The Making Of A Flux Pump

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Introduction

A superconductor is a material that conducts electricity with zero resistance and expels all magnetic field (flux) from itself when superconducting [1]. However, due to flux creep its current can decrease over time [2]. I built a flux pump which counteracts this by pumping flux into the superconducting magnet. This makes thick cables powering superconductors in machinery such as MRI scanners, which cause heat loss and waste electricity, obsolete, saving money for businesses that use superconductors.

Basic Concepts

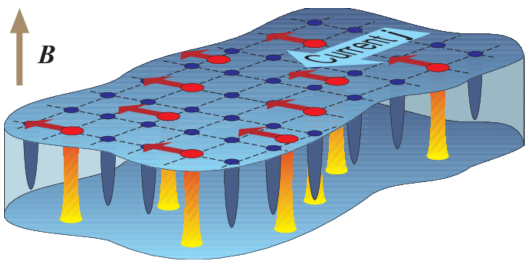
A superconductor becomes superconducting when the values of a set of parameters are below their critical threshold values [3]. A superconductor typically has three critical threshold values, one for each of temperature, magnetic field strength and current density [1]. The critical threshold values are not independent of one another – as the critical temperature is approached, the critical field tends to zero. Low temperature superconductors have a low critical temperature (<35K) [4], and high temperature superconductors (HTS) have higher critical temperatures (>35K).

There are two main types of superconductor, labelled type I and type II. A type I superconductor only has one magnetic field threshold (H_c) whereas a type II superconductor has two different magnetic field thresholds (H_{c1} and H_{c2}).

If the external magnetic field, H, of a type II superconductor is below H_{c1} the superconductor has no resistance. If $H_{c1}<H<H_{c2}$ the superconductor is in a mixed state. In this state, lines of magnetic flux enter the superconductor and are surrounded by rings of supercurrent (which is unimpeded current) [5] with the inside of the rings being normal (i.e. has resistance). A ring of supercurrent carries a single quantum of flux (i.e. a flux vortex) within itself [7]. If $H>H_{c2}$ the superconductor is normal.

Between H_{c1} and H_{c2} the flux vortices move within the superconductor due to the Lorentz Force (caused by the current and magnetic field), resisted by a dissipative drag [1], [6], [8]. However, these vortices are often pinned by impurities in the crystal lattice of the superconductor so they cannot move and zero resistance is maintained [6], [8]. As the temperature increases, thermally induced vibrations allow the vortices to jump from the pinning sites [6], [8], dissipating energy and creating resistance. This is called magnetic flux creep. Due to this energy loss, the superconductor's current slowly decreases [1]. As any of the parameters increase towards their critical thresholds, flux creep increases.

This diagram is from [7], the flux vortices are in red, are in and between pinning sites (dark blue circles in a grid) and are acted on by the Lorentz Force perpendicular to the magnetic field (B) and current, shown by the red arrows.



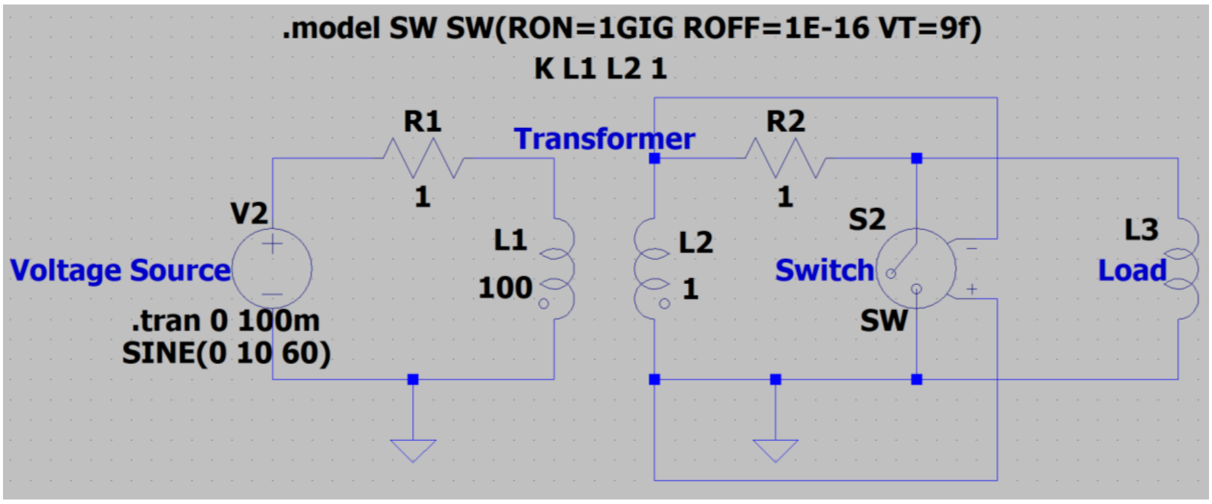
Resistance caused by soldered joints between superconductors can also dissipate energy, but this loss is negligible compared to flux creep [4].

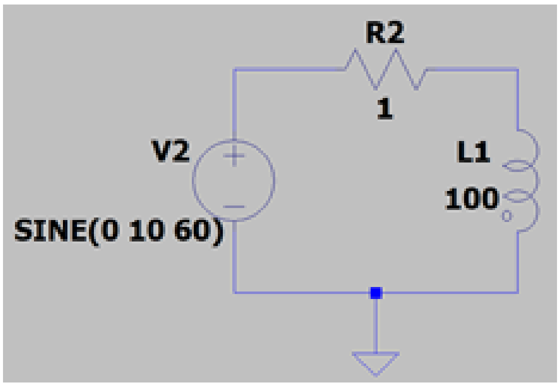
A flux pump compensates for these effects by injecting the HTS with flux, thus inducing a larger current in the magnet [5]. A flux pump is used to either maintain or increase the magnetic field strength in HTS magnets [5].

The papers [7] and [8] and book [6] describing flux creep are all reliable because they were published within the last twelve years and describe and reference the Anderson-Kim model for flux creep, which is thought to be correct and many other papers are in agreement. Although written approximately 20-30 years earlier, papers [1] and [2] give a similar description of superconductors to papers [3] and [4] and many others published within the last 10 years. Paper [5] is accurate because this flux pump uses the theory in it to verify the description. All sources except [1] and [6] have been published in peer reviewed journals, which demonstrates their accuracy.

The Simulation

I simulated the flux pump's circuit using LT Spice. It has two parts, one to either side of a transformer:





The left side (shown separately to the left) supplies the voltage. It has a voltage source which provides an A.C. voltage of amplitude 10V and frequency 60Hz and includes a resistor of resistance 1Ω. This side is connected to a transformer (L1-L2) which increases the current by 10-fold, using an inductance ratio of 100:1

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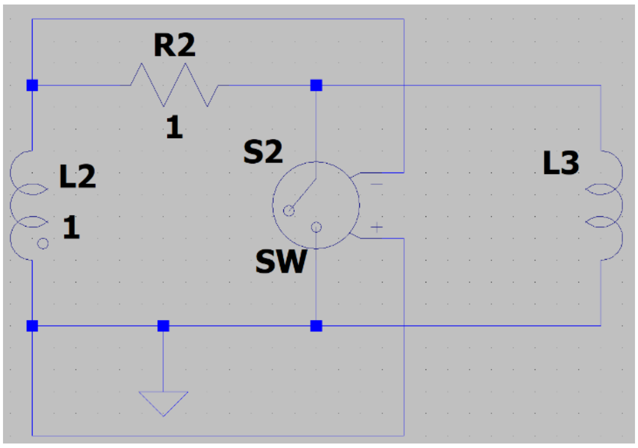
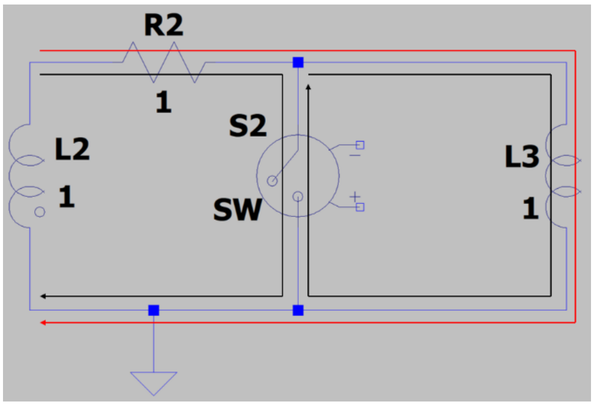


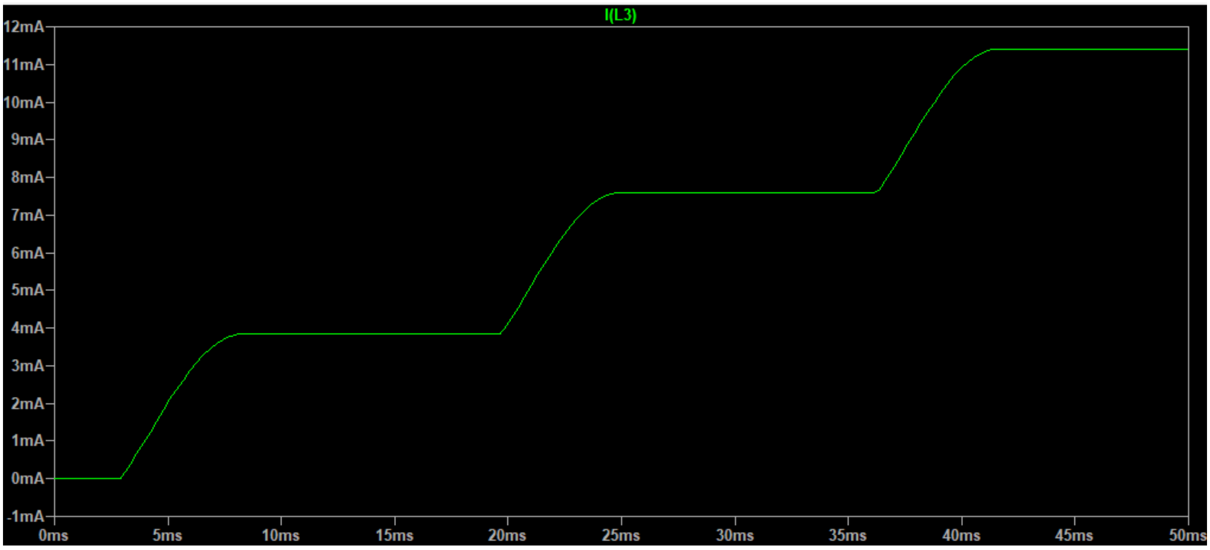
The second, load side of the circuit (shown to the right) is the superconducting part, which would be made completely of superconducting tape. In this part there is a load coil L3, in which the magnetic field is pumped up during operation of the circuit. A switch (S2) is connected across the load and is opened or closed (shorting the load). In the simulation the switch is controlled by the voltage in the circuit, that is via the wires going into the + and - terminals of the switch. However, if the switch were a real superconductor, its state would depend on an external magnetic field through it. In the real flux pump switch S2 is formed by a superconducting "bridge" connected across the coil L3 – if the magnetic field strength through the bridge exceeds a critical threshold, the superconductor ceases to be superconducting and the switch opens.



The red arrow is the circuit when the switch is open, and the black arrows are the circuits when the switch is shut, the reference voltage lines have been removed so it is less confusing

There are effectively three circuits in the load side, depending on the state of the switch. If the switch is open, the current goes through the load, i.e. superconductor, and it is charged. If the switch is closed the current goes through the switch instead of the coil and the current in the coil just goes round the L3-S2 loop, allowing the load to stay at the same current until the switch opens again. In the simulation the threshold voltage for the switch is 0.9V, below which the switch is closed, and the smaller current goes through the switch. Above this threshold the switch is open, allowing only the higher current through the load. This permits the current through the load to charge up, until the voltage drops below the threshold and the switch shuts.

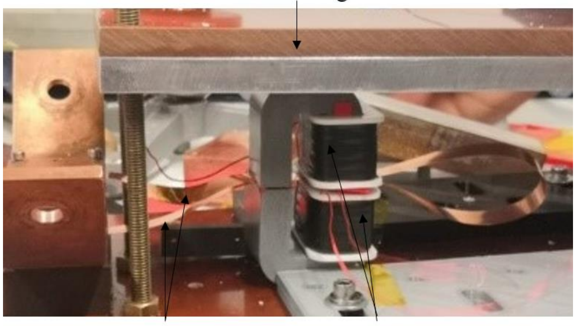
The charging of the superconductor load is shown in this graph: the current through the load is shown on the y-axis against time on the x-axis. The current increases by roughly 4mA every cycle (when the switch is open); it stays constant when the switch is closed.



The Real Flux Pump

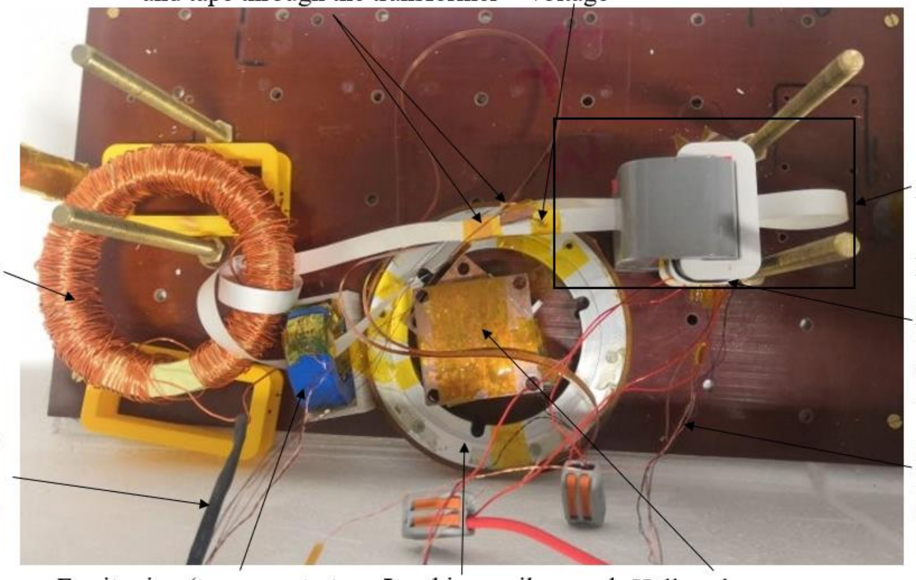
Two normal wires were soldered to a length of 40cm YBCO ($YBa_2Cu_3O_7$) superconductor, 5cm from each end, to monitor the voltage through it. They were soldered using a small amount of 100% iridium solder. It does not damage the superconductor as the melting point of iridium is reasonably low.

The superconductor tape goes through the transformer i.e. forming part of the load side circuit. One end of the load, the bridge, and the superconductor tape through the transformer, are soldered together, using a soldering block (shown to the right). The top and bottom metal plates were heated up to 170°C, and were connected to a thermocouple, to measure the temperature of the blocks. The metal plates were held down by a weight to make sure they made a good thermal connection with the superconductors. The same is done to the other ends of the three superconductors.



The superconductor in the bridge was set-up as shown in the photograph to the left (this shows a separate bridge to the one in the flux pump). A loop of superconductor passes between two coils of wire which are above and beneath the tape. When a current passes through the coils it generates a magnetic field through the coils, which is perpendicular to the superconductor, and turns the superconductor normal, thus acting like a switch: By switching the current through the coils on and off, the magnetic field is switched on and off, and the superconductor is switched “off” (i.e. switch is open) and “on” (i.e. switch is shut). The coils are clamped in place by the metal block on top of the bridge to stop them from vibrating.

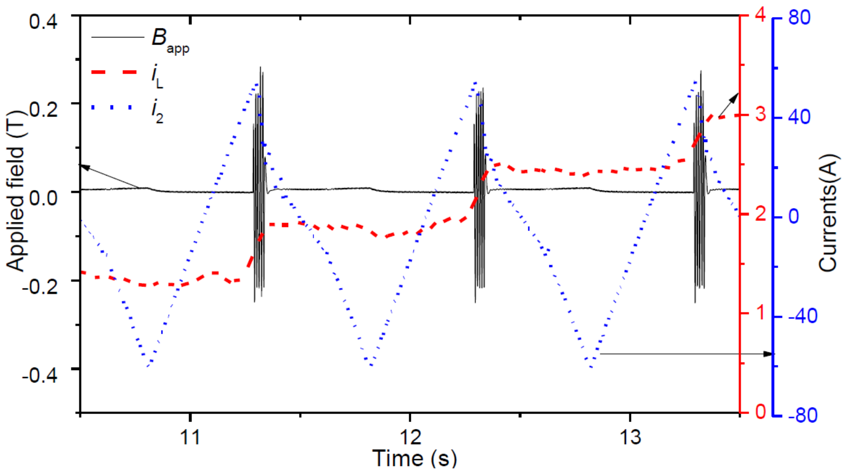
The full circuit was then set-up as shown below. The load is the brown superconductor tape wrapped around a metal ring in the centre (L3 in the simulation). The load is wrapped in a coil to act like an HTS magnet and show how the flux pump would be used in magnetic machinery where the magnetic field is concentrated in one place. When the switch is closed (i.e. the superconductor bridge has no resistance), the current does not flow through the load because it has an inductance, which is a virtual resistance caused by the alternating current. This virtual resistance does not cause a loss of current.



Hall Probe sensors (which measure current) are in a variety of places throughout the circuit. There are two between the coils in the bridge, one in the centre of the load, and another by the superconductor that passes through the transformer, in the blue ferrite ring (which is needed to concentrate the magnetic field on the sensor).

Conclusion

This flux pump would show that it is possible to compensate for the loss of current due to flux creep in HTS magnets. Unfortunately, there was not enough time to collect data, so I cannot prove that this flux pump works. Instead, a graph from [5] using a similar flux pump is shown below. Where i_2 is the current through the load side of the circuit, i_L is the current through the load and B_{app} is the magnetic field through the bridge caused by the coils.



This graph shows the current in the HTS coil is pumped up in a similar manner to the simulation. When the current in the circuit is at its maximum, the magnetic field B_{app}, caused by the coils in the bridge, "closes" the "switch", allowing current to pump up the load. Once the current i_L has decreased, the magnetic field is turned off allowing the current back through the bridge instead.

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