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# Flux density waveform control based on Newton-Raphson method

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## 1. CONTEXT

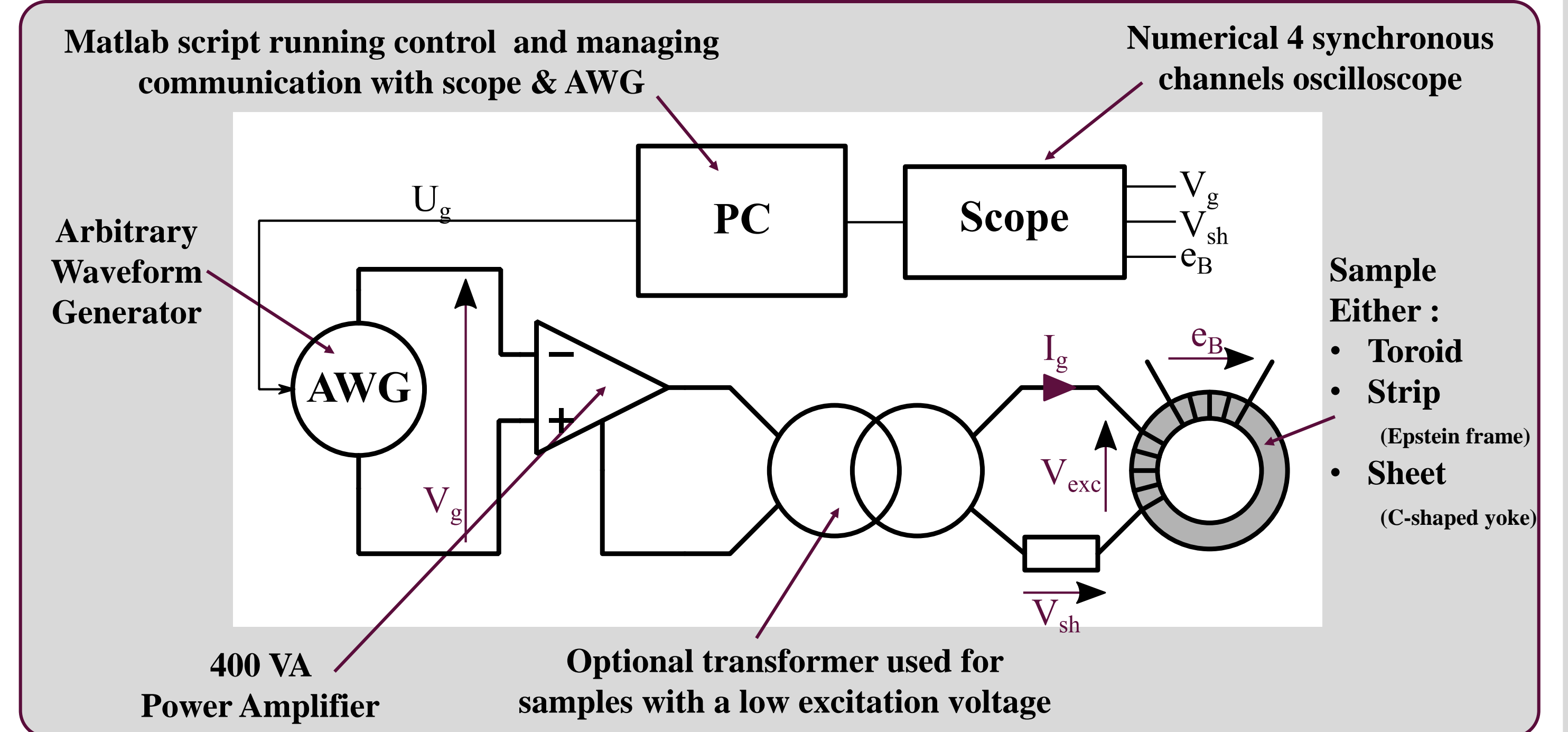
- ✓ Well-known need for flux density waveform control in magnetic measurements
  - Sinusoidal B for comparable and repeatable test conditions
  - Application specific conditions (PWM voltages, etc.)
- ✓ Diversity of flux control methods
  - Analog/Numeric, Iterative/Real-Time, etc.
  - Various control theory : proportional compensation, neural network, etc.

## 2. PROPOSED WORK

- ✓ Application of both Newton's method and Broyden's method to flux control
- ✓ Comparison between
  - Both proposed controllers
  - Several objective functions
  - The proposed methods and a classical form of control
- ✓ Benefit : High adaptability
  - Only the starting voltage has to be set between setup

## 3. EXPERIMENTAL SETUP

- ✓ Classical closed-loop setup for magnetic measurement



- ✓ Convergence conditions (for sinusoidal B) : (< 1 % error on magnitude) & (< 1 % THD)

## 4. CONTROLLERS

- ✓ Root-finding algorithm : nullify an objective function  $F$
- ✓ Newton or quasi-Newton method : input update by inverting the Jacobian  $J_F$  of  $F$ 

$$V_g^{(i+1)} = V_g^{(i)} + (J_F^{(i)})^{-1} \times F(V_g^{(i)})$$
- ✓ Instabilities damping
 
$$V_g^{(i+1)} = V_g^{(i)} + 0.5 \cdot (J_F^{(i)})^{-1} \times F(V_g^{(i)})$$

### Newton-Raphson's method (NR) Exact computation of the Jacobian

#### Application to flux control.

Hypothesis : Due to the periodicity of the system, we assume the following circular behaviour.

$$\begin{aligned} \Delta B_1 &= j_1 \Delta V_1 + j_2 \Delta V_2 + \dots + j_n \Delta V_n \\ \Delta B_2 &= j_1 \Delta V_2 + j_2 \Delta V_3 + \dots + j_n \Delta V_1 \\ &\dots \end{aligned}$$

$$\Delta B_n = j_1 \Delta V_n + j_2 \Delta V_1 + \dots + j_n \Delta V_{n-1}$$

→ Reduce the system dimension

### « Bad » Broyden's method (BB)

Make an initial guess for the Jacobian inverse and improve it iteratively (alongside the excitation  $V_g$ )

$$(J_F^{(i+1)})^{-1} = (J_F^{(i)})^{-1} + (s_i - (J_F^{(i)})^{-1} y_i) \frac{s_i^T (J_F^{(i)})^{-1}}{s_i^T (J_F^{(i)})^{-1} s_i}$$

#### Application to flux control.

Choice of the initial Jacobian inverse :

$$(J_0)^{-1} = \frac{1}{|V_0|} I_n$$

- ✓ Proposed objective functions

$$F_B(V_g) = \frac{(B - B_{ref})}{|B_{ref}|}$$

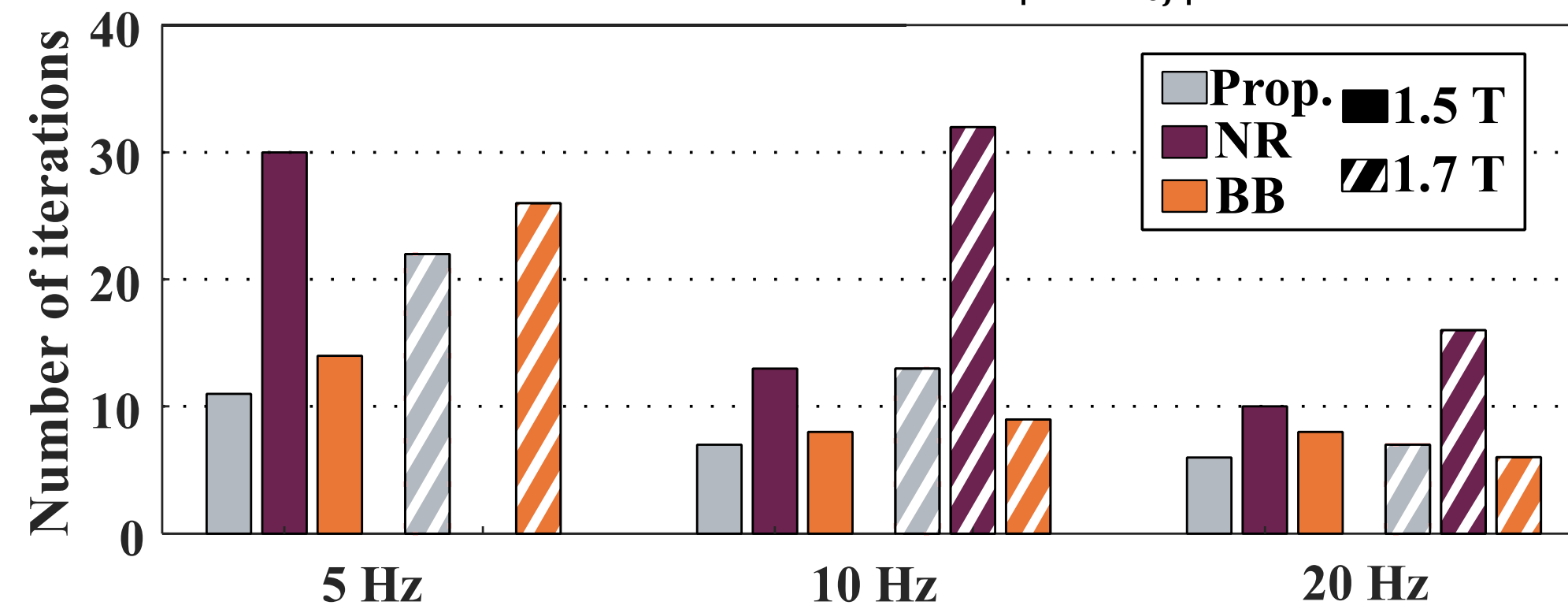
$$F_{dB}(V_g) = \frac{\left(\frac{dB}{dt}\right)_{ref} - \left(\frac{dB}{dt}\right)}{\left|\left(\frac{dB}{dt}\right)_{ref}\right|}$$

$$F_{Dual}(V_g) = \begin{bmatrix} \frac{(B - B_{ref})}{|B_{ref}|} \\ \left(\frac{dB}{dt}\right)_{ref} - \left(\frac{dB}{dt}\right) \\ \left|\left(\frac{dB}{dt}\right)_{ref}\right| \end{bmatrix}$$

## 5. OPERATION VALIDATION

- ✓ Control achieved with both controllers in a variety of test conditions
  - BB : Reach moderate saturation level on the [5 – 100] Hz band
    - Below : Control unstable ; Above : System limited
  - NR : Slightly lower induction level and narrower band ([10 – 100] Hz)
    - Erratic for 5 Hz
- ✓ Comparison to a simple digital controller for speed reference
  - With empiric best  $(\alpha, \beta)$ 

$$V^{(i+1)} = V^{(i)} + \alpha \frac{(B - B_{ref})}{|B_{ref}|} + \beta \frac{\left(\frac{dB}{dt}\right) - \left(\frac{dB}{dt}\right)_{ref}}{\left|\left(\frac{dB}{dt}\right)_{ref}\right|}$$



- BB shows a similar speed to the simple proportional controller with a lower setting time, NR is slower

## 6. OBJECTIVE FUNCTION

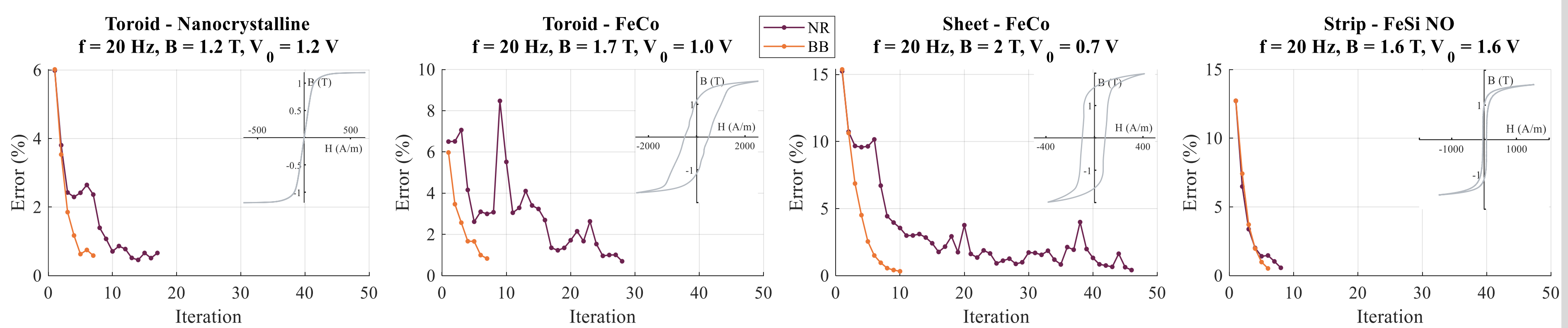
- ✓ Using BB controller, comparison between all three objective functions :  $F_B$ ,  $F_{dB}$  and  $F_{Dual}$

f (Hz)	$V_0$ (V)	Number of iterations		
		$F_B$	$F_{dB}$	$F_{Dual}$
5	0.6	31	$\infty$	28
10	0.8	24	$\infty$	12
20	0.5	$\infty$	20	10
	1	24	$\infty$	7
50	1	$\infty$	9	9
	1.4	20	$\infty$	8
100	2.6	14	8	7
200	4	$\infty$	6	7

- ✓ Results are coherent with physical interpretations :
  - $F_{Dual}$  is steadier against frequency and initial excitation  $V_0$
  - Balancing between inductive and resistive terms
  - $F_B$  works better for low frequency and high  $V_0$
  - $F_{dB}$  performs well with high frequency (inductive cases), and needs lower starting voltage

## 7. COMPARISON OF CONTROLLERS

- ✓ Application of both methods to several identical cases
- ✓ BB's method presents a smoother and steadier convergence than NR
- ✓ NR's method has a very low repeatability (not shown, up to 2x)



## 8. CONCLUSIONS

- ✓ Successful adaptation of Newton's and quasi-Newton methods
  - For  $f \in [10; 100]$  Hz and  $\hat{B}$  up to mild saturation
  - Link between convergence performances and Jacobian conditioning to be investigated
- ✓ Appropriate for laboratory measurement :
  - Sample/setup change is fast and simple
  - No parameters : only the magnitude of the initial voltage  $V_0$  has to be set
    - And, eventually, the starting waveform (sine in most cases)

## REFERENCES

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