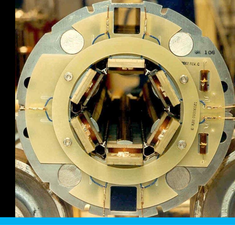
Nonlinear system identification of superconducting magnets of RHIC at BNL



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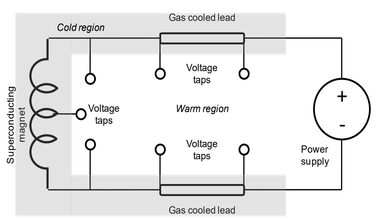
Objective

Remodeling of superconducting magnets for improving quench detection system reliability

Introduction

- Quench detection system[1] (QDS) protects against the magnet quenches thus saving RHIC from dangerous leak of 70MJ of magnet energy
- QDS detects quenches by comparing magnet output to a electrical behavioral model of SC magnet
- Model is manually calibrated that introduces inaccuracy, hence false failures
- Aim is automated generation of accurate magnet model to improve reliability and availability

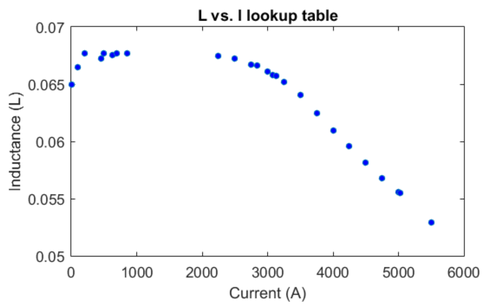
Original Magnet Model



Voltage Tap Circuit

$$V_c = L\frac{dI}{dt} + RI$$

- V_c is the calculated voltage, L is the SC magnet inductance, R is the lead resistance, I is the magnet current
- The observed voltage V_o is compared to V_c . Deviation of 25mV is triggered as a quench
- L is highly nonlinear due to saturation and hysteresis.
- L decreases nonlinearly with increasing current, and this variation of L vs. I changes with change in input current waveform.

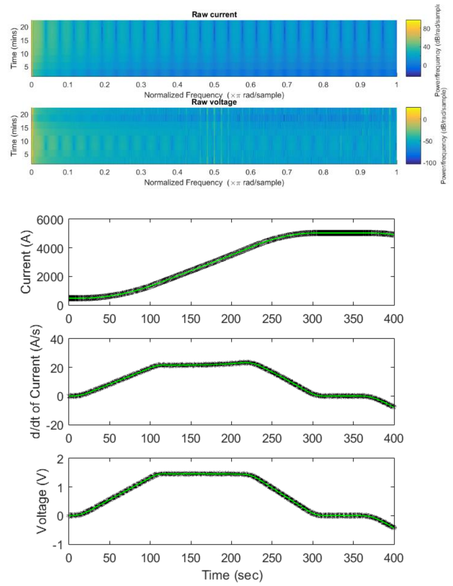


Manually calibrated *L vs I* table

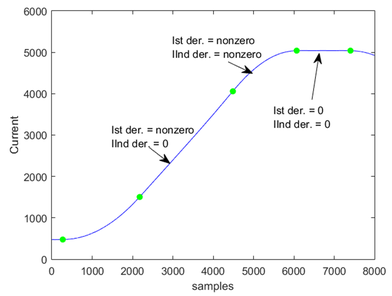
System Identification

Remodeling

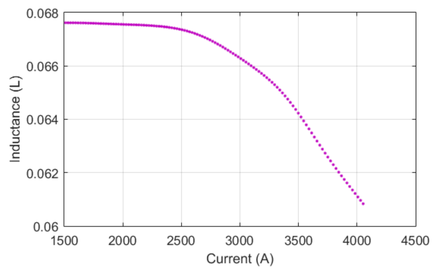
Statistical data analysis[2] of RHIC dipole magnets' current and voltage data[3] is done. The 1st derivative of current is explanatory variable and the calculated voltage is response variable



The noisy data is cleaned by analyzing the frequency spectrum and subsequently applying filtering



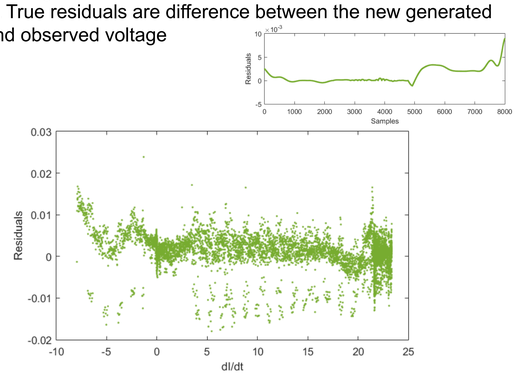
Segmentation of current data for finfinding regions with nonzero first derivative of current



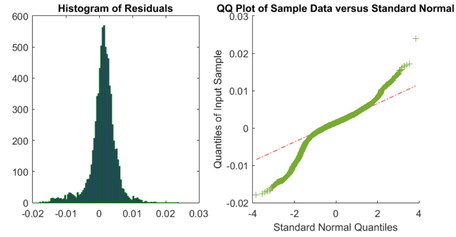
Piecewise regression for finding nonlinear variation of L with I. L is assumed constant for the regression segment

Residual Diagnostics

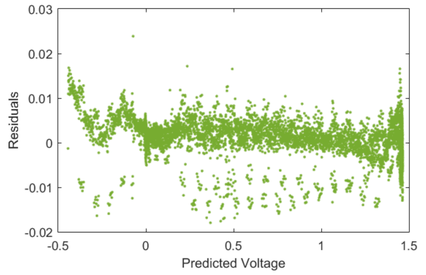
Residual diagnostics used to establish the validity of the regression model[4]. True residuals are difference between the new generated table and observed voltage



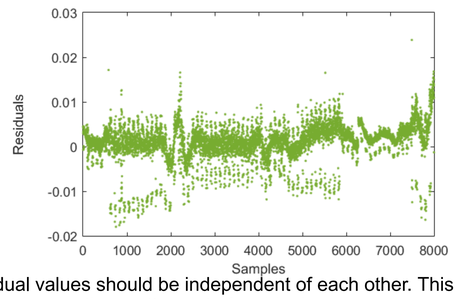
The explanatory variable should be linearly related to the response variable. This is analyzed by plotting residuals vs *dI/dt*



Residuals should have nearly normal distribution. This is checked by the residuals' histogram and quantile-quantile plot



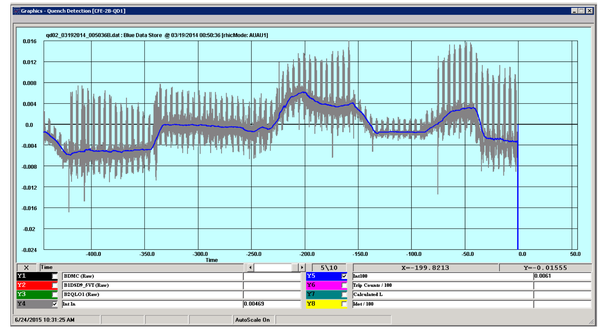
Residuals should have constant variability. This is analyzed by plotting the residuals against the response variable

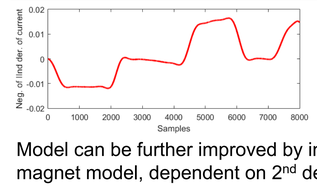


Residual values should be independent of each other. This is can be checked by the scatter plot of residuals

Discussion

- Residual analysis validates almost good fit
- Field test shows a maximum difference of 6mV i.e. << 25mV





$$V_c = L\frac{dI}{dt} + X\frac{d^2I}{dt^2}$$

Model can be further improved by including extra term in the magnet model, dependent on 2nd derivative of current

Conclusion

- Statistical analysis clearly depicts the L variation under saturation
- Automatic generation of L tables
- Saves valuable time when RHIC is running at 4K temperature
- Analytical model for saturation and hysteresis developed[5]
- Will facilitate the forecasting of inductance values.

Acknowledgement

We would like to thank D. Bruno for his constant support, help with testing the inductance tables and providing the magnet data. We also thank G. Ganetis for his guidance in explaining RHIC magnet characteristics.

References

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2. MATLAB® Release 2015a, The MathWorks Inc., Natick, MA, 2015
3. *Relativistic Heavy Ion Collider configuration manual*, Accelerator Division, Collider Accelerator Department, Brookhaven National Laboratory, NY, 2006
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5. P. Chitnis, K.A. Brown, "Analytical modeling of inductance for saturation and hysteresis of superconducting magnets", submitted for journal publication

Footnotes

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