A 300 kA Pulsed Power Supply for LBNF

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Abstract— The Long Baseline Neutrino Facility (LBNF) will produce the world's most intense neutrino beam. Three series connected magnetic horns will require 5kV, 300kA, 800µs pulses at a rate of 1.4 pps to focus the beam. Fermilab has designed and built pulsed high current supplies for horns in the past. Pulsed currents of 205 kA for Neutrinos at Main Injector (NuMI / NOvA), focusing a 120 GeV beam, and 170 kA for Booster Neutrino Beam (BNB / MiniBooNE) for focusing an 8 GeV beam have been operational for about 18 years. While the magnetic horns are expected to be replaced, the LBNF horn power supply is expected to last the lifetime of the project, 30 years. A resonant, half sine wave pulser was used for NuMI and BNB and has many practical advantages. The system has impedance limited fault currents by design, albeit large ones. Many fault modes of the system have been calculated. Several circuit changes were incorporated so that a single fault can be tolerated. The supply must also be reversible to enable both neutrinos and antineutrinos to be produced.

Keywords—magnetic horn; pulsed power; thyristor; stripline

I. INTRODUCTION

High current pulsed supplies have been built for many experiments, most recently at J-PARC for the K2K & T2K experiments [1] and at Fermilab for NuMI [2] and BNB beamlines which have also supported multiple experiments. T2K has 3 horns focusing 4.5 µs beam pulse with 250 kA, ~ 2.4 ms pulse width, 0.5 pps and < 1 kV which is quite similar to NuMI with 2 horns focusing an 11 µs beam pulse at 200 kA, 2.6 ms pulse width, 0.7 pps and < 1 kV. The BNB system has a single horn focusing a 1.6 µs beam pulse at 170 kA, 140 µs pulse width, 5 pps and < 6 kV. These have provided many lessons learned. They all use thyristor switches, capacitors for stored energy with a resonant L-R-C discharge and a transmission line or lines to deliver the high current to the horns. The horns are in a very high radiation environment. The transmission lines are significant fraction of the load inductance and resistance and lengths on the order of 30 m are required to keep the power supply and electronics in a lower radiation environment.

One of the first design choices is driven by the maximum voltage applied to the transmission line and magnetic horn. This limit determines if a pulse transformer is preferred and if horns can be put in series. This transformer needs to function in the relatively high radiation area near the horns to make the most effective use of the transmission lines. The choice to drive multiple horns in series is also based on allowable voltage. The second choice is the segmentation of the power supply into multiple units. This is driven by semiconductor limits on voltage and current and by reliability. The last choice is whether to recover the energy left in the capacitor after the pulse discharge. Recovering energy can reduce the size of the charging supply if losses in the transmission lines and horns are low.

The first choice for LBNF was to have a single supply drive all the horns in series without a transformer. Neither NuMI nor BNB have pulse transformers. The BNB horn and transmission line operates at up to 6 kV [3] in air and the horns could be designed to operate at up to 5 kV. The inside of the LBNF horns will operate in an argon environment while the stripline will be in air or nitrogen. The use of a single supply is a weak direct cost benefit. The stored energy is the same no matter how many supplies are used. The semiconductor cost is likely lower with a single supply, but the main power supply advantage is the reduced assembly and controls cost of a single supply. The second choice for LBNF was to have many parallel pulsers or cells. This was done in NuMI (12 cells) and BNB (16 cells). The third choice for LBNF is to use energy recovery. Detailed simulations show only 30% of the initial stored energy is lost per pulse. NuMI and T2K do not use energy recovery because the lost energy is a large fraction of the initial stored energy while BNB does use energy recovery. The final choice is to use the odd numbered / balanced stripline for our transmission line [3,4]. This construction balances forces and reduces losses and inductance over an even numbered stripline.

Another consideration for LBNF is the long-term development and testing of horns. A lesson learned from the experience with NuMI and BNB is that horns require ongoing improvements. This could be based on a failure mechanism that was unforeseen or on a desire to increase performance. LBNF expects an increase in beam power as part of the program and anticipates horn improvements as well. Testing of new horns at full current, operating pulse length and repetition rate is needed to verify performance and find early failures. Various scenarios were considered, and the decision was made to build two complete horn power supplies, one dedicated to testing and one for operation. The design of the horn supply also takes this into consideration using the same detailed design for both supplies and changing only the capacitance value and charging voltage.

The rationale for these major design choices for a reliable, high current magnetic horn supply are described next. Then the failure modes and design choices that mitigate the effect of failures, maintain reliability and maintainability are presented. Finally, early prototype testing results are shown.

II. DESIGN AND IMPLEMENTATION CHOICES

There are different performance limits for all the components in a pulsed supply: capacitors, inductors, semiconductor and connections. Practical considerations determined the width of the stripline to the load and that determined losses. Having an extremely uniform magnetic field in the horn drove a requirement for currents matched better than +/-1% in each of the four sets of stripline feeds. The number of cells in the pulser is required to be divisible by four to feed the
nine layer stripline layers (5 supply and 4 return layers) equally. The balanced horn current and the balanced stripline current meant the number of cells also had to be divisible by eight so the two outer layers could be driven with half of the current of the inner seven layers. This limited our choices to 8, 16 or 32 cells. One of our internal design guides for long lifetime is to limit the thermal cycling of semiconductors during each pulse. Experience with long life-cycle projects is to not use special purpose semiconductors that result in replacement issues in the future. The capacitor bank value and voltage depend on meeting the peak current and pulse length given a load inductance and resistance. Field simulations of the stripline and calculations of the horn determined a total inductance of 3.14 µH and resistance of 0.95 mOhms. This then determined the total capacitance of 19 mF and the 300 kA peak current determines the nominal charge voltage of 4.3 kV. We determined that for our operating parameters, design constraints, and component constraints the choice was 32 parallel pulsers, or cells, using standard inverter grade thyristors and a maximum operating voltage of 4.7 kV.

The schematic of a single cell is shown in Fig. 1.

The mechanical layout and connection scheme was the next design choice. This impacts electrical performance, electromagnetic coupling, thermal performance and serviceability. The components were designed to not require water cooling for heat removal. Arranging the highest power dissipating elements near the top will draw cooler air up and over other components. The highest losses are in the recovery choke so it is at the top. The saturating choke is heavy, low loss and so is placed at the bottom. Circuit topology then determines that the switch be above the saturating choke. The recovery diode is then below the recovery choke. The spacing between magnetic components is another concern because of external magnetic fields. The diode and switch are mounted a coil length away to reduce magnetic field coupling. The recovery choke is air core and there are significant magnetic fields outside the saturating choke as well. The cells are arranged in pairs in a single cabinet, with coil winding orientation alternating to reduce magnetic fields away from choke. The switch stripline comes up, then between the recovery chokes and finally out the front to the horn stripline

One of the requirements is to easily reverse the polarity of the supply. The first horn must always remain at the lowest voltage because the target is grounded and is inserted into the first horn. This means reversing the polarity of all the semiconductors. The thyristor and diode assemblies are constructed for easy reversal. A custom Litz constructed wire with 80 strands of AWG #20, high temperature magnet wire is used. The larger strand size should reduce peak stress in the copper and avoid metal fatigue failure due to cyclic stress. This is an equivalent wire size of AWG#2, which meets NEC code for this rms current, will fit standard 3/0 lugs after it has been stripped and retains more flexibility for changing connections. These flexible leads are shown by a wavy line in Fig. 1.

The connection from the capacitor bank to the switch is routed through the saturating choke using a continuous length of the same Litz wire mentioned above. The switch stripline carries the pulse current from the switch output to the horn stripline and back to the capacitor bank, also a stripline, through the current transformer. A wire is also routed along the stripline to connect the recovery choke to the capacitor bank. The current per cell is 280 A rms in the capacitor stripline and 230 A rms in the saturable reactor and switch. These striplines and wire routing reduce inductance and stray magnetic field that can couple to other parts of the circuit.

III. DESIGN AND FAULT TOLERANCE

Generally, a single fault should be detectable and determinable, recoverable and not cause irreparable damage to reduce down-time. This drives circuit design and topology. Short circuit at cell output, short circuit at load, short circuit in a capacitor, single cell switch no-fire and self-fire, and thyristor or diode short are just some of the fault conditions we examined.

A. Capacitor Fault

The energy in a single bank is limited to less than 10 kJ since series resistors or fuses cannot be used in the pulsed current path. Most metal-can capacitors will contain this much energy without rupturing. Experience with some self-healing capacitor technologies is that very low impedance busing can result in...
internal faults which do not clear. Therefore, a shorted capacitor must be able to absorb the energy from its cell neighbors.

B. Cell Output Fault and Saturating Choke

If the output of a cell shorts, the inductance between the short and the cell cap bank is estimated to be 7 µH: 4 µH from the saturated choke and 3 µH from stripline and connection inductances. This will lead to a short circuit current of 30 kA.

This short circuit will also cause a high turn off dI/dt as the thyristor current reverses. This would normally cause a high reverse current beyond which the snubber network is designed to tolerate. However the saturating choke comes out of saturation before the current reverses, and this reduces the negative dI/dt and the reverse recovery current to a manageable level. Short circuit testing during prototype testing will confirm the turn off dI/dt and Qrr and may reduce the saturating choke volt second rating.

C. Switch

The choice of 32 cells was based on a detailed thermal and electrical model of the SCR. The forward voltage vs. current was fit using (1) with \( A = 1.23 \), \( B = -0.0588 \), \( C = 0.000129 \) and \( D = 0.0192 \) as given by the datasheet for the device chosen, R1275NC21J, with \( V \) in Volts and \( I \) in Amps.

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V_{fwd} = A + B \ln(I) + CI + D I^\frac{1}{2}
\]

The energy vs. time into the device was simulated with a detailed thermal model of the device using Spice and common techniques [5]. With a 10 kApeak, 800 µs half sine pulse, the energy per pulse in the device is 17 J and the peak junction temperature change is 11 °C. If only 16 cells were used a 20 kApeak current per device is required and the energy per pulse would then be 51 J with a peak temperature change of 30 °C. Our design goal for long life (10² pulses) and thermal cycling at about 1 pps is 10 °C. This is likely conservative, but data is sparse for long life [6] and depends upon manufacturer techniques and failure mechanisms.

A simplified estimate of average power using the forward voltage drop at full current and the average current gave 21 W while the detailed simulation gives 24 W for a 0.7s period providing a check. This is not much power per device. Both NuMI and BNB use water cooling for their semiconductors. This has resulted in issues with non-conductive cooling lines plating up, especially for the higher voltage of BNB. We have changed all the cooling lines several times at BNB. The design for passive air cooling of the LBNF switch was completed while maintaining partial discharge and thermal requirements.

The SCR switch and diode assemblies required that the polarity of the devices could be switched quickly while the devices were mounted for low inductance. These requirements meant passive cooling via a heat sink was only possible on one side of the each of the four devices. The mounting assembly was keyed such that it would fit in either of the two switch position in a cabinet. The design needed to provide symmetry without polarity being accidentally swapped by a technician but also allowed easy swapping of the power leads to reverse the polarity of the assembly. The assembly design also needed to be clamped with 22 kN of force and this was accomplished using an off the shelf assembly. The final design achieved minimal inductance as well as ensuring the both the high voltage and thermal cooling requirement were met. The schematic of a single thyristor of four in a single cell switch is shown in Fig. 2.

A single switch assembly not firing while the other switches fire would cause the voltage across that switch to exceed the switch rating because it's capacitor would not discharge. The charge and balance resistors, Fig. 1, connect multiple cells together redundantly and the value of 1 Ohm is enough to return the thyristor operating margin to 66%.

D. Energy Recovery Diode and Choke

The energy recovery diode had a similar clamping force and voltage, less power dissipation, a simple RC snubber of 0.5 µF and 40 Ohms and the same voltage balancing resistor. Most of the mechanical design was carried over resulting in a similar but simpler assembly.

The energy recovery choke requirements were based on what we had success with for BNB. The main change was a reduction in losses to reduce heat load in the cabinet. It is still the highest heat dissipating elements in each cell.

E. Monitors

We monitor the voltage balance among the four switches and four diodes. We detect if one shorts during operation and stop pulsing. There is enough voltage margin in the remaining

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**Fig. 2.** Schematic of single thyristor in the four thyristor switch assembly showing part values and manufacturer
devices to withstand the forward voltage. We are operating at ~ 50% of device rating but reserve some margin for changes in load and fault conditions. The use of only three devices would provide insufficient margin for load changes or fault conditions.

We also monitor the capacitor current and voltage in each cell. All cells are compared against the average during the pulse to detect an imbalance in either current or voltage. This can be used to find poor connections or reduction in capacitance. Again, we detect imbalance and stop pulsing.

Finally, both the voltage and current monitors are differentially sourced and received reducing noise pickup. This configuration also leads to a much quicker reversal of polarity. The balanced, differential voltage monitors we have designed and used in several high power modulators while the current monitor is a custom order from Pearson Electronics Inc.

IV. TESTING

All the elements for a single cell test have been received except the mechanical structure and striplines. A mockup of the switch stripline passed partial discharge testing.

A. Energy Recovery Choke

We specified air-core choke of 800 µH, to operate at 5kV\textsubscript{peak}, 3 kA\textsubscript{peak} with losses less than 400 W at 120 Arms at 250 Hz. We ordered chokes from two vendors. Partial discharge testing showed inception of << 100 pC at 60 Hz at 6 kV\textsubscript{rms} from both vendors. The inductance from vendor A was low at 710 µH and the losses, based on ESR at 250 Hz, were high at 490 W. The inductance from vendor B was 800 µH and the losses were less than 400 W again based on ESR. Two different construction techniques resulted in a physical dimensions that are quite similar but different AC performance. Pulse testing will determine which construction method will be chosen.

B. Saturating Choke

We designed the saturating choke based on the success and experience from our BNB design. The clamping force was improved to reduce vibration and we added other mechanical features to aid in mass production. We measured the partial discharge inception voltage at about 5 kV\textsubscript{rms} and extinction at about 4.2 kV\textsubscript{rms}. This is slightly below our inception design goal of 6 kVrms but acceptable. We measured an unsaturated inductance of 410 µH and measured the saturation current of 300 A. The saturated inductance was calculated to be 4 µH.

C. Switch

Partial discharge testing showed << 100 pC at 60 Hz at 6.5 kV\textsubscript{rms}. The clamping force was verified using Fujifilm Medium prescale paper and measured a uniform compression across each thyristor.

The maximum average temperature rise of the heatsink was found via testing with average power to be approximately 17 ºC. This gives a maximum junction temperature of 68 ºC with 40 ºC ambient and 11 ºC cyclic, well within our experiential design constraints of 90 ºC maximum. Looking back at a 16 cell solution with 3 times the temperature rise for both cyclic and average, the choice of 32 cells was the best.

V. CONCLUSIONS

The completed design, Fig. 3, meets all our requirements for lifetime, low EMI and maintainability. We have tested all the elements at average power. Once the cabinet and stripline have arrived and assembly is completed, pulsed testing during normal and fault conditions will be done.

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REFERENCES

[1] Sekiguchi, K. Bessho, Y. Fujii, et al, “Development and operational experience of magnetic horn system for T2K experiment”, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 789, 2015, Pages 57-80

[2] K. Bourkland, K. Roon, D. Tinsley, “205 kA Pulsed Power Supply for Neutrino Focusing Horns”, Conference Record of the 25th International Power Modulator Conference Symposium, 2002, pp 266-269

[3] K. Bourkland, C. Jensen, D. Tinsley, W. Markel, "High Current Pulsed Striplines", Conference Record of 13th IEEE International Pulsed Power Conference, 2001, pp 800-803

[4] M. Davidson, H. Pfeffer, N. Curfman, T. Omark, "Design Challenges in High Current Pulsed Striplines", IEEE International Power Modulator and High Voltage Conference, 2022

[5] App Note AN2015-10, Infineon, Transient Thermal Measurements and Thermal Equivalent Circuit Models

[6] R. Künzi, "Thermal Design of Power Electronic Circuits", Proceedings of CAS-CERN Accelerator School, May 2014,CERN-2015-003