DEVELOPMENT OF A HIGH SPEED CROWBAR FOR LANSCE*

C. Friedrichs, J. Lyles, J. M. Doub
Los Alamos National Laboratory

Abstract
Each of the four 200 MHz Final Power Amplifiers (FPAs) in the LANSCE proton linac has its own capacitor bank and crowbar. The dissipation in the 10Ω crowbar limiting resistor is as high as 67 kW, and oil cooling is used. Our stated upgrade goal was to substantially reduce the limiting resistor dissipation and eliminate the oil cooling. Early tests showed that the fault energy quickly rose to unacceptable levels as the current limiting resistance was reduced. FPA arcs are normally quenched by interrupting the FPA modulator current, and the crowbar waits 10 µs for this to occur. The successful upgrade strategy was to replace the 10Ω resistor with a 3Ω air cooled resistor and to add a high speed crowbar circuit which operates only if there are simultaneous arcs in the FPA and its modulator. This paper describes the high speed circuit and its interface with the existing crowbar. Test results are also given.

1 INTRODUCTION

The 200 MHz amplifiers in the LANSCE linac are currently being operated with 838 µs pulses at 120 pps. The first module is a low power (400 kW) segment, while the second, third, and fourth modules operate at the 3 MW level. The plate current for each 3 MW FPA is typically 250 A peak and its Intermediate Power Amplifier (IPA) plate current is typically 10 A peak. Both currents are drawn from a common capacitor bank. While the average current delivered by the capacitor bank is only 26 A, its RMS value is 82 A. The remainder of this paper will present the parameters relevant to the second, third and fourth modules only.

When an arc occurs in one of the RF amplifiers, the preferred method of protecting the RF amplifier is to interrupt the remainder of the plate modulator output pulse rather than to fire the crowbar. Normal operation can then resume at the next pulse. The existing crowbar design allowed approximately 10 µs for current interruption to occur before crowbar triggering was initiated.

A typical crowbar circuit will contain a crowbar current limiting resistor between the capacitor bank and the crowbar. This resistor keeps the crowbar current within the limits of the crowbar device. A second resistor must be placed between the crowbar and the load it is protecting. Without this second resistor, a load arc would short out the voltage across the crowbar, and under that condition it would be very difficult or impossible to fire the crowbar device. The existing crowbar circuit used a 5Ω, Ohm-Weve® resistor in each of these positions. The total dissipation in both resistors during normal operation is 67 kW. High dissipation as well as dust precipitation on the resistors rendered air cooling impractical, so oil cooling was included in that design.

2 CIRCUIT DEVELOPMENT

A simplified crowbar circuit is shown in figure 1. The capacitor bank is made up of forty eight 4.6 µF capacitors in parallel, resulting in a total bank capacitance of 221 µF.

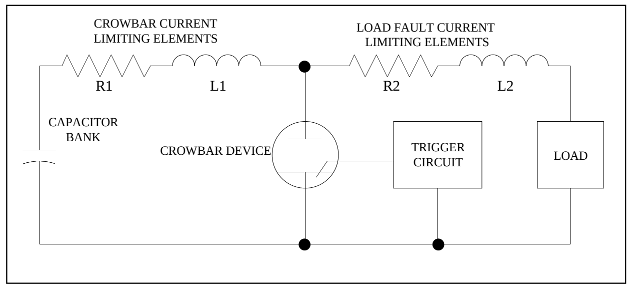

Figure 1: Simplified diagram of a typical crowbar circuit.

2.1 Limiting Resistor Selection

Early in the development program, we elected to use a bank of Carborundum® resistors to make up the crowbar limiting element. This resistor bank is made up of ninety six (two per capacitor) 115Ω resistors in parallel. The total bank resistance is 1.2Ω. Each resistor is 18 inches long and is rated at 150 W, 43,000 J, and 150 kV. During normal operation, each resistor will dissipate 84 W. During the crowbar operation, with a 32 kV capacitor bank voltage, each resistor will dissipate 1200 J of energy. The value of the load fault limiting resistor, R2, could not be predetermined because we wanted its value to be as low as possible. We built a 2.5Ω experimental resistor, using Nichrome® wire in an Ayrton-Perry winding configuration. We then shorted out sections of the resistor to see how low we could go without compromising load protection. Our fault test device is made up of a high voltage switch which shorts out the load through a 60 cm length of 30 ga. copper wire. If the wire remains intact after the test, adequate protection has been demonstrated. After numerous tests, we settled on a value of 2Ω for the load fault limiting resistor. The Ayrton-Perry winding configuration consists of two parallel windings in opposite directions on the same form.

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Each winding consists of 3 strands of 12 ga. Nichrome® wire in parallel. Each winding is made up of 40 turns on a 36 inch circumference with a coil length of 70 inches.

2.2 Inductance Considerations

The loop inductances, L1 and L2 will affect the performance of the crowbar, and a reasonable effort to estimate their values is imperative. The following equation, which predicts the inductance of a circular loop was used to estimate loop inductance.

$$L_0 \cong r\mu\left[\ln\left(\frac{8r}{a}\right) - 2\right]H \quad [1]$$

r is the loop radius, a is the conductor radius, and μ is the permeability of free space.

The loop for L1 was assumed to be equivalent to a 2 meter diameter circle, the loop for L2 was assumed to be equivalent to a 4 meter diameter circle, and the loop conductor was assumed to be 0.025 meters in diameter. These assumptions were based on the actual rectangular geometries of the loops. Calculations based on these dimensions result in 5 μH for L1 and 12 μH for L2. It is important that both the L1 loop and the L1+L2 loop be over damped. If an under damped condition exists, ringing will occur and the crowbar device may extinguish well before the capacitor bank energy is dissipated. In order for the overdamped condition to exist, the following inequality must be true.

$$L < 0.25 * R^2 * C$$

The limiting value for L1 is 79 μH and the limiting value for L1+L2 is 565 μH. Based on the estimated inductance values, both loops appear to be very well damped.

2.3 Crowbar Device

The existing crowbar used a 7703EHV mercury vapor ignitron. This device is rated up to 50 kV, 100 kA, and 30 coulombs in crowbar service. The 7703EHV has a 0.5 μs ionization time, and requires a 3 kV trigger pulse. All of these parameters are well suited to the high speed crowbar upgrade, so this device is incorporated into the new design.

2.4 Trigger Circuit

The high speed crowbar triggering threshold is designed to be about 3000 A; a value slightly above the emission capability of both modulator tubes. This high threshold allows the existing crowbar circuit to function as it was originally intended. The requirement for high speed triggering exists when both the RF tube and the modulator arc simultaneously and the fault currents are determined by the limiting elements. Based on early tests to determine the value of R2, 3 μs was established as the time limit from fault current inception to full conduction of the ignitron. In order to meet this requirement, we sought to optimize a simple trigger circuit which has been used in various crowbars for at least 30 years. The circuit is shown in figure 2 along with the interface with the existing crowbar. The high voltage diodes serve a dual purpose. They act both as steering diodes to accept a trigger from either circuit and as voltage clippers to prevent negative voltage from appearing on the ignitor.

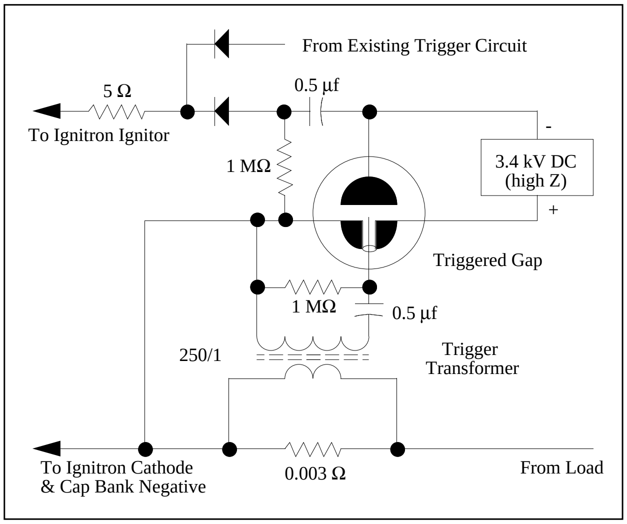

Figure 2: Simplified diagram of the High Speed Crowbar Trigger Circuit.

In order to get the best performance from this circuit, we went through several iterations to select the proper trigger transformer and triggered gap combination. The fault sampling resistor is made up of 6 strands of 12 ga. Nichrome® wire in parallel, 2.15 inches long. During the optimization process we found that better performance was obtained when the six strands were placed in a close cluster about 1 cm in diameter.

The final configuration uses an EG&G® TR1647 trigger transformer and an EG&G® GP 90 triggered spark gap. Normally, one would couple the gap output to the ignitron input using a 1:1 pulse transformer; however by applying a negative voltage to the opposite electrode, capacitive coupling may be used to provide the required positive pulse to the ignitron input. The EG&G application notes for the GP90 recommend a positive trigger and positive polarity on the opposite electrode. Our configuration, which applies a positive trigger and negative voltage to the opposite electrode, was approved by EG&G applications engineering for crowbar service.

3 AIR COOLING

The Carborundum® resistors which make up R1 are positioned vertically and distributed throughout the capacitor bank such that two resistors are located immediately above each capacitor. The wire wound resistor, R2 is positioned horizontally, close to the capacitor room ceiling, between the capacitor bank output and the capacitor room DC output cables. Two exhaust fans are positioned in the capacitor room ceiling immediately above the wire wound resistor, R2. Each fan will exhaust 2250 cfm through an exhaust area of 1.9 square feet. Air is drawn into the capacitor room through four 1 micron filters, each with an area of 2.1 square feet. Two of the filters are positioned such that their air is drawn over the Carborundum® resistors, and the other two filters are positioned low on the vertical wall below the wire wound resistor. The temperature of the resistors is maintained well below their operating limits, and dust accumulation within the capacitor room is minimal. Annual cleaning of the capacitor bushings is sufficient.

4 RESULTS

The most important result of the High Speed Crowbar Development is that the upgraded circuit has been in service in Module 2 at LANSCE for all of the present run cycle. There has been no degradation in Module 2 performance after 4 months of continuous operation. If the crowbar circuit were deficient, erratic performance would be expected in the RF tubes.

As mentioned earlier, our test for crowbar adequacy is to short the capacitor room output through a 60 cm length of 30 ga. copper wire. The test circuit has been operated numerous times, and the crowbar has never failed to protect the wire.

The voltage across the ignitron is shown in figure 3. The initial drop in voltage results from the fault which shorts the load. After about 1.5 µs, the ignitron goes into full conduction, and the voltage falls to zero.

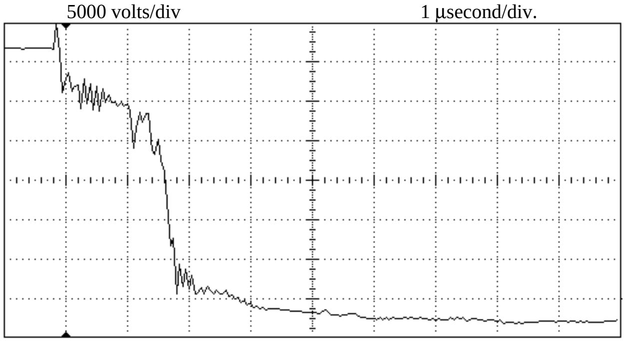

Figure 3: Ignitron voltage during fault.

The output of a current transformer placed in series with the fault test is shown in figure 4.

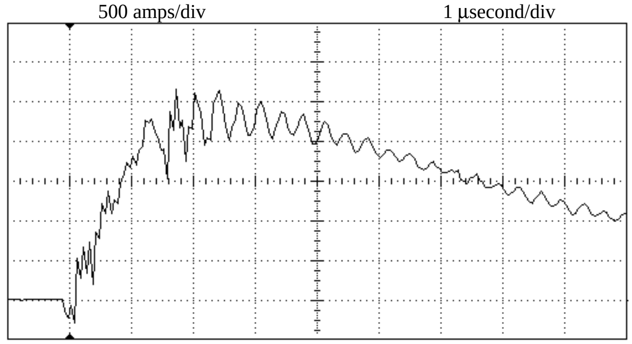

Figure 4: Current through the fault test wire.

The effects of the loop inductances are readily apparent. The fault current rises monotonically to about 2500 A, at which time the ignitron fires, then decreases monotonically back to zero. If no inductance were present, the current would rise abruptly to 10,000 A, then decrease abruptly to zero when the ignitron fired. The energy dissipated in the wire is less with the inductance than it would be without it. The information learned from this picture suggests that if some of our loop 2 inductance could be transferred to loop 1, the value of R2 could be reduced below 2 Ω. Since the performance of the high speed Crowbar is adequate, no further investigation is anticipated.

ACKNOWLEDGMENTS

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REFERENCES

[1] Simon Ramo and John Whinnery, *Fields and Waves in Communication Electronics,* John Wiley and Sons, 1965, p311.