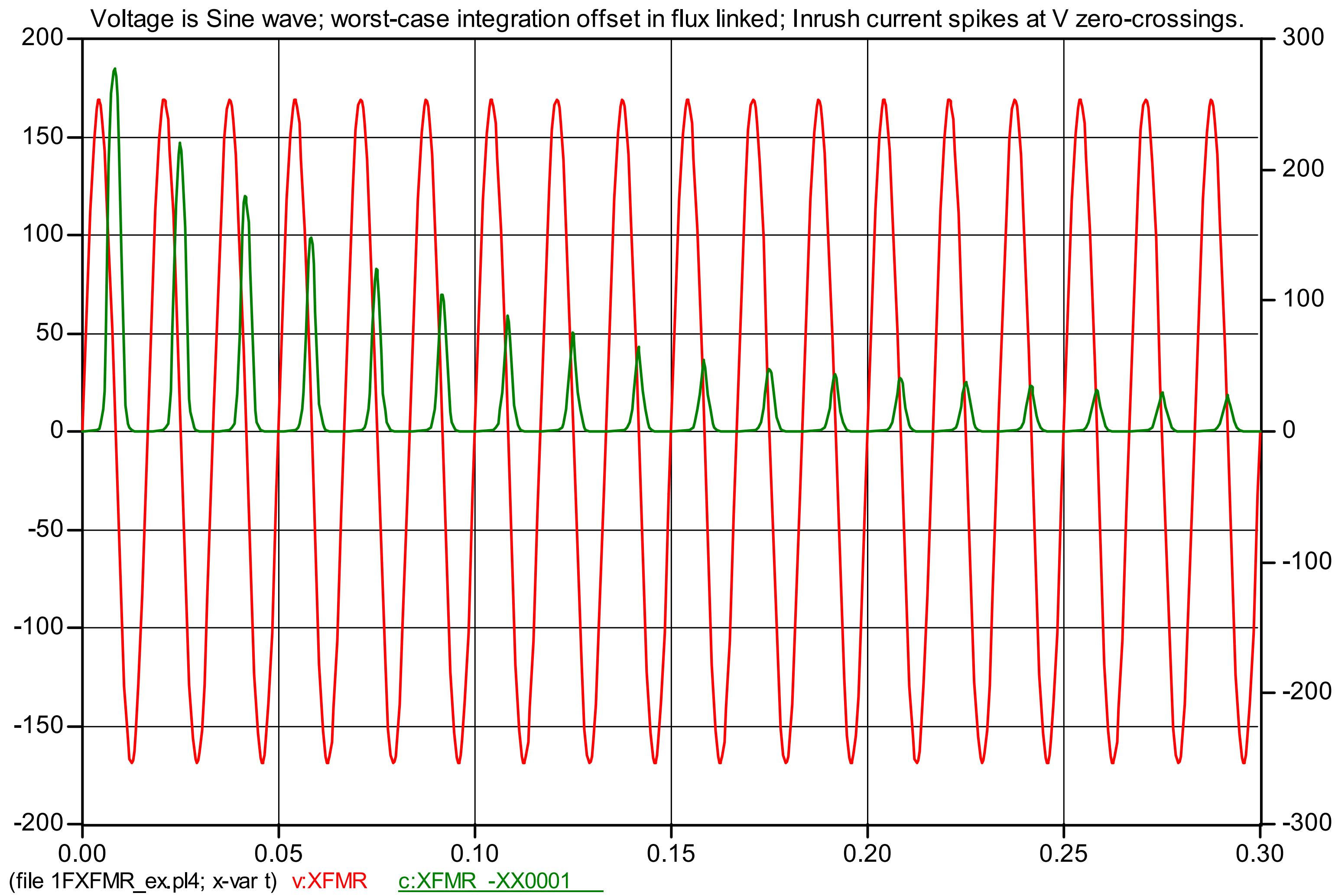


λ(0) = 0; voltage source (red) is Sine wave which turns on at t=0. Note worst-case integration offset in flux linked (green).





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 inductancem 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).