Transient Negative Inductance in Ferromagnetic Material

A Project Report Submitted
in Partial Fulfillment of the Requirements
for the Degree of

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by

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CERTIFICATE

*This is to certify that the work contained in this report entitled "**Transient Negative Inductance in Ferromagnetic Material**" is a bonafide work of **Priyankka G R** (**Roll No. 121801039**), carried out in the Department of Electrical Engineering, Indian Institute of Technology Palakkad.*

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Chapter 1

Introduction

In the previous phase and the first half of the second phase, we looked at switching in a ferroelectric system using the Nucleation limited switching. The NLS theory considered a poly-crystalline ferroelectric with each grain being assigned a activation field value. This activation field value determined the switching time of the grain. The switching time was then used to calculate a probability of switching for a given external electric field. Using this and a Monte Carlo algorithm, we were able to obtain the transient behaviour of a ferroelectric when a external field is applied. This mechanism is very similar to that of an ising model, commonly used to describe a ferromagnetic material. In the ising model, instead of the switching time, the energy difference when a magnetic dipole switches, along with the Boltzmann distribution is used to determine the probability of switching. This brings us to the possibility of the ising model also being able to show the transient negative behaviour.

In this phase of the project, we have looked at transient negative inductance in ferromagnetic material. We first start by considering the system to be a single domain and mono-crystalline. We use the Landau expression to build a single domain phenomenological model. By adding a resistor to slow down the transient period, we see the transient negative inductance effect. Next, we have considered an Ising model which considered each dipole in the ferromagnet to be an individual entity, making this model a multi- domain model. We then have done experimental work to show this transient negative inductance behaviour.

There is one other account of such an transient negative inductance behavior in ferromagnets, shown in [1]. In order to provide a model for this effect, the work has assumed an expression for the relationship between current and flux. We provide both a single and multi-domain model for the transient NI behavior and show experimental evidence for the same.

Chapter 2

Landau based model

2.1 Theory

Here, we consider the ferromagnet to be a bistable single domain system whose energy landscape is taken to be a double well with the two stable states representing the spin up and spin down states of the ferromagnet as shown in Fig. 2.1. To be consistent with the experimental setup, we consider a torroidal ferromagnet. We use the phenomenological model proposed by Landau. The double well is energy of the system as a function of flux (which is a function of magnetisation) given as:

$$U = \alpha\phi^2 + \beta\phi^4 - \phi I_L \tag{2.1}$$

Here, α and β are the landau coefficients. By differentiating U wrt ϕ and equating to zero, we get a relationship between the flux and the current passing through the ferromagnetic inductor. This expression when plotted as Flux vs Current traces the S-curve. The region with the negative slope is where we expect to see negative inductance behaviour. But, as it can be seen from highlighted regions in Fig. 2.1, this region corresponds to an energetically unstable region and hence when measured, the system shows hysteritic behaviour. But, while the system switches from one state to the other, it briefly goes through the unstable negative inductance region. We call this, transient negative inductance.

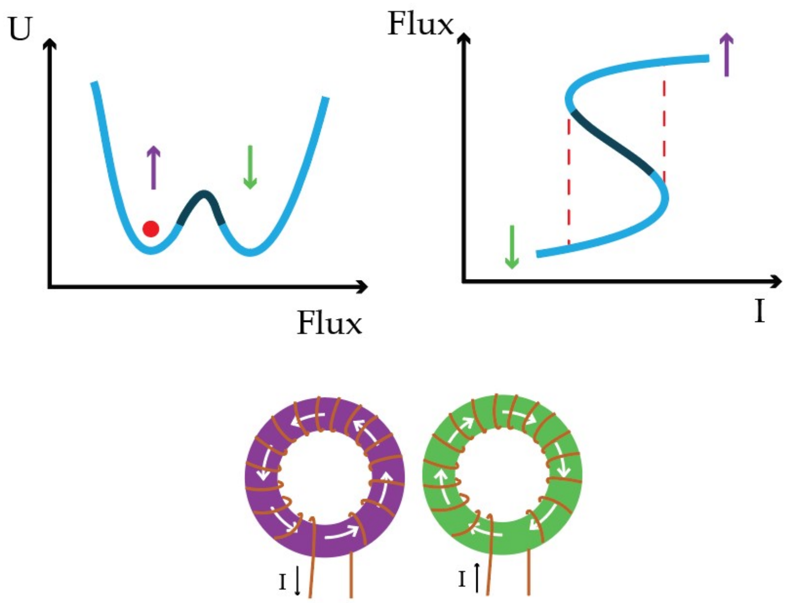

Fig. 2.1 Top Left: The double well energy landscape; Top Right: The S-curve; Bottom: torroidal ferromagnet under consideration indicating the two stable states of the system.

In order to look at the time dependence of this switching when an magnetic field(via applying a current) is applied, we use the Time Dependent Landau Ginzburg equation.

$$\begin{aligned}\rho\frac{d\phi}{dt} &= -\frac{dU}{d\phi}\\ \rho\frac{d\phi}{dt} &= -2\alpha\phi - 4\beta\phi^3 + I_L\end{aligned} \tag{2.2}$$

2.2 Simulation

In order to see the transient NI effect clearly, we use a current source and a parallel R-L circuit. Below are the circuit equations involved.

$$I = I_R + I_L \tag{2.3}$$

$$
\begin{aligned}
V = I_R R = I_L R_L + \frac{d\phi}{dt} \\
V_L = I_R R - I_L R_L \\
= (I - I_L) R - I_L R_L \\
V_L = IR - I_L (R + R_L)
\end{aligned}
\tag{2.4}
$$

$$
\begin{aligned}
V_L &= \frac{d\phi}{dt} \\
\phi(t) &= \phi(t - dt) + V_L dt
\end{aligned}
\tag{2.5}
$$

$$
\begin{aligned}
\rho \frac{d\phi}{dt} &= -2\alpha\phi - 4\beta\phi^3 + I_L \\
I_L &= \rho \frac{(\phi(t) - \phi(t - dt))}{dt} + 2\alpha\phi_{(t-dt)} + 4\beta\phi^3_{(t-dt)}
\end{aligned}
\tag{2.6}
$$

We again use the same iteration scheme with a parallel R-L circuit equations. Below is the iteration scheme used:

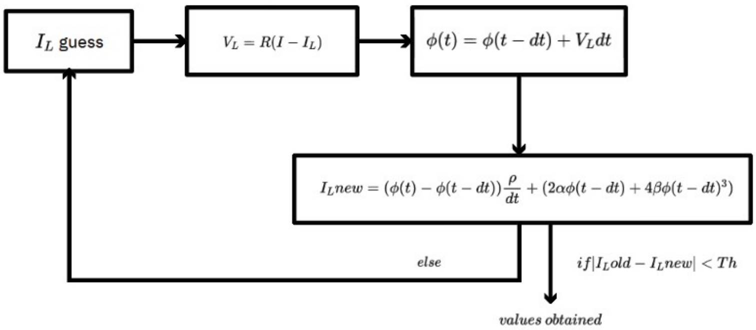

Fig. 2.2 Iteration scheme for Landau based model (Parallel R-L)

Below are the plots obtained from the simulation by applying a step current input.

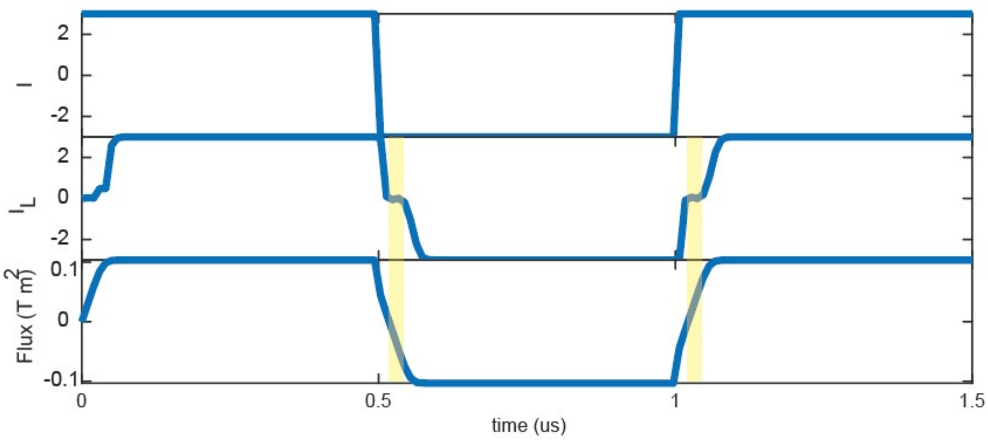

Fig. 2.3 Transient NI effect obtained using the landau model

Chapter 3

Ising based model

3.1 Theory

The ising model is a multi domain model for ferromagnetic materials. It is commonly used to show phase transitions wrt temperature. We adapt this model to show the hysteresis and the transient negative inductance behaviour. Here, we consider a 3D ising model. We have a 25*25*75 grid, with each point representing a lattice site that has 'one' magnetic dipole. We start with the Hamiltonian of the system given by :

$$\mathcal{H} = \sum_i \sum_{<ij>} J_{i,j}\sigma_i\sigma_j + \sum_i H\sigma_i \tag{3.1}$$

The first term represents the interaction energy between the lattice site and it's nearest neighbours. The second term is the energy of the lattice site under the effective external magnetic field H. Here, the sigma's are the ising value each lattice site takes, i.e. +1 or -1. In order to see the time dependent behaviour of this model, we take a lattice point at random and switch the site, i.e +1 $\rightarrow$ -1 or -1 $\rightarrow$ +1. The energy change in the system due to this switch is given by:

$$d\mathcal{H} = 2\sum_{<ij>} J_{i,j}\sigma_i\sigma_j + 2H\sigma_i \tag{3.2}$$

The flip is retained if the change is energy is negative, leading to a more stable system, else the flip is retained with probability determined by the Boltzmann distribution.

$$probability = exp^{\frac{-d\mathcal{H}}{kT}} \tag{3.3}$$

Here, we consider a normalized system of values and make k=1, the effective magnetic field to be $\frac{H}{Hc}$. This random site choosing and switching happens multiple times per second, determined by the 'switching speed' of the system. The total magnetisation of the system is them calculated as $M = \sum \frac{\sigma}{N_x * N_y * N_z}$ where n, m and l are the system dimensions. This gives us the normalized magnetization ranging between +1 and -1. We multiply the H with Hc and M with Mc obtained from experimental results to obtain the actual values for magnetisation and magnetic field.

3.2 Simulation

We consider a 3D cuboidal ising model. The system considered is a torroid and hence the smaller faces of the cuboidal are looped i.e for a lattice size in the leftmost plane, the neighbouring lattice site is the one in the rightmost plane as shown by the red faces in Fig. 3.1

Fig. 3.1 The 3D system for the ising model with circular boundary conditions.

The transient NI effect is seen by applying a step current input to a parallel R-L circuit. The iteration scheme is shown below:

The results from this simulation are shown below:

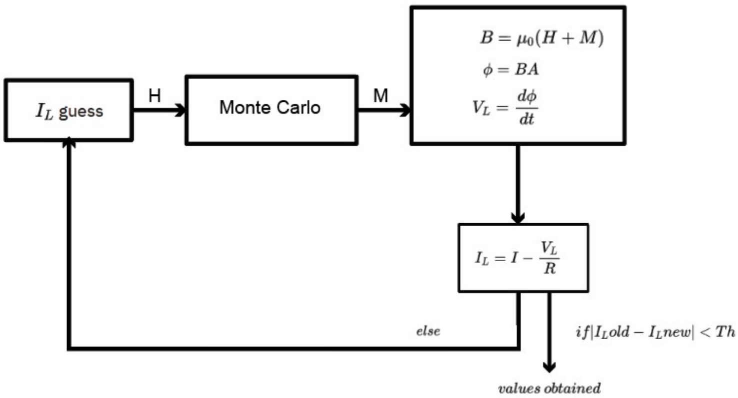

Fig. 3.2 Iteration scheme for Ising based model-parallel R-L

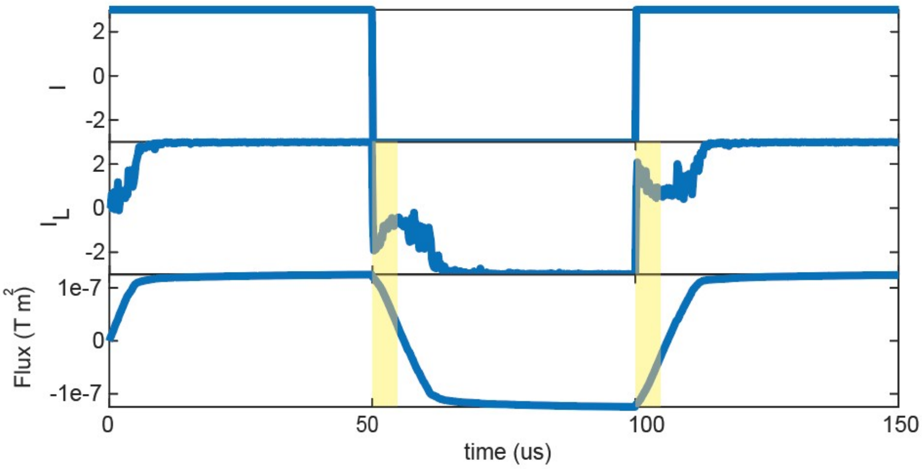

Fig. 3.3 Transient NI behaviour obtained using Ising model

It can be seen that at around $50\mu s$ and at $100\mu s$, when the current is switched, the system briefly goes through the NI region, highlighted in yellow. The current through the inductor briefly increases at $50\mu s$ while the flux decreases and at around $100\mu s$, the current briefly drops while the flux keeps increasing. Ideally, we should be able to see the same effect experimentally, provided we are able to produce a proper current step input.

Here, we can see the 3D simulation structure, with each grid representing a lattice point. The blocks have been plotted for when the lattice fully switches from one direction to the other. The blue and yellow represent $+1$ and -1 states of the lattice site respectively.

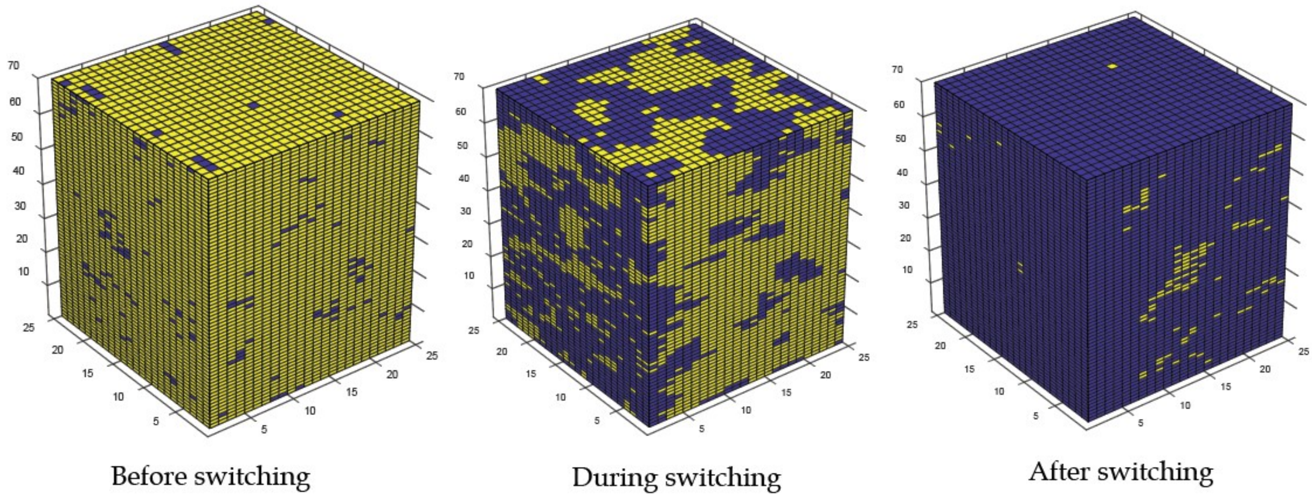

Fig. 3.4 Simulation of 3D ising model

Chapter 4

Experimental Work

4.1 Hysteresis Measurement

We first obtain a hysteresis of the torroid. We use the TN9-6-3-3R1 torroid from *Ferroxcube* and 28 gauge enameled copper wire as winding. The coil has 20 windings. We use the Tektronix AFG1062 function generator as the voltage source and the data acquisition is done on Keysight DSOX1102G oscilloscope. The function generator has a current supply limit of around 40mA but our ferromagnetic core requires a higher current to saturate. So, we use a power amplifier circuit to increase the current capability of the circuit.

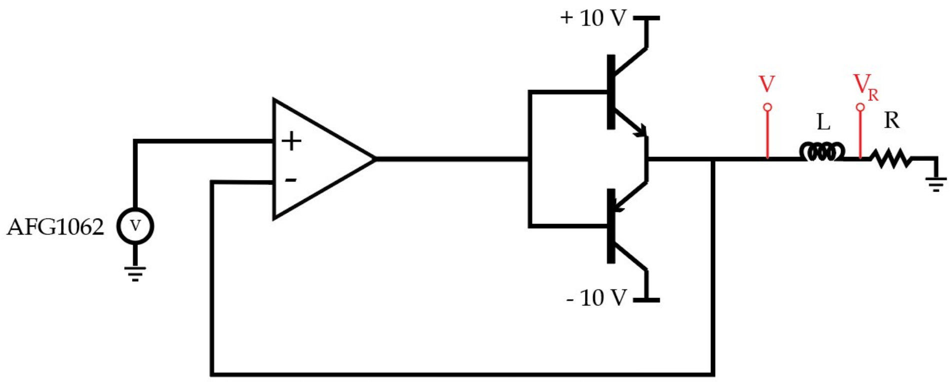

Fig. 4.1 Experimental Setup to measure hysteresis

The PNP and NPN transistors make up the push pull amplifier and the op amp helps get rid of crossover distortion. The transistors used are the CK100 and the CL100S which have a current rating of 1A. A ramp voltage input of time period $340\mu s$ is applied. The result is compared with the hysteresis given in the data sheet of the torroid. Voltages are measured at the points marked with red lines. We measure the voltage across the inductor and the resistor and the voltage across the resistor. Current is calculated as $I = \dfrac{V_R}{R}$ and the voltage across the inductor is given by $V_L = V - V_R$. The flux in the integral is given by $\phi = \int V_L dt$

Below is the applied voltage, the current through the circuit and the flux in the inductor plotted in time domain.

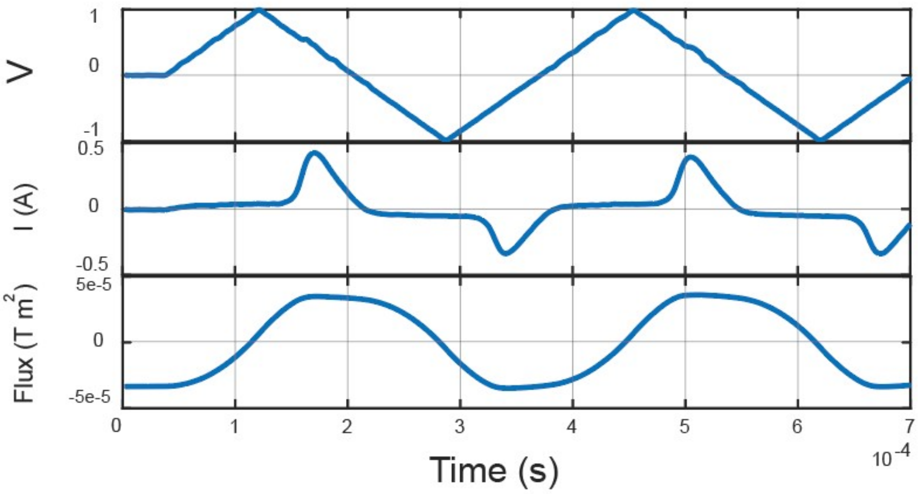

Fig. 4.2 Hysteresis measurements in time domain

Plotting the Flux ϕ across Current will give us the hysteresis shape. We now convert the Flux vs I plot to a B vs H plot using the following equations.

$$
\begin{aligned}
H &= \frac{IN}{l_c} \\
B &= \frac{\phi}{AN}
\end{aligned}
\tag{4.1}
$$

Where l_c is the effective length of the torroid which is $22.9mm$, N is the number of turns which in our case is 20 and A is the area perpendicular to the direction of magnetic field

B which is $4.44mm^2$. This gives us the B vs H plot as shown in Fig. 4.5 The experimental

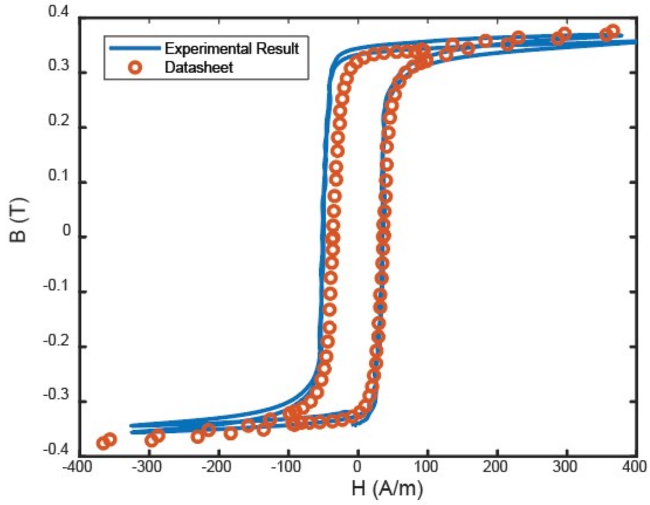

Fig. 4.3 B vs H curve obtained experimentally

results obtained are in good agreement with the data sheet hysteresis .

4.2 Transient Negative Inductance measurement

In order to see the transient NI effect clearly, we use a current source to prove a step current input to a parallel R-L circuit with a series resistor. The series resistor helps us measure the actual current through the circuit. The Keithley 2450 source meter is used as the current source. A simple test script was written using the Keithley test script builder to program the source meter to give the step current input. Since the device is a low frequency device, the step current input has a transient time of 1ms. Below is the circuit used to do the measurements. The voltage across the parallel R-L and the series R is measured, and the voltage across the series R is measured.

The results obtained are shown below. The highlighted region is the transient negative inductance region. We can see in the zoomed in version that the flux continuously increases while the current briefly decreases.

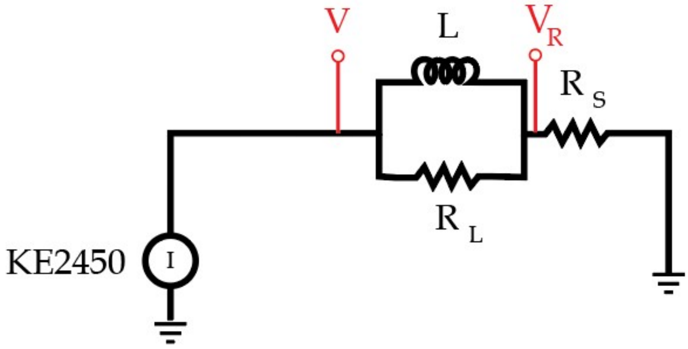

Fig. 4.4 Experimental Setup used to obtain the transient negative inductance effect

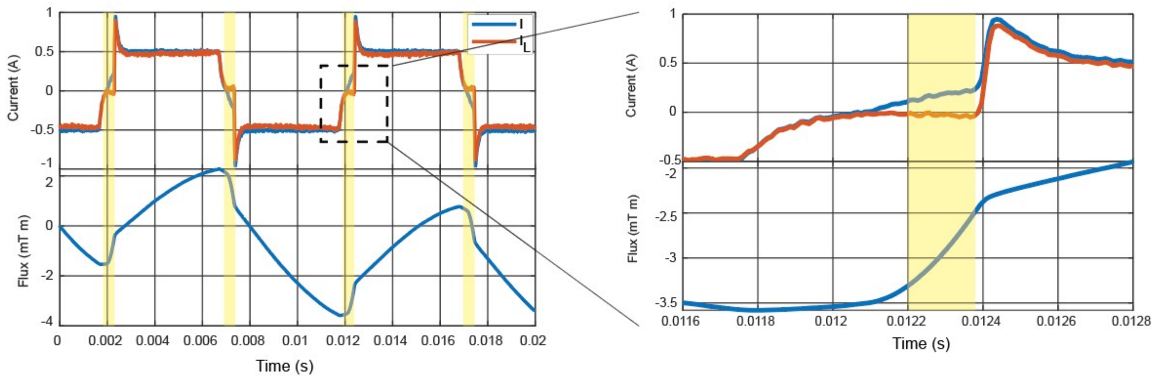

Fig. 4.5 Results showing transient negative inductance effect in a ferromagnetic core

Chapter 5

Conclusion and Future Work

We have been able to show transient negative inductance behaviour using a single domain Landau model and a multi domain Ising model. We have also shown preliminary experimental evidence for the same. From here, the simulation models are to be calibrated to the experimental evidence so that the two can be compared. Although we could not produce a clean step current input to observe the NI effect, we were still able to see a region during the switching where the current decreased as the flux increased and vice versa. We hope to make cleaner measurements with either a better current source or with a circuit to make build a voltage controlled current source. If this is done, we would have proper experimental evidence of transient negative inductance along with a single domain and multi domain model to support the results.

References

[1] S. Kumar and R. S. Williams, "Tutorial: Experimental nonlinear dynamical circuit analysis of a ferromagnetic inductor," *IEEE circuits and systems magazine*, 2018.