Circuit modelling of Transformer-Rectifier Flux Pumps

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Modelling

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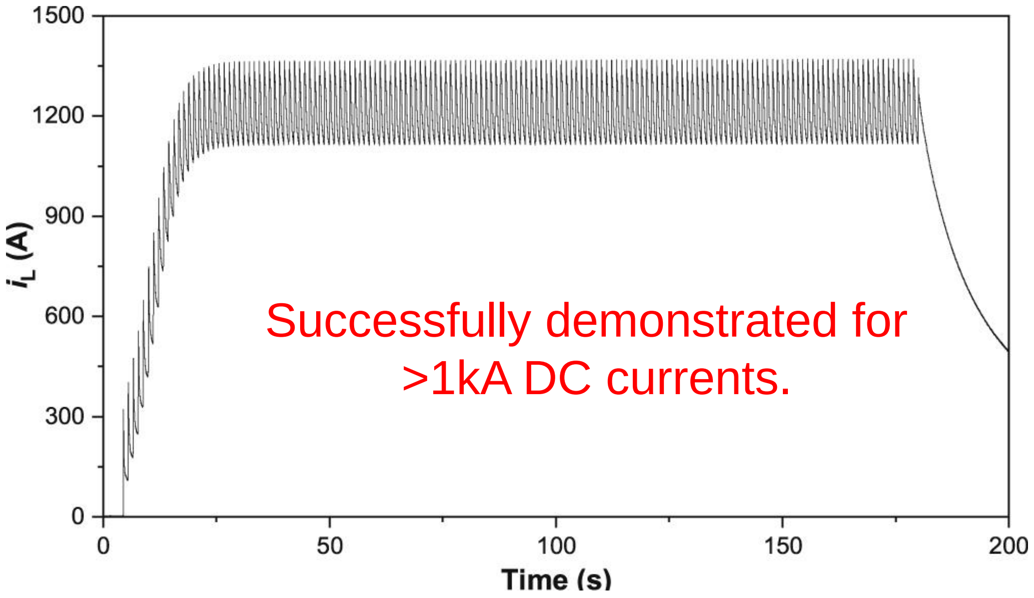
Outline

- What is a flux pump?
- How does a Transformer-Rectifier FP work?
- Model – How is it build?
  - Developing varying resistance models
  - Incorporating $I_c(B)$ and $n(B)$ values into the resistance models
- Model verification with experimental results
- Summary

What is Flux Pump?

A flux pump essentially works as a stable high current source for powering the superconducting magnets.

- Very compact
- Light weight
- Works in cryogenic temperature
  - No need for room temperature to cryogenic temperature high current leads
- High efficiency



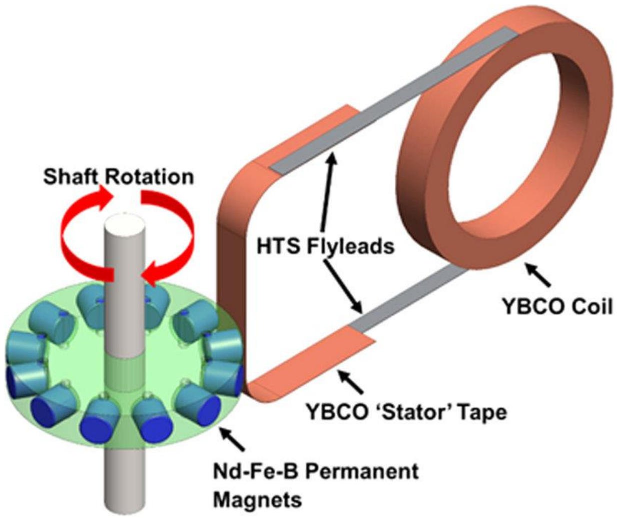
Successfully demonstrated for >1kA DC currents.

Jianzhao Geng *et al* 2020 *Supercond. Sci. Technol.* **33** 045005

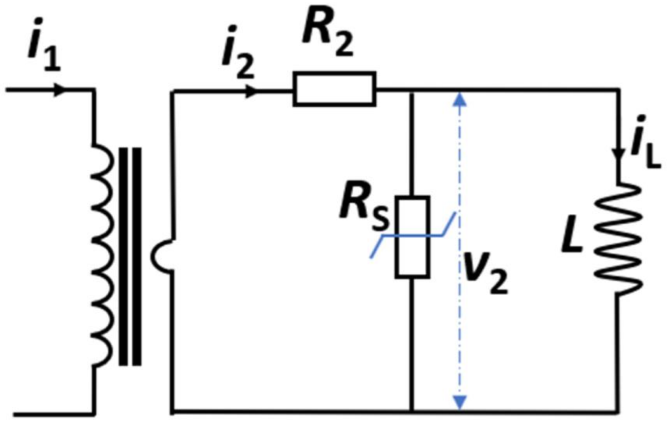
Flux Pump types

Flux pumps are currently being categorized into 2 types:

- Dynamo flux pumps
- Transformer Rectifier flux pumps



Chris W Bumby *et al* 2016 *Supercond. Sci. Technol.* **29** 024008



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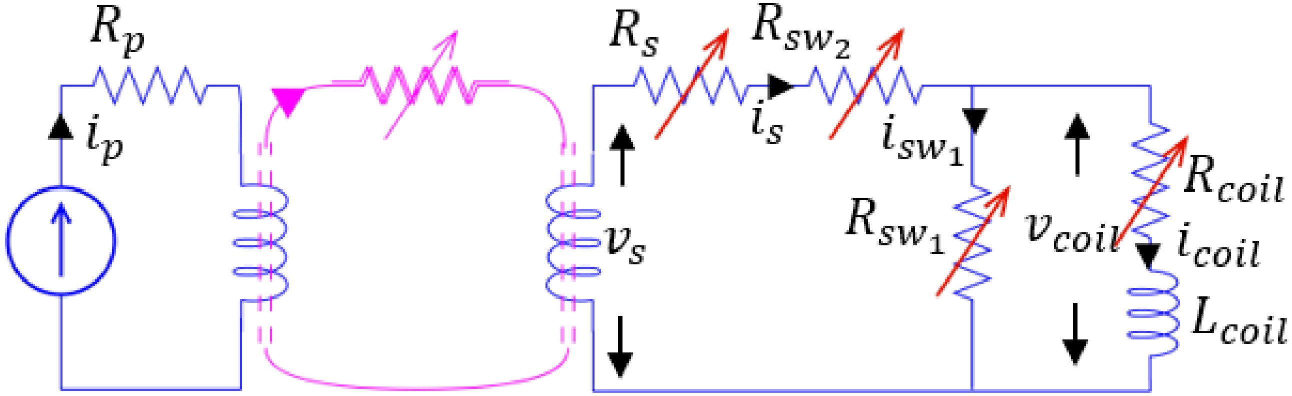
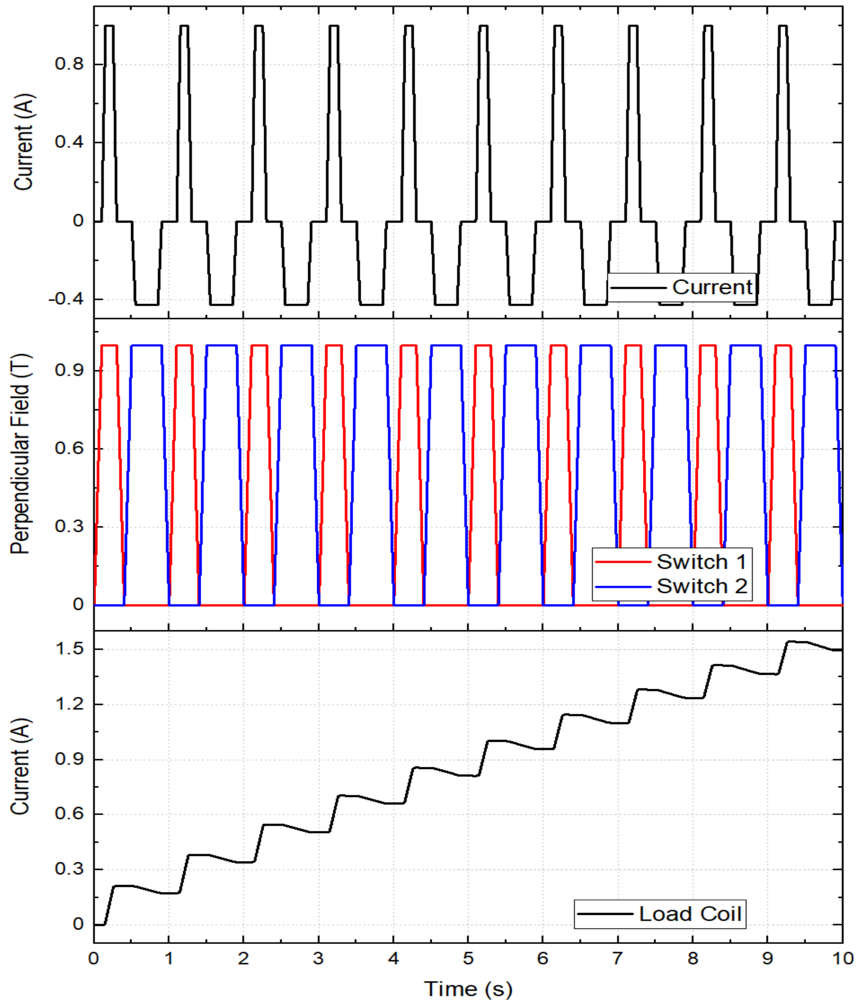
Transformer Rectifier FP

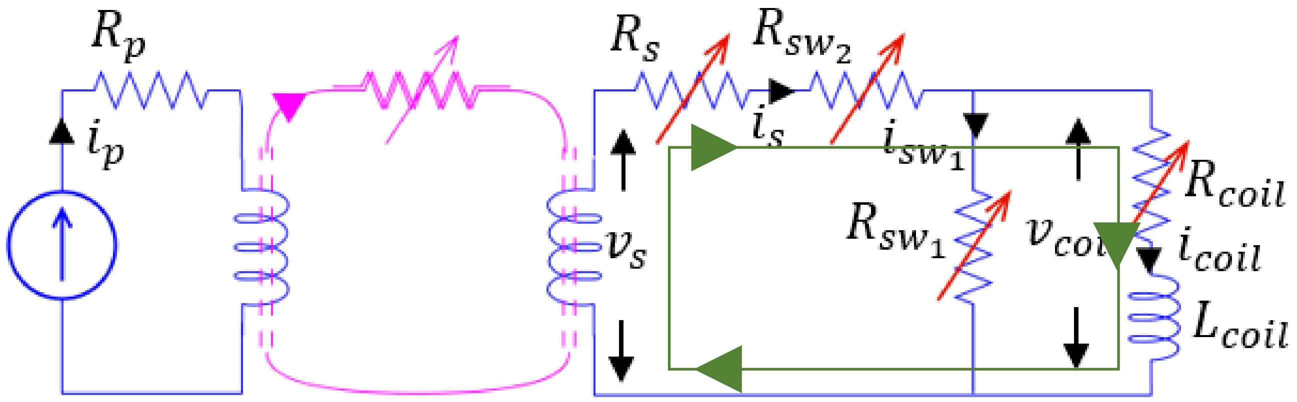
Parameter	Description
R_p	Constant Resistance of the Copper winding
R_s	Varying HTS secondary resistance as a function of current
R_{sw1}, R_{sw2}	Varying resistance of the switches as a function of both current and field.
R_{coil}	Varying resistance of the HTS load coil as a function of the current



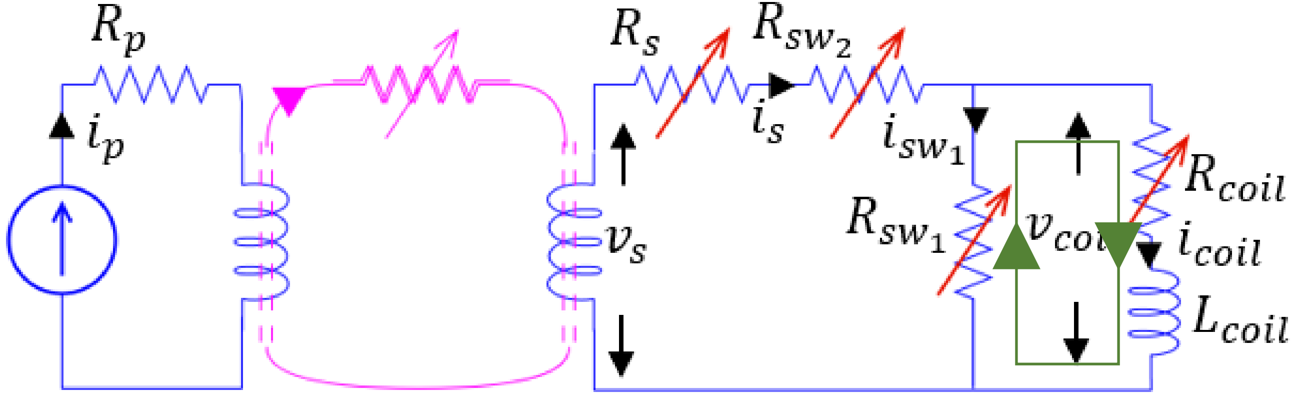
Transformer Rectifier FP



Charging path



Discharging path



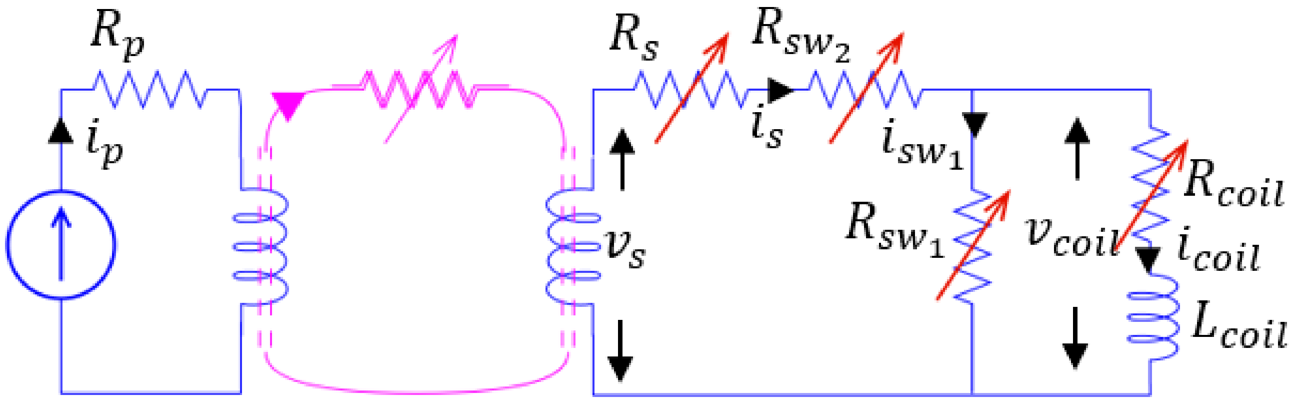
Circuit Model

Key components:

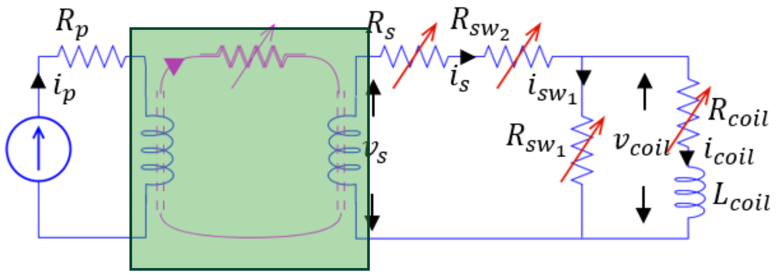
- Transformer model
  - Electro-magnetic model
- Varying resistance model
  - R(I)
  - R(B,I)

Key assumptions:

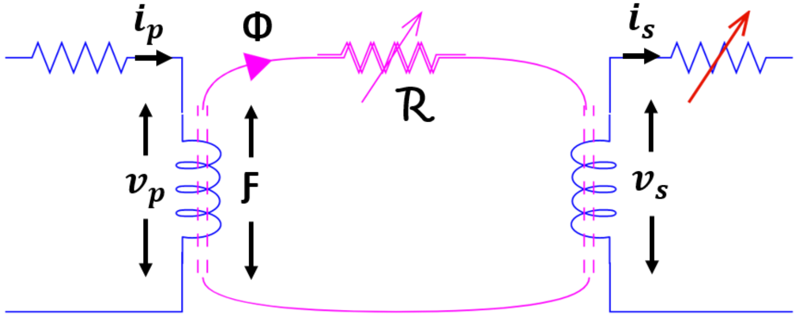
- Isothermal (LN$_2$ temperature)
- AC loss not included



Circuit Model (Transformer Model)



Non-linear Electro-magnetic model

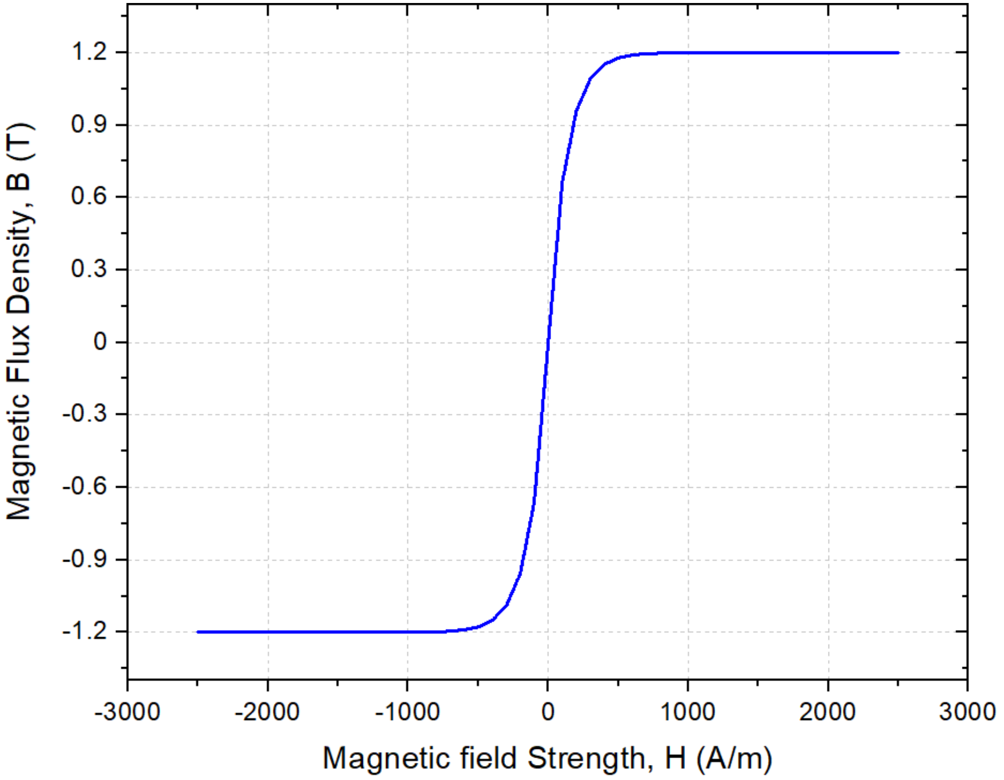


$$V_p = -N_p \frac{d\varphi}{dt} \qquad V_s = -N_s \frac{d\varphi}{dt}$$

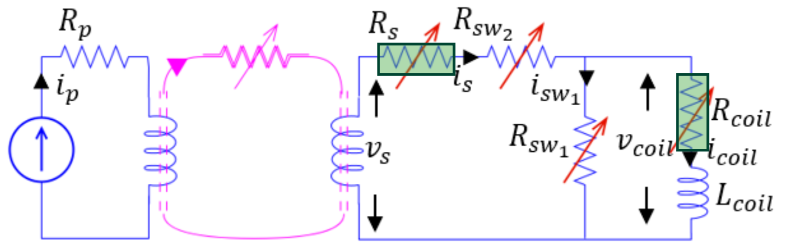
$$\mathrm{F}_p = N_p I_p \qquad \mathrm{F}_s = N_s I_s$$

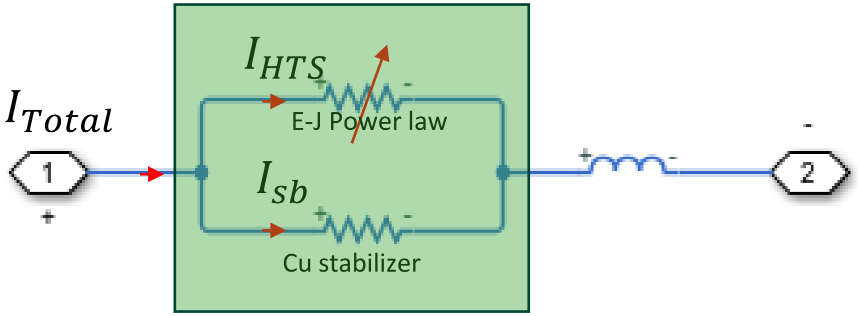
$$\mathrm{F}_{\mathcal{R}} = \varphi \times \mathcal{R}(B - H)$$

$$\mathrm{F}_p = \mathrm{F}_{\mathcal{R}} + \mathrm{F}_s$$



Circuit Model (Varying resistance)

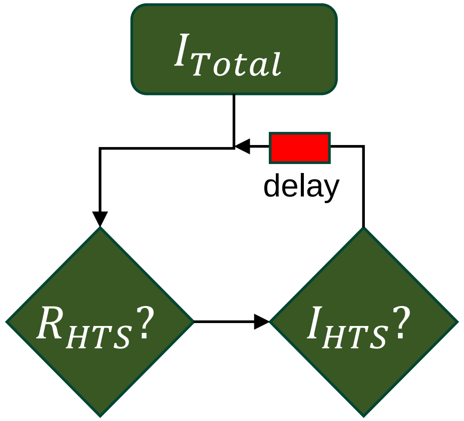




$$R_{sc} = \frac{E_o}{I_c}\left(\frac{I_{HTS}}{I_c}\right)^{n-1} \times l_{tape}$$

$$R_{sb} = \frac{\rho_{sb}}{w \times t_{sb}} \times l_{tape}$$

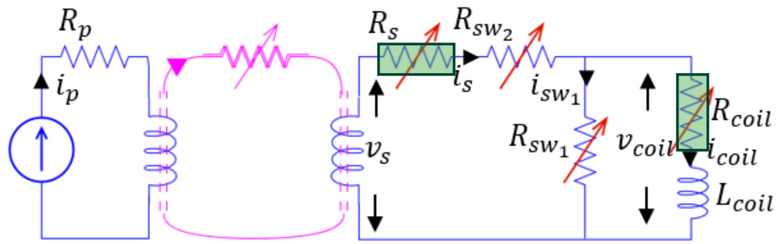
$$\frac{1}{R_{tape}} = \frac{1}{R_{sc}} + \frac{1}{R_{sb}}$$

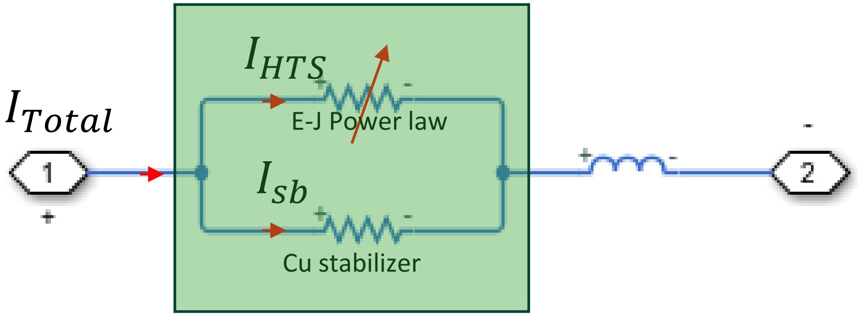


We can break this circular problem by adding a delay!

- Time step needs to be small
- Slows down simulation
- Transient modelling results depends on the time step.

Circuit Model (Varying resistance)

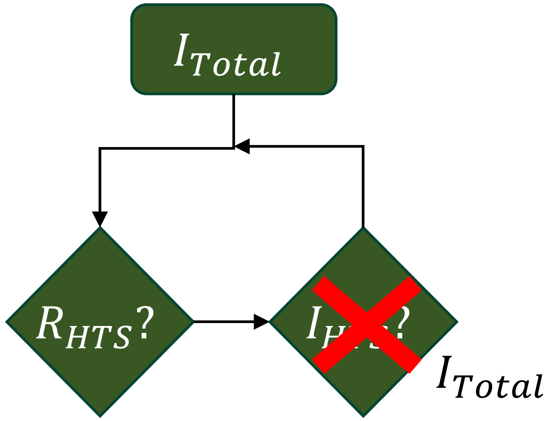




$$R_{sc} = \frac{E_o}{I_c}\left(\frac{I_{HTS}}{I_c}\right)^{n-1} \times l_{tape}$$

$$R_{sb} = \frac{\rho_{sb}}{w \times t_{sb}} \times l_{tape}$$

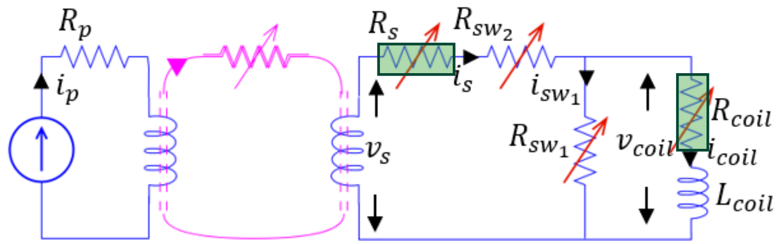
$$\frac{1}{R_{tape}} = \frac{1}{R_{sc}} + \frac{1}{R_{sb}}$$

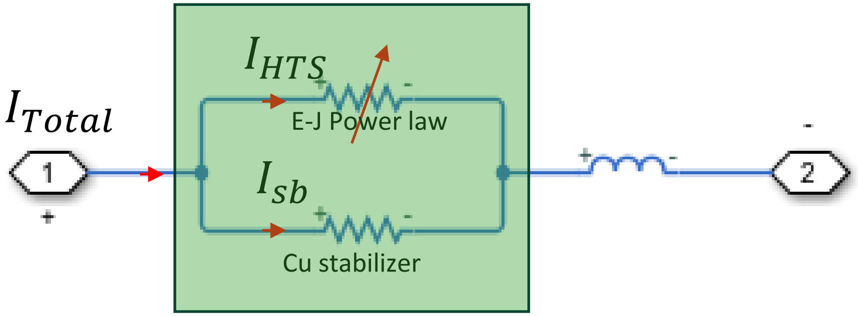


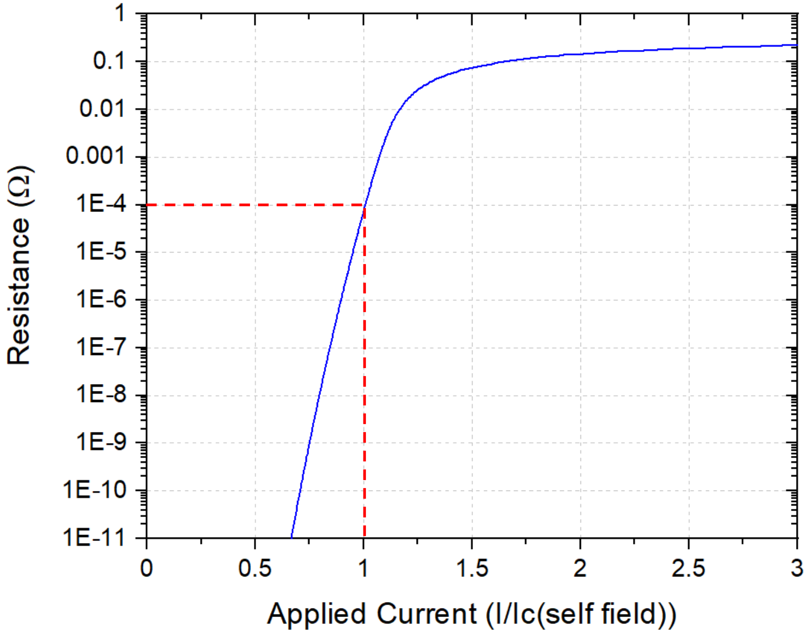
We can also break this circular problem by using the total current!

- Time step doesn't need to be small
- Quick simulation
- Not accurate!

Circuit Model (Varying resistance)







Assume, I_{HTS}

Evaluate, R_{HTS}

$$R_{sc} = \frac{E_o}{I_c}\left(\frac{I_{HTS}}{I_c}\right)^{n-1} \times l_{tape}$$

Evaluate, V_{HTS}

$$I_{HTS} \times R_{HTS}$$

$$R_{sb} = \frac{\rho_{sb}}{w \times t_{sb}} \times l_{tape}$$

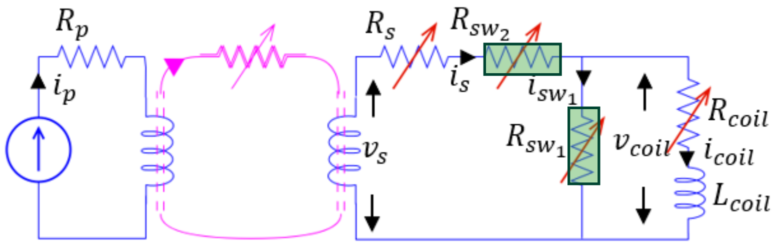
$$I_{sb} = \frac{V_{HTS}}{R_{sb}}$$

$$I_{Total} = I_{HTS} + I_{sb}$$

$$\frac{1}{R_{tape}} = \frac{1}{R_{sc}} + \frac{1}{R_{sb}}$$

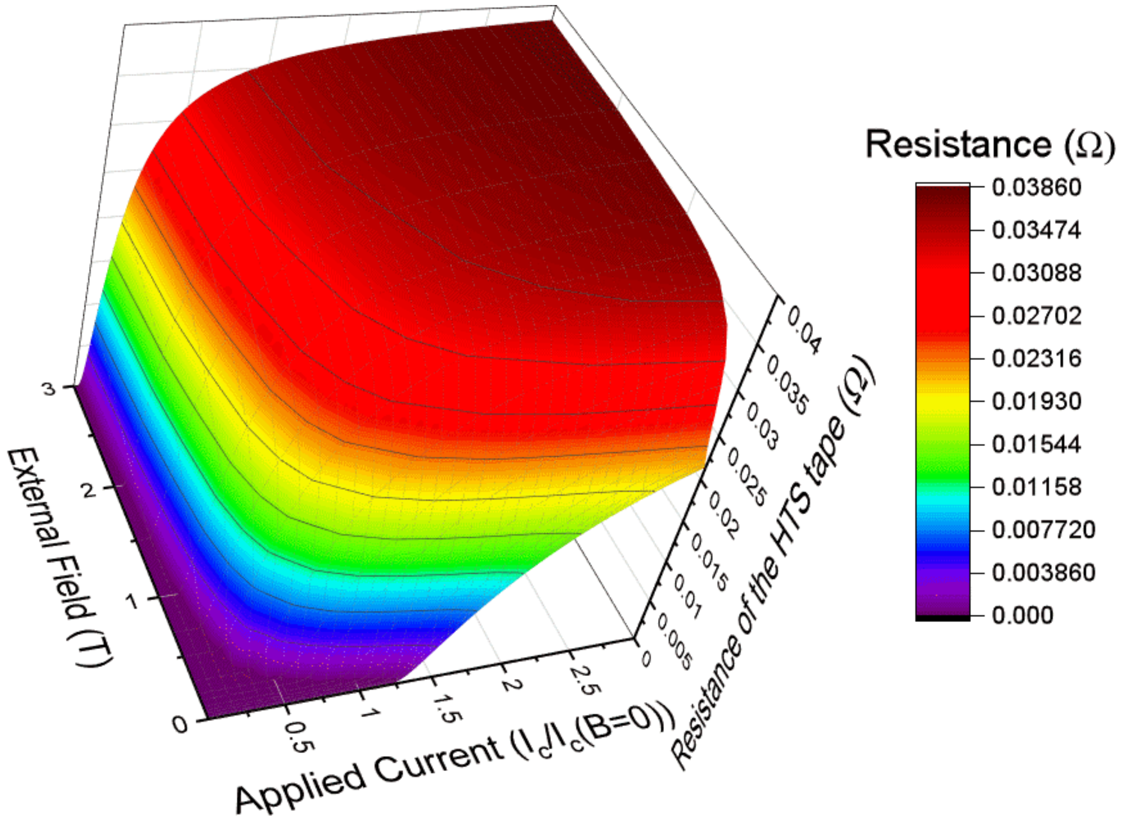
I_{Total} vs V_{HTS} **or** I_{Total} vs R_{tape}

Circuit Model (I_c(B) switch)



Using a 2D lookup table, we can incorporate $B_c(B, \theta = 0°)$ characteristics into the circuit models.

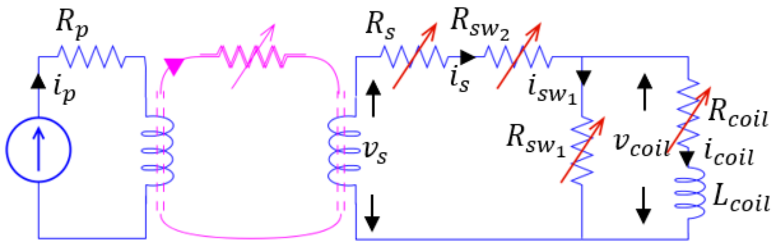
- Ensure you have plenty of points to interpolate smoothly.
- A relative tolerance of 10^{-20} can also be achieved without convergence error.



Note: This can be made as 3D look up table as well, if any one wants to incorporate Temperature/angle dependence.

HTS wire database: http://htsdb.wimbush.eu/

Model verification

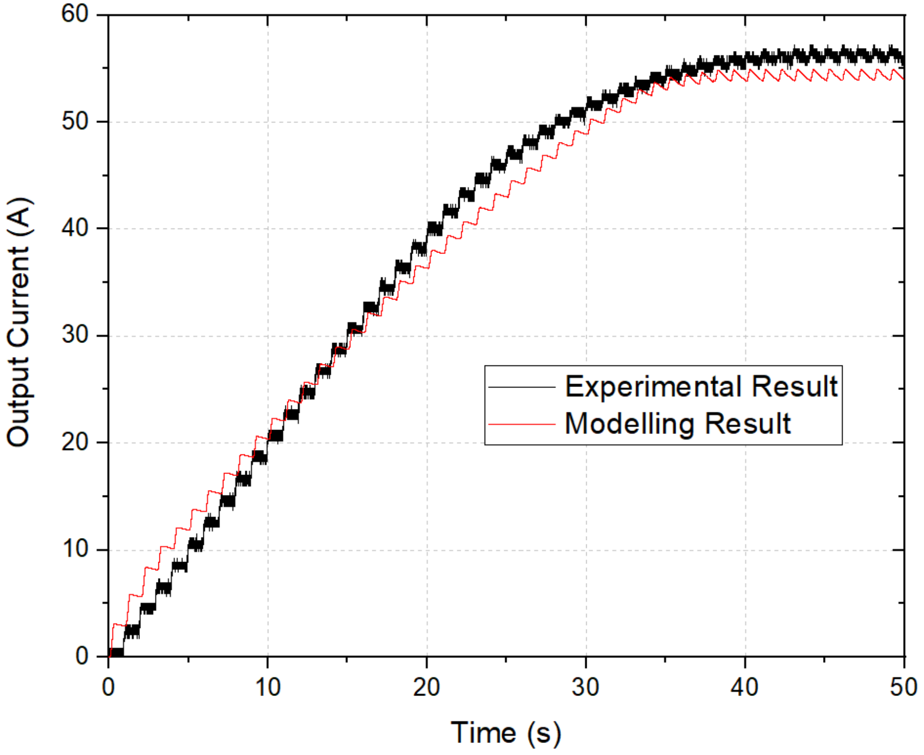


Switch Specifications

Parameters	Values
I_c of the HTS tape	351.54 A
Length of the HTS tape	60 mm
Width of the HTS tape, w	6 mm
Thickness of the stabilizer, t_{sb}	50 µm
Resistivity of the stabilizer, ρ_{sb}	0.19 µΩ.cm

Load coil Specifications

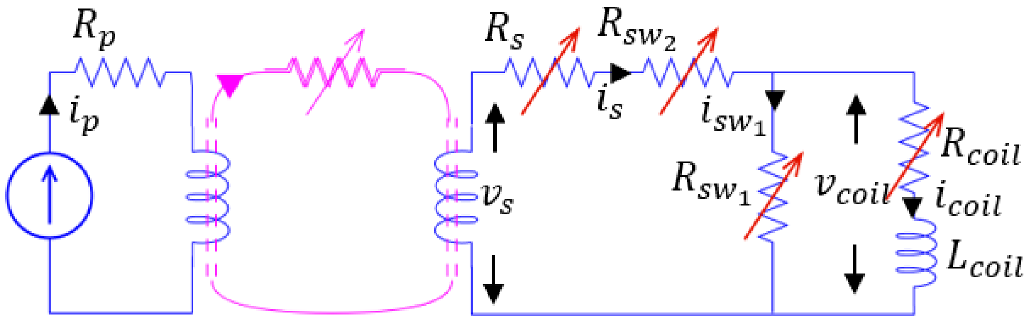
Parameters	Values
Inductance of the load coil, L_{coil}	2.42 mH
I_c of the HTS tape	55A
Length of the HTS tape	40 m
Width of the HTS tape, w	4 mm
Thickness of the stabilizer, t_{sb}	50 µm
Resistivity of the stabilizer, ρ_{sb}	0.19 µΩ.cm

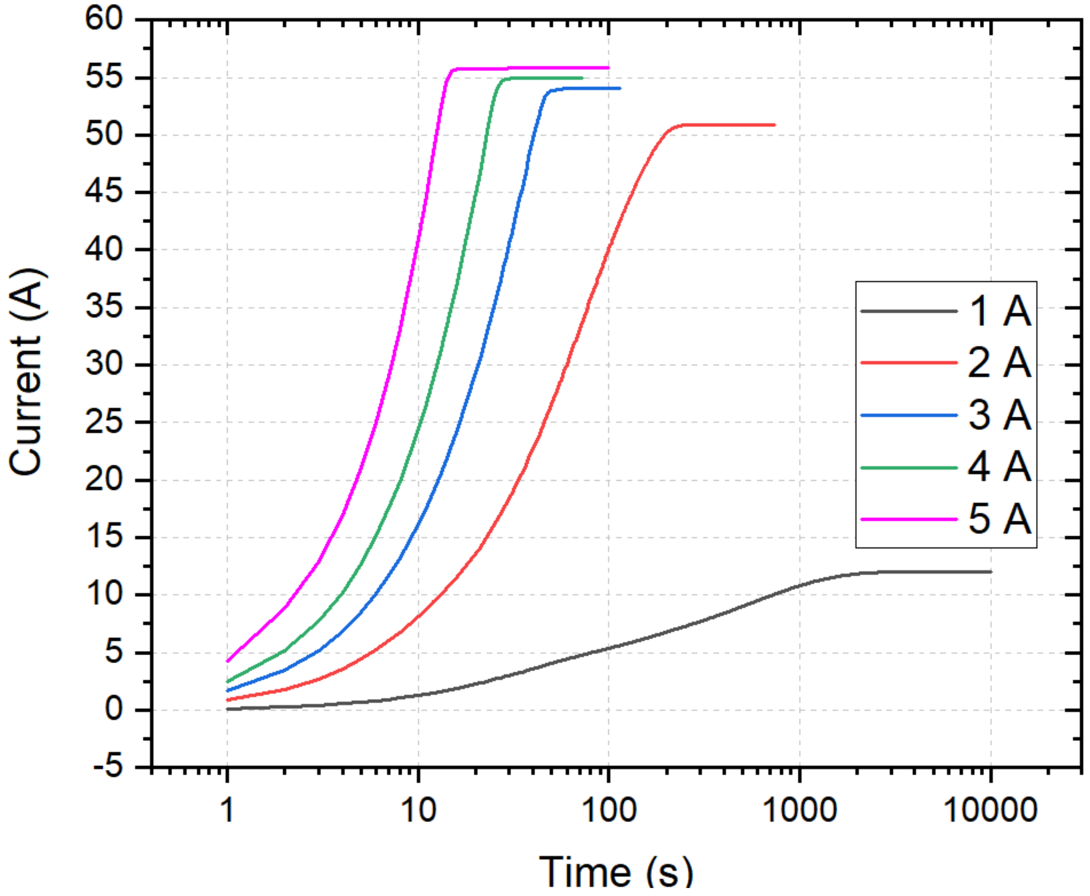


Varying the Input current magnitude

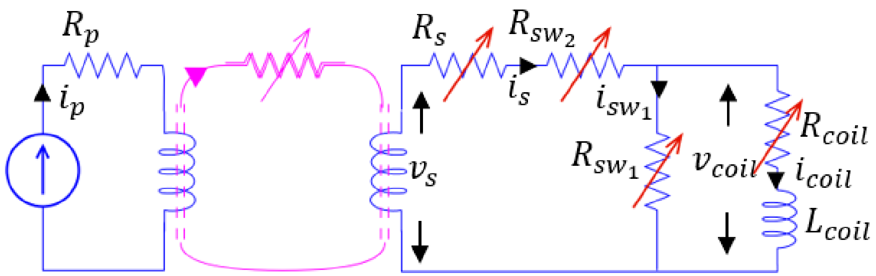
Operating Conditions

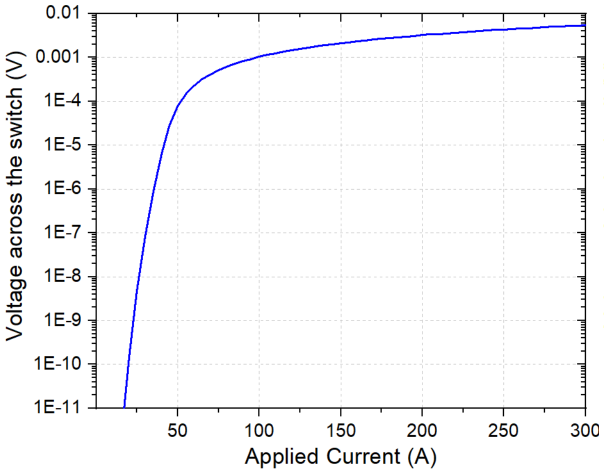
Parameters	Values
Field applied	1 T each on SW1 and SW2
Frequency	1 Hz

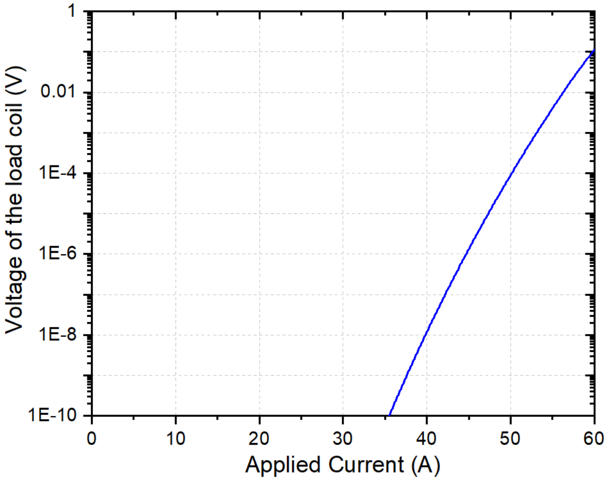


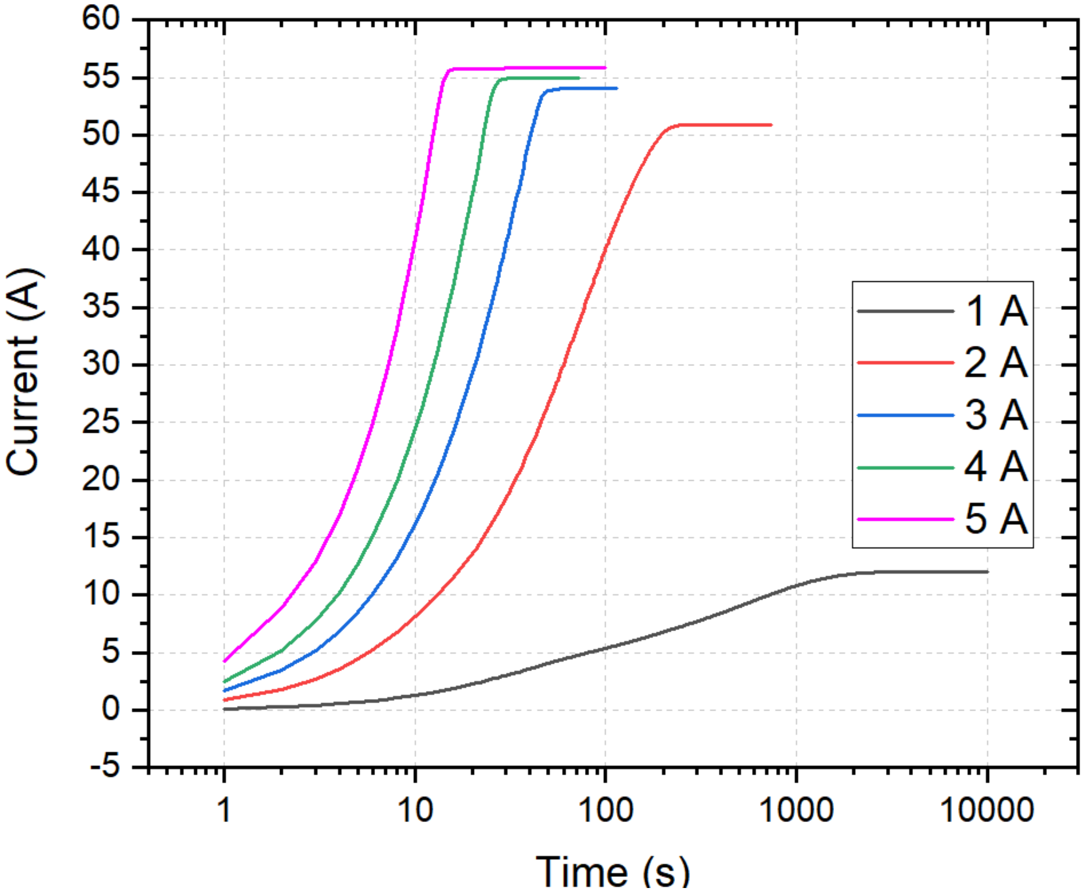


Varying the Input current magnitude





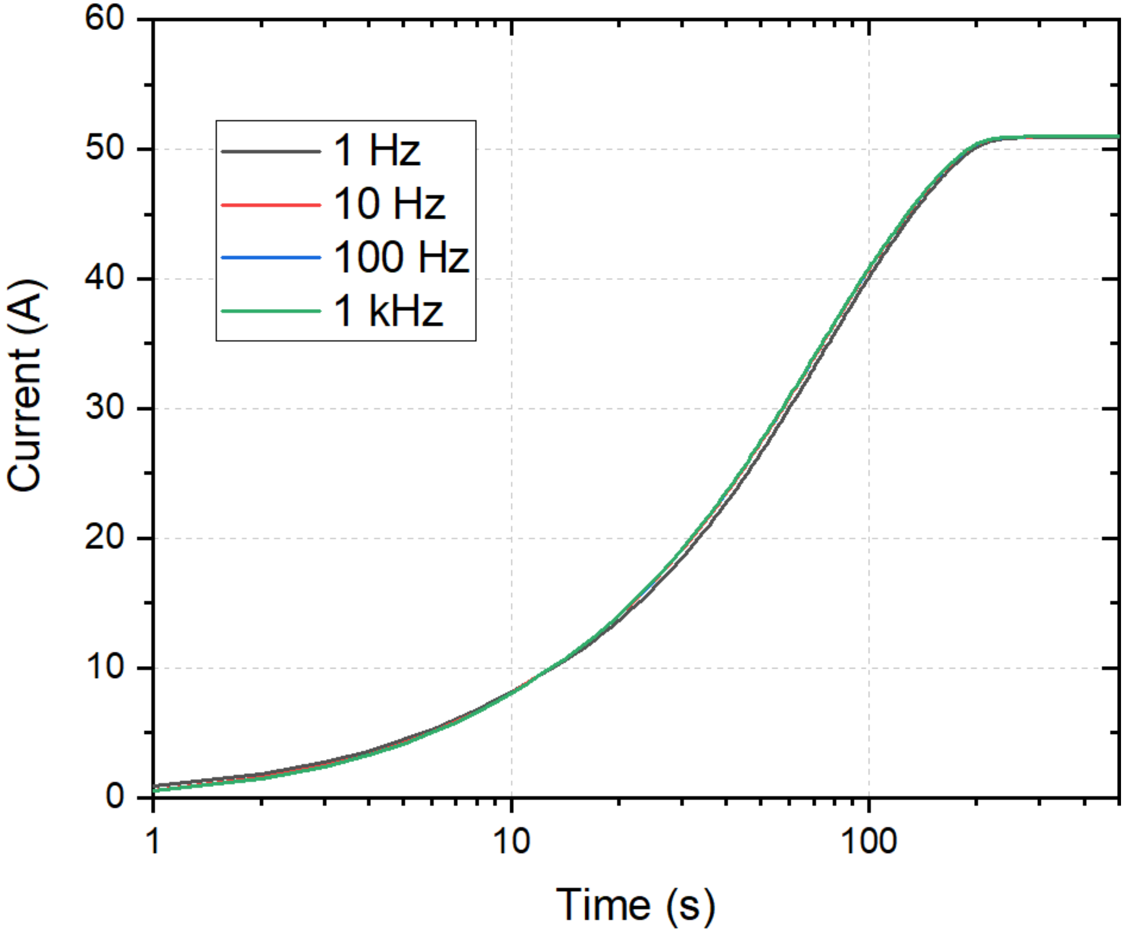




Varying the Frequency

Flux Pumping works on the net DC voltage applied across the load coil.

- Saturated current and charging time doesn’t change with frequency.
- But AC losses will come into effect for higher frequencies.
- Similarly, the ripple content increases with lower frequency. Thus an optimization is needed to find the ideal frequency.
- Experimentally verified.



Conclusions

- $I_c(B)$ characteristics of the HTS tapes were included in the circuit model, enabling us for much higher accuracy.
- Electromagnetic circuit models are built and verified against the experimental results.
  - Gives us the ability to test the system level models from the existing component level models.
- This helps us to understand and optimise the flux pump for high efficiency and high current.
- Unlike, dynamo flux pumps, transformer rectifier flux pump current characteristics doesn’t change with frequency.