A Pulse Forming Network for Quench Protection of Superconducting Magnets

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***Abstract*—The design and simulation of a Rayleigh line pulse forming network (PFN) is presented for active quench protection of superconducting magnets. In this context, the PFN is a ladder network of capacitors and inductors designed to deliver energy to quench heaters over a significantly longer period than a single capacitor or capacitor bank. The PFN is advantageous for protection of coils constructed with REBCO tape, which have a slow normal zone propagation speed and a high critical temperature. PFN's also have an inherent safety advantage over battery bank energy sources. The rise time of a typical Rayleigh network for this purpose can be on the order of 10-100 ms which is unacceptably slow compared to the timescale for thermal runaway during the onset of a quench. Thus, as a modification to the Rayleigh Line PFN, an extra stage consisting of a discharging capacitor with no accompanying inductor is added to achieve a nearly instant rise time. The advantages of this strategy are discussed, and the flexibility of the system is investigated when varying resistive loads, charge voltages, and component design.**

***Index Terms*—Active quench protection, high temperature superconductor, HTS, REBCO, superconducting magnets, quench heater, quench protection, pulse forming network, Rayleigh line network, REBCO.**

I. Introduction

PROTECTING superconducting (SC) magnets against quench is a significant challenge when designing SC magnet systems. The onset of thermal runaway typically occurs on a timescale of 0.1 – 10 s (depending on the current density and the amount of conductive stabilizer) and therefore quench must be promptly detected and protected against to prevent irreversible damage. Protecting coils wound with high temperature superconductors (HTS) is particularly challenging thanks to their large temperature margins and slow normal zone propagation speeds.

Quench protection consists of four steps that may intersect with each other: (1) quench detection; (2) protection activation; (3) normal zone propagation (in case of internal protection); and (4) magnet ramp down; this work discusses steps (2) and (3). Quench protection systems can broadly be classified into 2 categories: active and passive. Active quench protection systems actively deposit energy from an external source into the coils to drive volumetric quench (quench heaters [1], CLIQ [2], FLIQ [3]) while passive quench protection systems either remove stored magnetic energy (dump resistors [4]) or distribute it across the coils (quench backs [5]) via passive electrical devices. The primary objective of both strategies is to minimize hotspot temperatures by preventing highly localized deposition of stored magnetic energy into the SC coils.

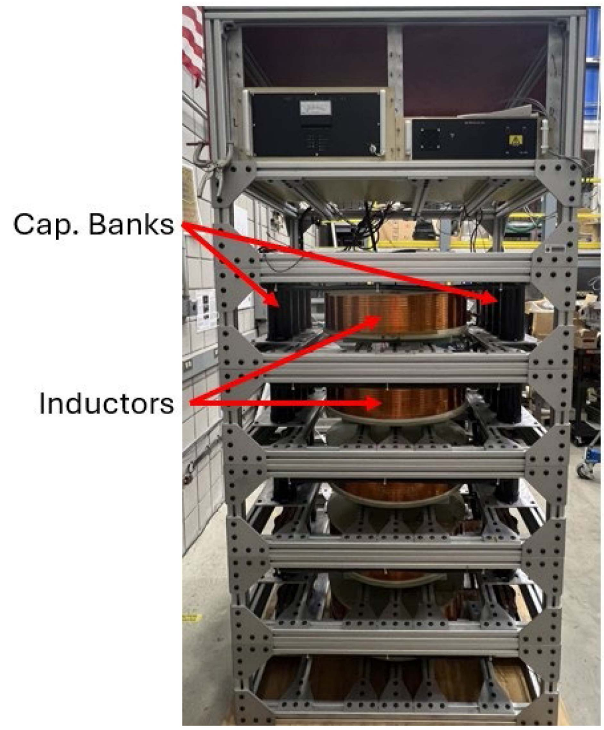

Fig. 1. The Rayleigh line PFN used as the energy source for the quench heaters in the series of test coils fabricated and tested at the NHMFL.

The National High Magnetic Field Laboratory (NHMFL) has wound and tested a series of test coils as part of the 40 T magnet development program [6], [7]. This work will focus on the pulse forming network (PFN), shown in Fig. 1, which has served as the energy source for the quench heaters in these test coils. In Sec. II typical energy sources for active quench protection systems will be discussed. Sec. III will focus on the Rayleigh line PFN architecture as well as general design strategies and

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considerations. Finally, Sec. IV will give specifications for the test coil series PFN and will compare its simulation and performance under varying conditions and configurations.

II. Energy Sources

The ideal energy source for an active quench protection scheme varies based on the requirements of the coils to be protected. These requirements include the stored/delivered energy, flatness of the pulse, pulse duration, rise time, switching components, and electromagnetic forces. Typical choices for energy sources are banks of either capacitors or batteries.

Capacitor banks are often preferred thanks to their simplicity and low level of volatility. They only need to be charged when in use and discharge of the system only requires closing one switch (i.e., once the switch is closed the capacitors can simply discharge all their stored energy). They also have a nearly instant rise time. However, they come with the drawback that the initial voltage/current can be very large, and the pulse has an exponential decay profile. Thus, the power generated by the heaters is frontloaded and may risk localized overheating if the rate of thermal conduction from the heaters into the coils is too slow.

Battery banks reliably deliver a square voltage profile to the load thereby reducing the risk of localized overheating. On the other hand, battery banks must always stay charged (prolonged storage in a discharged state causes degradation) and this can be potentially volatile. For the same reason, they can only supply a small fraction of their total stored energy. Because of this, battery banks require two switching actions: on *and* off. Reducing the number of switching actions is favorable as it reduces the possibility for component malfunction.

A less common, but in some cases favorable, option is a pulse forming network (PFN). A PFN is a ladder network of capacitors and inductors designed to store energy and deliver a roughly square pulse of current/voltage to a load over a given (relatively short) period. Since energy in a PFN is stored by capacitors, it shares the advantages that it only needs to be charged when in use and, once switched on, it is allowed to completely discharge. Yet, the PFN is not without drawbacks. It has a relatively slow rise time ($\sim$10 – 100 ms) and the addition of inductors increases system size and cost.

III. Rayleigh Line Pulse Forming Networks

The PFN shown in Fig. 1 uses a Rayleigh line architecture which is a network architecture where all inductors and capacitors (or capacitor banks) have the same inductance and capacitance, respectively, as given by (1). The circuit diagram for a general Rayleigh Line PFN is shown in Fig. 2. In this case, aluminum electrolytic capacitors are used since they are good for high energy applications. These capacitors are not bipolar and thus protection diodes are needed to prevent backward charging. Protection diodes are not a general feature of Rayleigh line PFNs but will be used throughout this work. Eq. (1) gives the ideal circuit parameters when ignoring the series resistance of the inductors and capacitors. Thus, the "Ideal" and "Real" cases, specified in Table I, are both fictional cases (which exactly

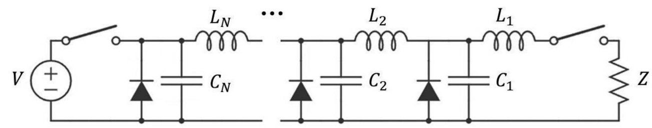

Fig. 2. A generic Rayleigh line PFN with diodes added for capacitor protection. Here $\boldsymbol{L_i = L}$ and $\boldsymbol{C_i = C}$ for $\boldsymbol{i} = 1, \ldots, \boldsymbol{N}$.

TABLE I
Parameters for Ideal, Real, and NHMFL PFN

Parameter	Symbol	Ideal	Real	NHMFL	Unit
Stored Energy	E_{tot}	100*	100*	55 (Max)	kJ
Load Energy	E_z	100	62	Varies	kJ
Pulse Duration	t	0.5*	0.5*	~0.5*	s
Charge Voltage	V	500	500	500 (Max)	V
# Cells	N	5*	5*	5*	
Load Impedance	Z	0.31	0.31	Varies	Ω
Capacitance/bank	C	160	160	88 (8x 11 mF)	mF
Inductance	L	15.6	15.6	30.6	mH
Inductor Resistance	R_L	0	75	105	mΩ
Capacitor Bank Resistance	R_C	0	5	6	mΩ
Other Resistance	R_O	0	0	Varies	mΩ
Efficiency	η	100%	62%	~60%	

* = specified

obey Eq. (1)) to demonstrate the performance of the PFN when component resistance is ignored ("Ideal") or included ("Real"). The parameters for the NHMFL PFN are also shown in Table I and its performance will be presented in Section IV. Note that the NHMFL PFN does not obey (1) since it was built to serve a variety of load resistances and charge voltages.

A. Ideal Rayleigh Line PFN

For the ideal Rayleigh line PFN, the capacitance, C, and inductance, L, can be calculated via [8]:

$$C = \frac{t}{2NZ} \quad L = \frac{Zt}{2N} \tag{1}$$

Where t is the pulse duration, N is the number of cells, and Z is the load impedance. For a given charge voltage, V, half of the voltage is dropped across the network, and the other half is applied across the load. These simple formulas assume the resistance of the inductors and capacitors (R_L and R_C) are negligible ($R_L \ll Z$and $R_C \ll Z$) and there is no mutual inductance.

In conventional applications, Z and t are specified and then N is chosen to yield a reasonable L, C,and PFN size. For this case, the ideal capacitance and inductance are calculated via Eq. (1). However, for protection of SC magnets it is typically the energy delivered to the load, E_Z, and pulse duration, t, that are typically specified (as determined via quench simulations).

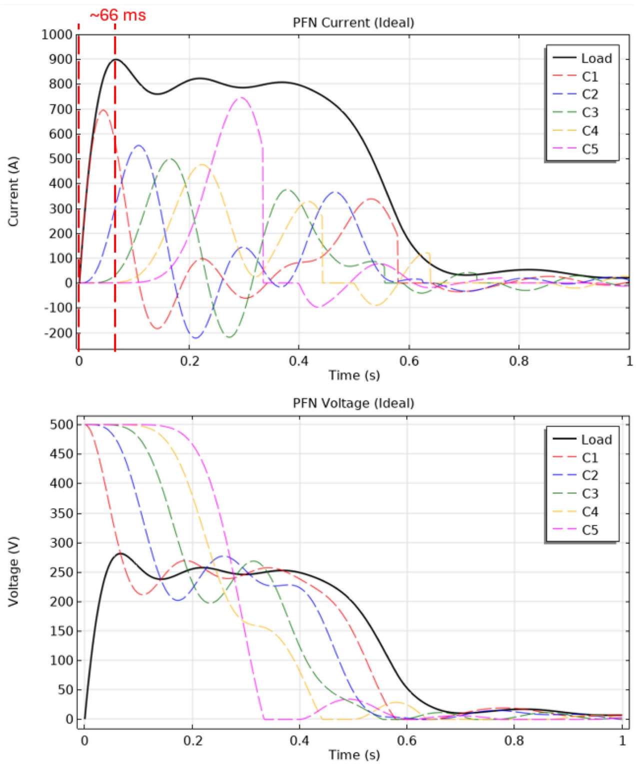

Fig. 3. Simulated current (top) and voltage (bottom) pulse across the load (black, solid) for the ideal PFN described in Table I. Also shown are the currents and voltages for each of the capacitors during discharge (colored, dashed).

Thus, one must consider the total stored energy of the system:

$$E_{tot} = \frac{1}{2} NCV^2 \tag{2}$$

These requirements lead to a hardware specification for the capacitors or banks of capacitors and a choice for N such that the PFN can supply the specified energy. Once t, C, and N have been specified, the ideal Z and L can be calculated. The heater network and inductors should be designed to match the ideal impedance and inductance. The parameters for an example case of the ideal PFN are in Table I and the current and voltage pulse behavior are shown in Fig. 3. Also shown in Fig. 3 is the series of capacitors discharging, lagged by the inductors downstream of them.

B. Real Rayleigh Line PFN

Unlike the ideal case, the inductors and capacitors in a real PFN have non-zero resistance which will change the pulse behavior and reduce the efficiency of the PFN. Additionally, any mutual inductance must also be considered. Table I gives the specifications for an ideal and a real Rayleigh line PFN. In this case, the inductors were designed using a Brooks coil geometry [9] which maximizes the inductance for a given length of wire. The inductors have an inner diameter of 305 mm and are wound with rectangular Cu wire with cross section 10 mm x 6 mm with a total of 15 turns (axial) and 19 layers (radial).

Fig. 4 shows the difference in pulse shape for the ideal and real PFN. Additionally, Table I gives the efficiency, η, of the PFN defined as:

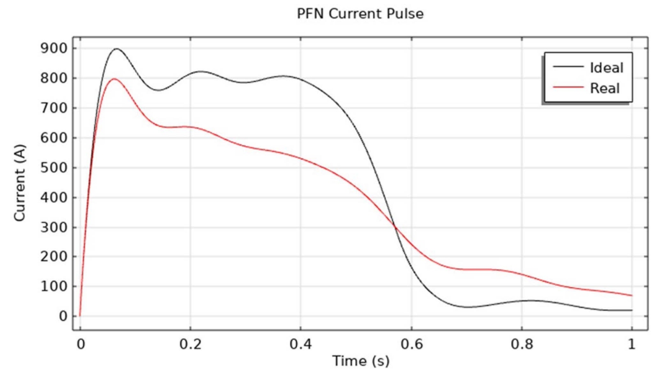

Fig. 4. Comparison of the current pulse generated by the fictitious "Ideal" (black) and "Real" (red) PFN example cases presented in Table I. The pulse amplitude and decay are significantly affected by including the inductor resistance.

$$\eta = \frac{E_z}{E_{tot}} \tag{3}$$

Since the capacitors in a bank are operated in parallel, the net resistance of the bank is small compared to the load. On the contrary, the inductors have a resistance comparable to that of the load thus they consume a significant amount of the available energy and reduce efficiency. Therefore, it is desirable to minimize the resistance of the inductors (while still achieving the target inductance) to maximize the efficiency of the system.

IV. Test Coil Series PFN

A series of REBCO test coils (TC) have been fabricated and tested at the NHMFL as part of the 40 T magnet research and development program (TC1, TC2, TC2b, TC2c, Large Scale Coil [LSC]). The LSC, the largest of these coils, contains ~4 km of 4 mm width REBCO conductor, has 260 mm inner diameter, and stores ~200 kJ of energy at full operating current. Each of these coils used a quench heater based active protection system with the PFN energy source shown in Fig. 1. The specifications for the NHMFL PFN are given in Table I

In this application, the PFN sits at room temperature outside of the cold space and is connected to the heater bus via a pair of ~50 ft long AWG 4/0 copper cables which contribute ~5 mΩ resistance. The leads have a large cross-sectional area, and their resistance is small compared to that of the heater network. Thus, only a small fraction of the total energy is dissipated in the leads and their temperature rise is < 1 K.

This PFN was simulated and tested under a variety of charge voltages and operating conditions demonstrating predictable and repeatable performance. For these simulations, the resistance of the capacitors and inductors was included as well as the mutual inductance between inductors (as determined by the geometry of the PFN assembly).

A. PFN Performance

Fig. 5(a) compares the simulation and performance of the PFN using a dump resistor at room temperature with $R = 0.44\ \Omega$ as the load. The PFN was tested at a series of charge voltages and

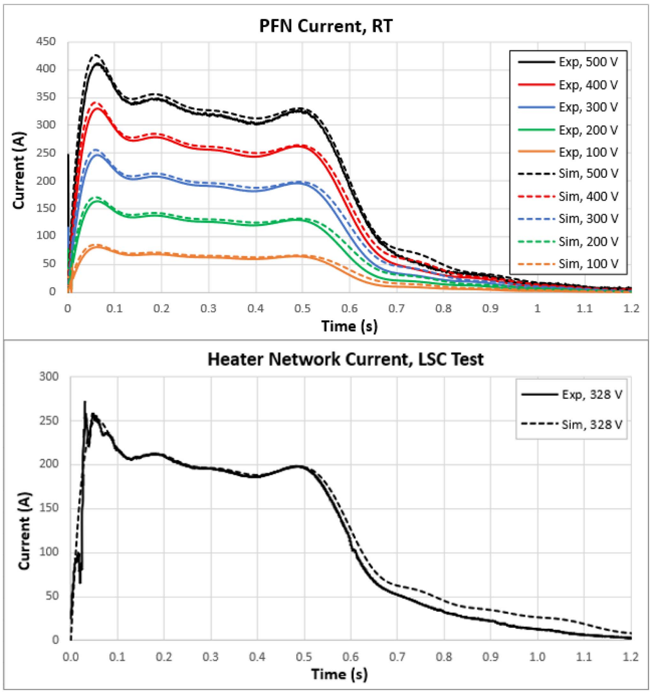

Fig. 5. Simulation (dashed) and experimental (solid) performance of the NHMFL PFN. (Top) The PFN current pulse was measured at a series of charge voltages using a $\boldsymbol{R} = 0.44\ \boldsymbol{\Omega}$ dump resistor (room temperature) as the load. (Bottom) Current pulse from the PFN when used for quench protection in the Large Scale Coil.

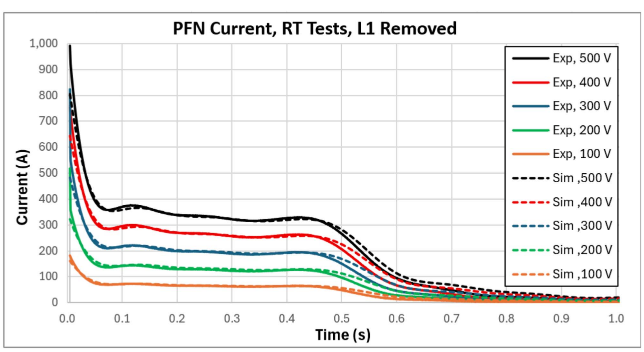

Fig. 6. Experimental (solid) and simulated (dashed) current profiles for the NHMFL PFN with the L1 inductor removed.

the simulation closely matches the results of the test. Fig. 5(b) shows the simulation and performance of the PFN for actual quench protection of the Large Scale Coil (LSC). During this experiment the heater coils were nested inside the LSC which was in a liquid helium bath. The heater coils had $R = 0.54\ \Omega$ at $T = 4.2$ K. In both cases the PFN had a rise time of ∼60 ms which is undesirable for quench protection.

B. Modified PFN Performance

To reduce the rise time, the PFN was later modified by removing the L1 inductor from the circuit. By removing the L1 inductor, the C1 capacitor discharges like a simple RC circuit and the rise time of the PFN is nearly instant. Fig. 6 shows the performance of the PFN without the L1 inductor at a series of charge voltages using a dump resistor at room temperature.

Removing the L1 inductor leads to a large initial voltage/current spike and leads to a non-square pulse. However, this is acceptable for quench protection as there is no necessity for a square pulse (capacitor banks are often used in quench protection systems). However, the L2-L5 inductors still serve a purpose: they reduce the instantaneous power delivered to the heaters. It takes time for the heat generated by the heaters to percolate through layers of electrical insulation and into the REBCO pancakes. Thus, if the instantaneous power is too large there is a risk of locally overheating the heaters. This risk is mitigated by distributing heat generation over a longer period. This modified PFN will continue to be used in future coils.

C. Limitations to Scaling Up

Coils requiring larger amounts of energy will require more total capacitors. Thus, either the capacitance per bank (i.e., number of parallel capacitors per bank) or the number of cells will need to increase (or both). In terms of cost, it is preferable to increase the number of capacitors per bank. Increasing the number of cells, N, increases the PFN size and cost. Keeping N fixed, notice that, from (1), the ideal inductance, $L \propto \frac{1}{C}$. Thus, increasing the capacitance lowers the required inductance. However, there are limitations to the efficiency of the PFN. Approximating the inductor as an ideal solenoid:

$$L \approx \frac{\mu_0 n^2 \left(\pi r^2\right)}{l} \propto n^2,\ R_L \approx \frac{\rho n \left(2\pi r\right)}{A} \propto n\ \rightarrow R_L \propto \sqrt{L}$$

Where n is the total number or turns, A is the conductor cross section, l is the inductor length, and r is the inductor radius. Now, noting that $Z \propto L$ and $E_{tot} \propto \frac{1}{L}$ one can conclude that:

$$\frac{R_L}{Z} \propto \frac{1}{\sqrt{L}} \propto \sqrt{E_{tot}} \tag{4}$$

This implies that as the stored energy increases, so does the ratio of the inductor resistance to the load resistance. As this ratio becomes larger the efficiency of the PFN decreases since proportionally more energy will be lost to the inductors. Thus, efficiency decreases for increasing stored energy.

V. Conclusion

A Rayleigh line PFN has been designed, tested, and used as the energy source for quench protection in several REBCO wound SC coils. Its experimental performance is accurately predicted by simulation (in several different operational modes) signifying that design performance is reasonably attainable for future cases.

When scaling to larger energy applications, for example in the 40 T project, the PFN becomes physically larger and increasingly less efficient. However, these limitations are not disqualifying and a PFN is still a candidate energy source for the 40 T protection system.

The NHMFL PFN has demonstrated reliability, simplicity in operation, and flexibility and will continue to be used for quench protection of future test coils. In all, PFNs are a viable option for the energy source in quench protection systems with several advantages compared to other typical energy sources.

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