FERMI NATIONAL ACCELERATOR LABORATORY

Simulation of Quench

In An 11 T Dipole Magnet

Charles R. Orozco x 15700N

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On 19 September 2008, approximately 100 of CERN's dipole magnets quenched due to faulty electrical systems. This problem resulted in rapid heating of the magnets and the loss of 6 tons of liquid helium as well as the destruction of 53 dipole magnets, which had to be replaced at a cost of $21,000,000. This in turn delayed the LHC from accelerating particles to "high energy" until November 2009, more than a year later. To avoid such a catastrophe ever happening again, it was decided that each magnet would be fitted with a heater and a dump resistor to facilitate the quick and safe shutdown of the magnet. To that end, I was commissioned to update a simplified 3D model of the dipole magnets with new geometry and retool the analysis performed on the old model in 2003 to work with the geometry of CERN's dipole magnets. The analysis was performed using ANSYS 7.0 in 2003 and 13.0 in 2011. Unfortunately, I was unable to perform the analysis in full as the 3D analysis takes 10 days to run on the computer that was available to me at the time of project completion. I was, however, able to successfully run a 2D simulation, the results of which lie below.

Background of SC magnets

Conductors vs. SuperConductors

According to both Ampère's law and the Biot-Savart law, current flowing through a wire produces a magnetic field proportional to that current. This is quite a useful phenomenon as evidenced by Fermilab's use of electromagnets to accelerate protons and antiprotons in the Tevatron. However, a common problem associated with electromagnets is a practical limit on how high the magnetic field strength can go. One limit is current density. It is not always easy to generate the rather large currents necessary for high-field magnets. In reality, however, this is a small problem that is easily overcome using a Pelletron device. The main limit that needs to be addressed to construct and use high-field electromagnets is the heat. Normal electromagnets rely upon normal wires made of a non-superconducting material (i.e. copper). Normal wires, indeed, all wires operating at or around room temperature display some form of electrical resistivity dependent upon the material used and the length of the wire. Furthermore, according to Joule's first law, current flowing through a resistive wire over a period of time will generate heat.

$$\boldsymbol{Joule's\ First\ Law}$$

$$Q = I^2 \cdot R \cdot t$$

$$Q\text{: } heat\ in\ joules$$

$$I\text{: } current\ in\ amperes$$

$$R\text{: } resistance\ in\ ohms$$

$$t\text{: } time\ in\ seconds$$

For high-field magnets, which use unusually high current to generate the large magnetic field, this can be a catastrophic effect, which usually results in the melting of the wire and the destruction of the magnet. The simple solution, of course, is to make one of the three parameters above (I, R, t) zero. Current cannot go to zero or else there would be no magnetic field. Time cannot go to zero for the obvious reasons. This leaves resistance as the one parameter which can be changed. This is where superconducting wire comes into play. At normal (i.e. room) temperatures, superconducting materials behave like normal materials, offering a standard resistive response to current flow; however, when superconducting materials are cooled to below a certain temperature, known as the critical temperature, they enter the superconducting state. When in the superconducting state, these materials exhibit the special property of offering no electrical resistance. This in turn solves the problem of Joule heating. However, there is a catch. For most superconducting materials, this critical temperature is somewhere between 0.1 and 40K, well below the boiling point of liquid nitrogen (77K). This is an important property because while liquid nitrogen is easily manufactured, it is clearly not cold enough to drive these materials into the superconducting state. Instead, these materials require liquid helium, which has a boiling point of 4.2K, to achieve the superconducting state. Liquid helium is far more difficult to manufacture and store and therefore is more expensive. Examples of these materials include Niobium-Titanium (NiTi), which is in use at Fermilab's Tevatron and Niobium-Tin (Ni_3Sn), which is in use at CERN's Large Hadron Collider (LHC).

Use of Superconducting magnets in colliders

Superconducting magnets are at the forefront of technology for high-energy physics today. Every particle accelerator in use today uses superconducting magnets for a variety of purposes. For instance, both the Tevatron and the LHC use dipole magnets to bend the particle beam in a circle. These two accelerators also use quadrupole magnets to focus the particle beam. These magnets are made by winding superconducting wires, mixed with copper wires, into a cable. This cable is then covered by a layer of insulation. This covered cable is then coiled into the dipole or quadrupole shape. The superconducting magnet is then installed in the tunnel and cooled to 4.2K. The next bit is critical. The magnet is then fed an enormous current density which creates the magnetic field described above. An important feature of superconducting magnets is that is kept in the superconducting state, the current can flow through the material indefinitely.

Background of the quench problem

As stated before, the superconducting state is heavily dependent upon the superconducting material remaining below the critical temperature. A quench is when a small part of the magnet rises above the critical temperature causing that portion to unexpectedly enter the resistive state. This can occur for a variety of reasons. For example, the particle beam may let off some stray energy which strikes the magnet, creating heat. A common problem for high-field magnets is that the field becomes too large for the magnet to sustain and subsequently the magnet quenches. Whatever the case may be, when the magnet quenches, it sets off a chain reaction which, if unchecked, can result in the destruction of the magnet.

First, a small portion of the magnet goes from the superconducting state to the resistive state. This in turn causes this part of the magnet to produce heat through Joule heating. The heat then spreads in two ways. The first (and most direct) route is along the conductor itself. The heat spreads, winding along the wire as it makes its way through the magnet. The second route is laterally, through the insulation. This is a much slower route, as the insulation is designed to keep heat from spreading; however, given enough time, it is not a perfect barrier. Both of these methods of heat conduction result in other parts of the magnet entering the resistive state, leading to a chain reaction which heats the magnet to dangerous temperatures. This sequence of events takes only a few tenths of a second to complete, so any preventative measures must react quickly. If unchecked, a full magnet quench can destroy a magnet, costing the end user millions of dollars to replace.

A smaller, but no less significant concern when a superconducting magnet quenches is the loss of liquid helium. When a superconducting magnet quenches, and the preventative measures are not enough, the heat can reach the liquid helium and boil it off. This is significant because when a superconducting magnet quenches, even if the safety measures work perfectly to preserve the magnet, it is still possible to lose the helium, as helium's boiling point is ~4.2K, and quenching temperatures can reach upwards of 150K.

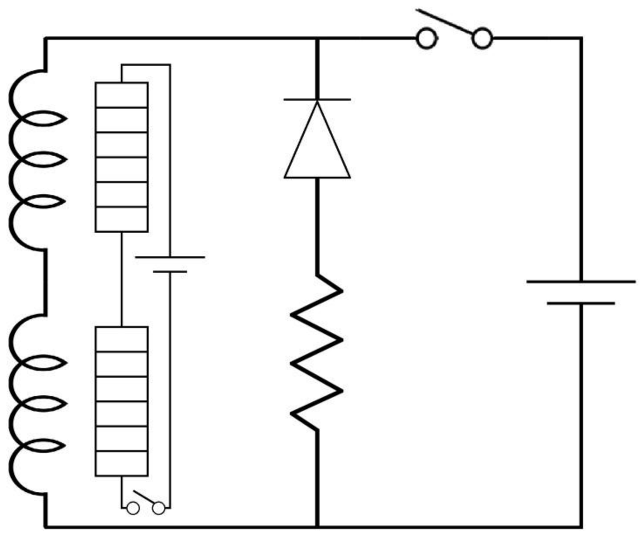
Quench detection

The first problem to solve in a quench scenario is how to detect when a quench is happening. As stated above, when the magnets are in the superconducting state, the current flowing through them can continue indefinitely with no measureable degradation. An important feature of superconducting magnets is their ability to offer no electrical resistance when in the superconducting state. As per Ohm's law, this means that while the entire magnet is in the superconducting state, the voltage measured across the magnet will be zero. This also means that if any portion of the magnet enters the resistive state, a voltage can be detected. It is this phenomenon that allows us to detect when a quench occurs. However, because of necessary fluctuations in the current and magnetic field, there is a background noise that can obfuscate the voltage being detected. A work around was developed to solve this problem whereby the voltage is taken across the upper and lower sections of the magnet and compared. If one exceeds the other by a certain amount (1V), then it is regarded as a quench.

Proposed solution to the quench problem

The proposed solution to the quench problem involves two components: a heater on the outer and inner surfaces of the coil and a dump resistor. These two measures working in tandem can return a superconducting magnet to the "off" state with no damage to the magnet. The main goal of both is to rapidly increase the resistance of the entire circuit to dissipate the current in the superconducting cable as fast as possible. The two heaters act to warm all parts of the magnet causing more portions of the magnet to enter the resistive state, which has the overall effect of heating the entire magnet slowly, instead of heating a small portion of it rapidly.

The dump resistor tries to achieve the same thing as the heaters, but instantaneously. When a voltage is detected across the magnet, a switch in the circuit is flipped, immediately adding a resistance to the circuit and helping to dissipate the current. A diagram of the circuit is shown here.



Working from the left the components are as follows: 2 magnet layers, two heaters, resistor and diode, switch, main power supply.

Previous Simulations and Project Goals

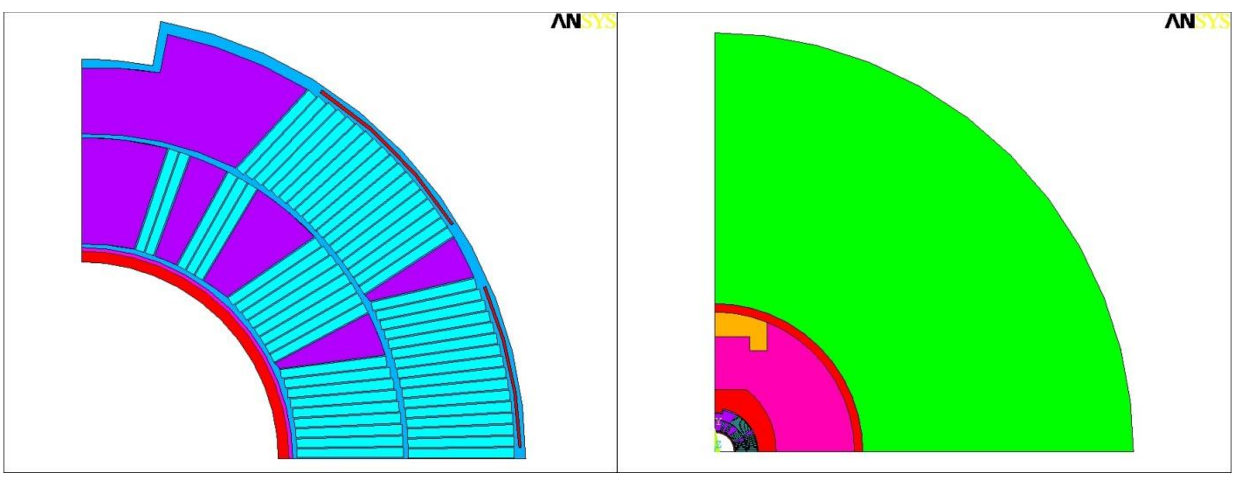
A simulation was run in 2003 by Eric Marcin which tested three scenarios for quench protection using ANSYS 7.0. The first scenario used only a dump resistor connected in series to the magnet. The second used both the dump resistor and heaters placed on the outer edge of the outer layer of the magnet. The third scenario used only the heater. No scenario was run in this program to simulate the quench with no protection. A second simulation was run in 2003 by a group of scientists from Fermilab and KEK, a simulation which included a scenario wherein the quench was played out with no protection. This simulation was also performed using ANSYS 7.0. The first simulation concluded that a heater alone does not do much in the way of keeping the magnets from overheating; however, the combination of a dump resistor and the heater provided the best results, with the quenching turn reaching only 174K.

Both of these scenarios are limited in application with regard to today's superconducting magnets because the geometry used to build the magnet models is outdated. This is the goal of this project: to update the geometry and efficiency of the previous simulations to provide an analysis off of which decisions can be made with regard to future superconducting magnet manufacturing.

Finite Element Analysis

The Model

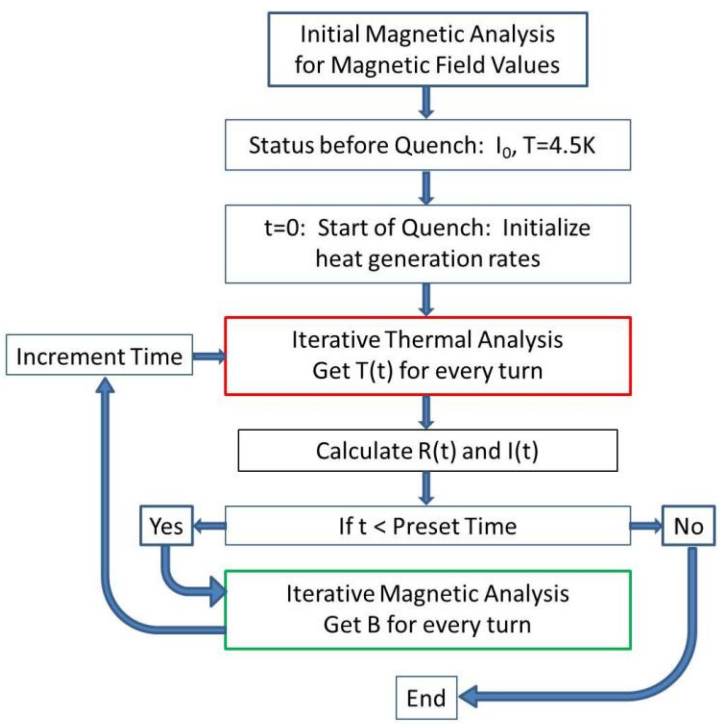
The original model for this analysis was created at CERN, using an internal program called Roxie. The data received at Fermilab consists of individual Cartesian coordinate points provided in sets of eight. When plotted, these points create the 3D structure of the magnet. However, there was one problem: this model treats the insulation surrounding the cable and the cable as one. For the model to be accurate, the cable and the insulation would need to be separated. It is far too complicated to create a viable 3D geometry, so, as per the previous simulation, I created a 2D cross-section and extruded it to create a faux-3D model. From there, I edited the previous code to work with the new geometry. However, due to troubles the computer had with the 3D simulation and time constraints, only a simulation on the 2D cross section was practical. It is of note that the model utilizes symmetry to simplify the analysis and is of only half of one dipole magnet.



On the left, the light blue rectangles are the superconducting cable turns, of which there are fifty-six. The purple wedges are bronze and keep the geometry in position despite the large Lorentz forces at play. The medium blue is insulation. This keeps the turns electrically and thermally isolated from each other. The thin, pink quarter-circle is a layer of helium, which is used to keep the system at 4.5K. The red quarter-circle is the beam tube, around which the magnet is placed. The two red strips embedded in the insulation are heaters, one of the proposed solutions described above.

On the right, the innermost red section not previously defined is the collar. This keeps the two dipole magnets correctly located with respect to each other. This assembly is locked in place by the pink yoke, which is locked in place by the yellow key. Everything is then covered by the red skin. The green mass outside the full assembly is air, which is used to model the heat flow out of the system.

The Analysis

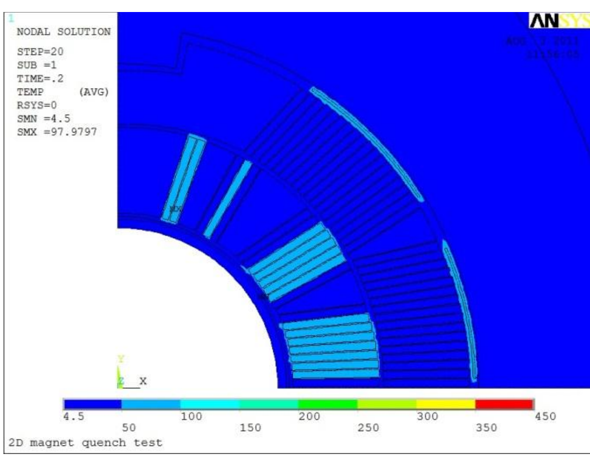


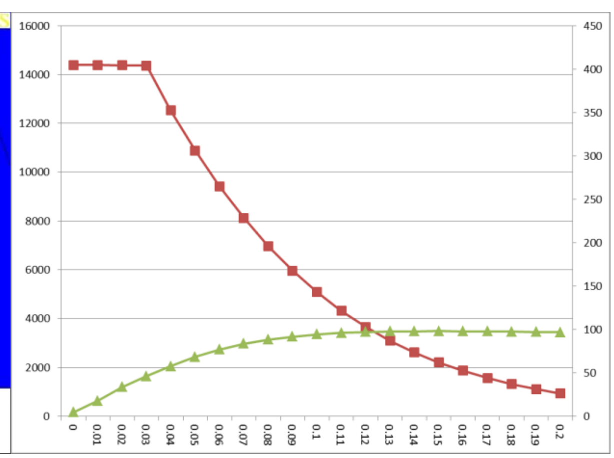
The tricky part of making this analysis is the necessary switching between the thermal and magnetic analyses. It requires exporting a variable and saving and exiting an analysis in progress at every step. For example, during one load step (unit time), the thermal analysis must run to get the new temperature distribution, from which resistivity of the wire, current, and power can be calculated. The current is then written to a file before the thermal analysis is saved and closed. The magnetic analysis then runs, using the exported current value to determine a new magnetic field strength distribution. This magnetic field distribution is then written to a file before the magnetic analysis is closed. The thermal analysis is then opened from the save point and the existing magnetic field values are rewritten using the values obtained from the previous magnetic analysis.

The analysis was run for the following four cases:

1. No Protection (Dump Resistor deactivated; Heater deactivated)
2. Heater Only (Dump Resistor deactivated; Heater operational)
3. Dump Resistor Only (Dump Resistor operational; Heater deactivated)
4. Both Protections (Dump Resistor operational; Heater operational)

For each of these cases, a plot was created of the temperature distribution of the pertinent parts of the geometry. These can be seen in the Appendix. For ease of comparison, all of these plots are colored according to the same temperature scale. Also included in the Appendix are plots of temperature and current vs. time for each of the scenarios. Again, the scales on both vertical axes are the same for all four plots. Two representative plots are shown here.





For reference, the green line represents temperature and the red line represents current. Both of these images are in relation to Case 4 below.

What did the analyses tell us?

Case 1 (No Protection)

This scenario resulted in temperatures in excess of 400K. This is enough to begin to cause structural damage to the magnet. At these temperatures, the differing thermal expansions cause the epoxy to crack, which in turn would allow the Lorentz forces to rip the magnet apart.

Case 2 (Heater Only)

This scenario resulted in a maximum temperature around 272K, approximately the standard freezing point of water. This is a significant improvement over no protection, but still leaves a lot to be desired. At this temperature, the above effects may occur, though it is far less likely.

Case 3 (Dump Resistor Only)

This scenario resulted in a maximum temperature around 104K. This is enough to keep the magnet from becoming damaged; however, if this measure fails, there is no fallback position.

Case 4 (Both Protections)

This scenario resulted in a maximum temperature around 97K. This is not a huge improvement over Case 3; however, this provides each mode of protection an independent back-up, vastly decreasing the odds of a catastrophic failure.

Future of the analysis

At this stage, the analysis is far from complete. In the coming months, others here will continue to refine and improve the framework built this summer. The following is a short list of improvements that need to be made.

1. Material properties for Stainless Steel, Air, and Helium need to be added/updated

2. The geometry needs to be updated for to differentiate between the two kinds of insulation
3. A 2D extrusion and a full 3D geometry need to be developed to fully understand the effects of a quench.
4. A stress analysis needs to be created to simulate the effects of thermal expansion and Lorentz forces.

Conclusion

Quenching is a problem that all those who work with superconducting magnets must face. If left unchecked (or if existing protections fail), the damage can be catastrophic and can result in the destruction of a magnet. Replacing destroyed magnets can cost upwards of hundreds of thousands of dollars. However, with some simple precautions, quenching need not be an issue. The addition of thin heaters around a magnet, in addition to a dump resistor, eliminates almost all worry about a quench.

References

Marscin, Eric, Ryuji Yamada, and Ang Lee. United States. 2D/3D ANSYS Quench Simulation Model. Batavia: Fermilab, 2002. Print.

Marcin, Eric, and Ryuji Yamada. United States. *3D ANSYS Quench Simulation Program with Full Magnet Coil Geometry*. Batavia: Fermilab, 2003. Print.

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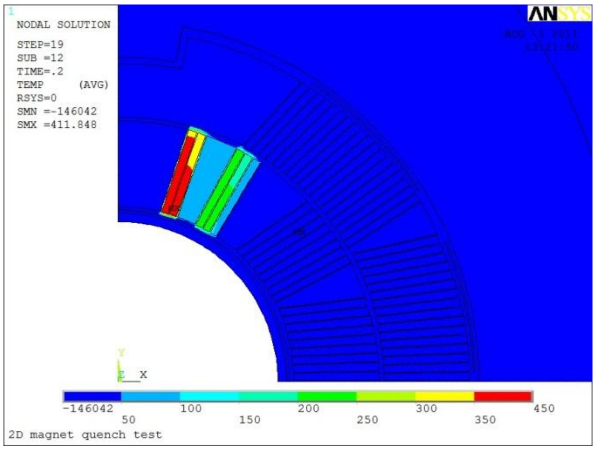
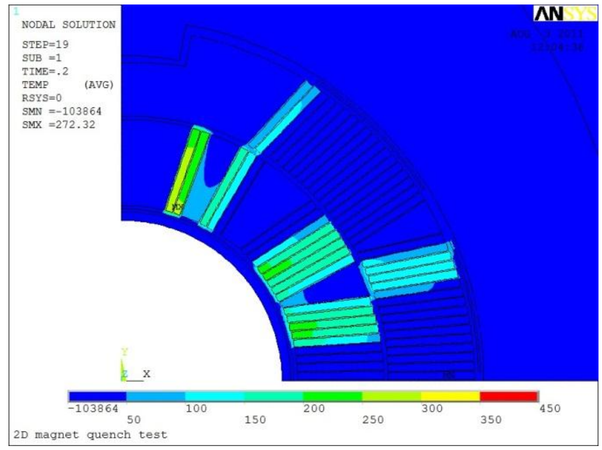
Appendix

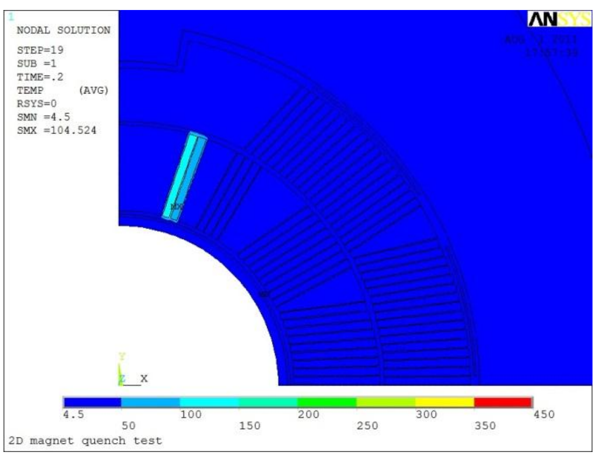
Temperature Distribution Plots



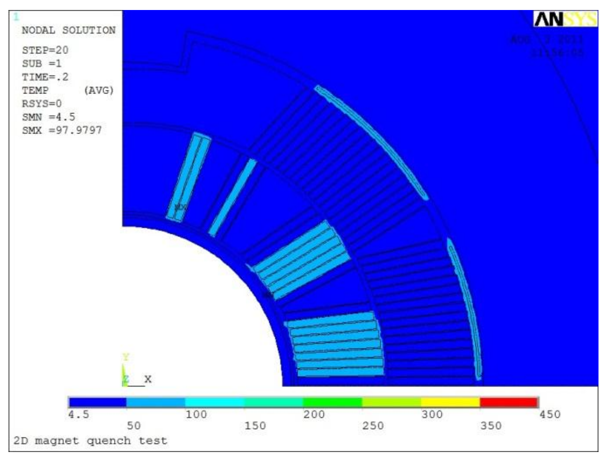
Case 1



Case 2

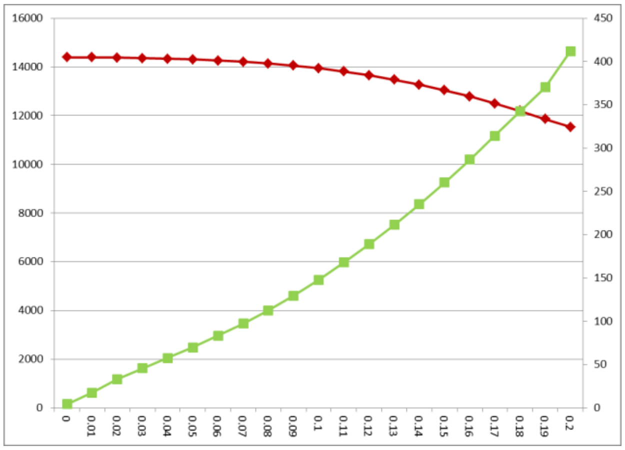


Case 3

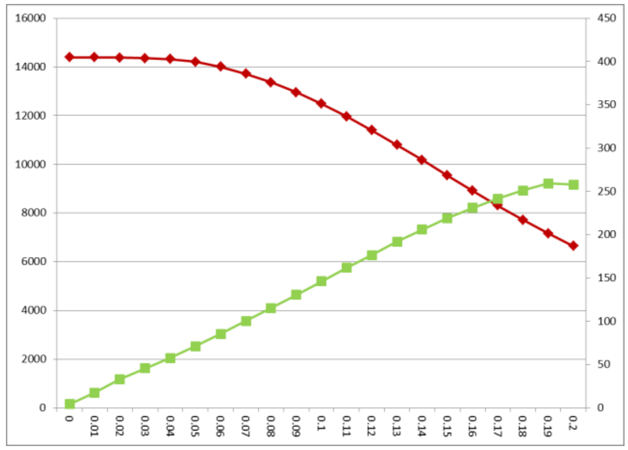


Case 4

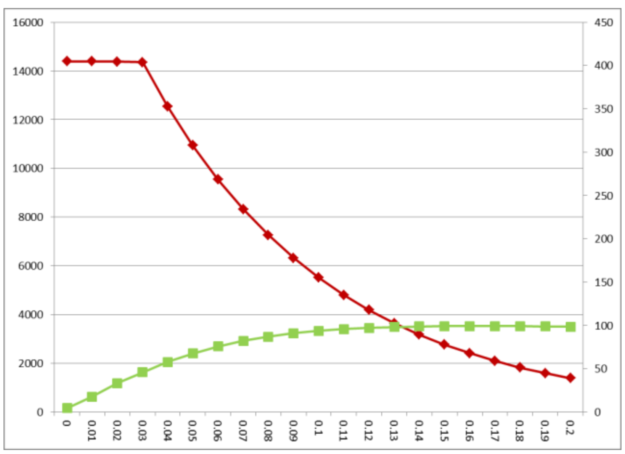
Temperature and Current vs. Time Plots



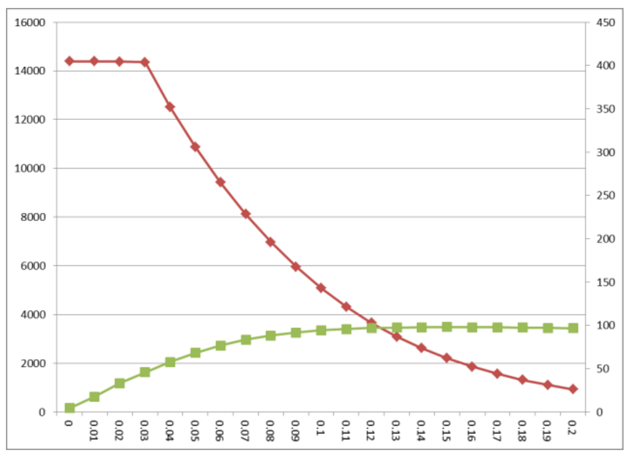
Case 1



Case 2



Case 3



Case 4

Equations

Copper resistivity:

$$\rho_0 = \frac{\rho_{300K}}{RRR} + 0.5\times10^{-10}\times B\,[\Omega\cdot\mathrm{m}]$$

$$\rho_{Cu}(T,B) = \begin{cases} \rho_0 & (T < T_1) \\ (1 - \frac{T - T_1}{T_2 - T_1})\rho_0 + \frac{T - T_1}{T_2 - T_1}\rho_1 & (T_1 \le T < T_2) \\ \rho_1 & (T_2 \le T) \end{cases}$$

Ni_3Sn resistivity:

$\rho_{SC} = 0 \;\; for \;\; T < T_C$

$$\rho_{Nb_3Sn}(T) = \min\left(7.65\times10^{-10}\times T + 2.3\times10^{-7}, 2.6\times10^{-10}\times T + 3.32\times10^{-7}\right)[\Omega\cdot\mathrm{m}]$$

Cable resistivity:

$$\rho_{cable} = \frac{(1+\lambda)\rho_{Cu}\rho_{SC}}{\lambda\rho_{Cu} + \rho_{SC}}$$

Cable resistance:

$$R_c = \rho_{cable}\cdot\frac{l_d}{A_C}$$

Critical current density:

$$j_c(B,T) = j_{c0}\left(1 - \frac{B}{B_{c0}}\times\frac{1}{1 - 0.75\left(\frac{T}{T_{c0}}\right)^2 - 0.25\frac{T}{T_{c0}}}\right) * \left(1 - \frac{T}{T_{c0}}\right)$$

Current:

$$I(t) = I(t-1)\frac{1 - ts(R_D + R_{total})}{L}$$

All of the above parameters are either defined by another equation or in the program.