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FERMILAB CAPACITOR TREE

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Summary

The Fermilab Capacitor Tree is a capacitor bank used in series with the feeders carrying 3-phase, 13.8 kV power to the main ring power supply system. Its function is to reduce the voltage droop of the power supplies at high currents, by acting in series resonance with the leakage inductances of the system. This paper describes the electrical system and our operational experience since May, 1976.

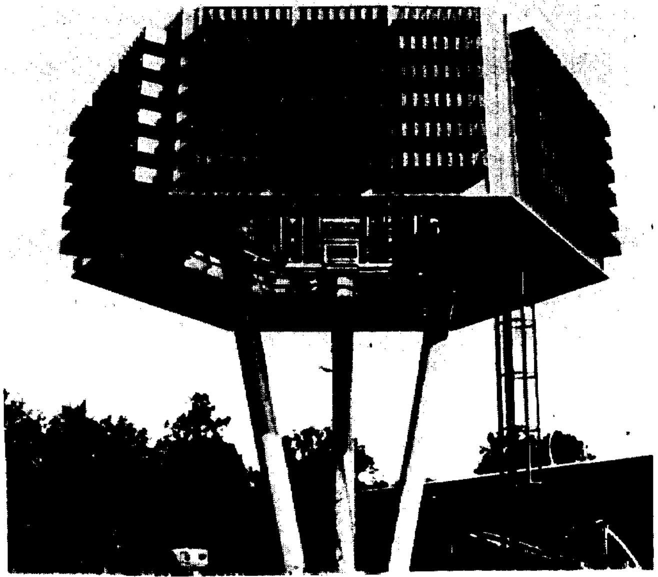
Capacitor Tree Function

The power distribution for the main ring power supply system is diagrammed in Fig. 1. Transformer #82A steps down the 345 kV line voltage to two 13.8 kV secondaries. Each secondary feeds half of the sixty power supplies, located respectively on the east and west sides of the main ring circumference.

The leakage inductances of the #82A transformer and of the 30 parallel power supply transformers constitute a significant series impedance - j0.95Ω - dropping the output voltage of the power supplies by 20% at 400 GeV, and limiting the peak output power of the system to 240 MW (420 GeV excitation). This inductive impedance is compensated by the addition of the Capacitor Tree which consists of six j0.95Ω capacitor banks, one in series with each phase. The capacitors are installed in the ground legs of the transformer to minimize high voltage problems. Operation of the Captree in May, 1976 allowed the power supply system to ramp to 500 GeV, drawing a peak power of 360 MW.

Problems and Solutions

The Captree lowers the feeder impedance simply and



The Capacitor Tree

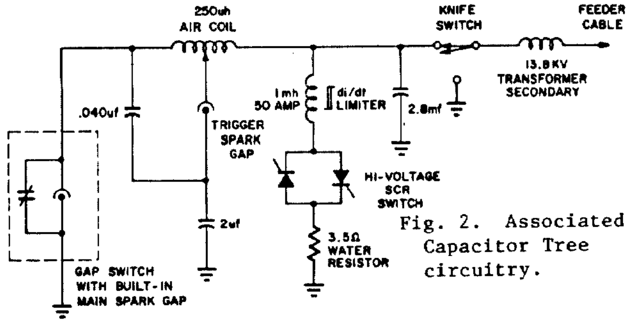


Fig. 2. Associated Capacitor Tree circuitry.

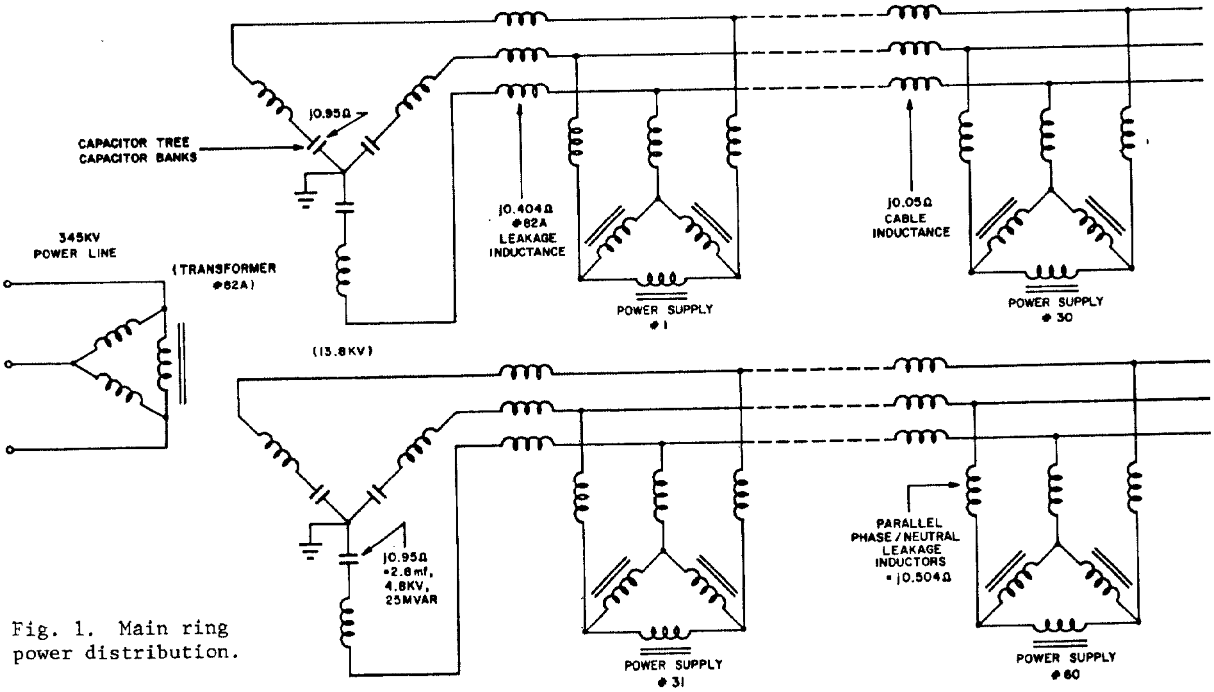


Fig. 1. Main ring power distribution.

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effectively, but it also causes some potential problems in the power system. Additional electronics and switchgear is required to alleviate the problems. Figure 2 shows the associated circuitry that accompanies each capacitor bank. The drawbacks of the Captree system and the use of the added circuit elements to counter them are described below:

A) Access and Maintenance

The Captree is not as passive a system as most power installations, and it requires maintenance. The knife switches shown in Fig. 2 remove the Captree from the circuit, and allow us to run power supplies without it. Twin-bladed knife switches keep the system grounded during the switching process.

B) Fault Protection

In the event of a feeder ground fault, the capacitors are protected from excessive voltage by spark gaps. A trigger spark gap, set at 12 kV, breaks down and triggers the main spark gap which shorts out the capacitor. The main spark gap is part of a mechanical by-pass gap switch that closes when an overvoltage condition is detected. This switch completes the shorting of the capacitor. A 250μh air coil in series with the gap switch limits the inrush current. The shorting of the capacitor also protects the #82A transformer and breaker from excessive ground fault current, which could otherwise develop because the current-limiting leakage inductance has been compensated.

C) Feeder Voltage Rise

When the power supplies ramp, the voltage generated across the capacitors is only partly cancelled by the voltage drop in the #82A transformer; the rest of the voltage is dropped inside the power supply transformers. As a result, the feeder voltage rises. Figure 3 diagrams the phase-to-neutral voltage vectors. At 400 GeV, the voltage rises from 13.8 kV to 14.4 kV; at 500 GeV, the voltage reaches 15 kV. These levels are acceptable in our system.

In the event of severe system shocks, such as the power supplies tripping off or the gap switch closing under load, the Captree can generate transients which drive the phase-to-ground feeder voltages as high as 15 kV. This is beyond the operating voltage of 8 kV, but within the BIL of the system.

D) Ferroresonance.

During the Captree design, calculations and small scale modelling indicated that the system would be subject to ferroresonance, and that some damping would be required. The installed Captree justified those expectations. If no damping resistor is used, small perturtations in the power supply system can momentarily saturate the power supply transformers and trigger a ferroresonant oscillation which grows in amplitude until the spark gap fires. Figure 4 shows such an oscillation. With insufficient damping, a sustained ferroresonance is possible (see Fig. 5A). Critical damping of large amplitude ferroresonance occurs at approximately 4 ohms. Figure 5B shows a damped oscillation which was triggered by the simultaneous bypassing of all the main ring supplies during a 400-GeV flattop.

The ferroresonance modes are interesting to observe. Figure 6 describes what happens with insufficient damping. The diagram is simplified to the case of a single phase system. When the power supply transformer primaries saturate, a burst of current charges the capacitor. The capacitor voltage then biases the line so as to saturate the transformers in the other direction. There are not enough volt-seconds to do this on the very next half-cycle, so the reverse saturation occurs 3/2 cycles later. Hence, the 20 Hz ferroresonant frequency. The function of the damping resistor is to discharge the capacitor before it can generate enough volt-seconds to cause another saturation.

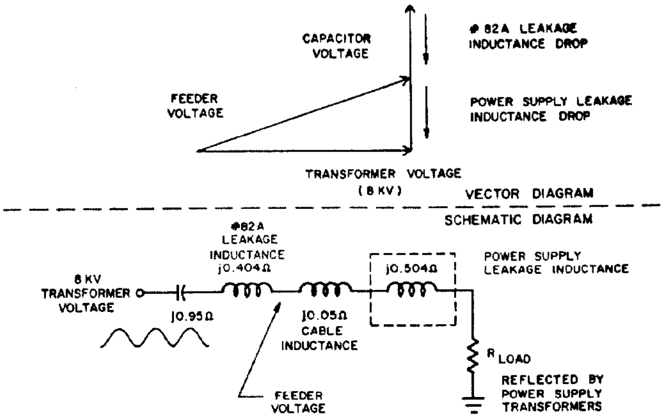

Fig. 3. Feeder voltage (phase/neutral).

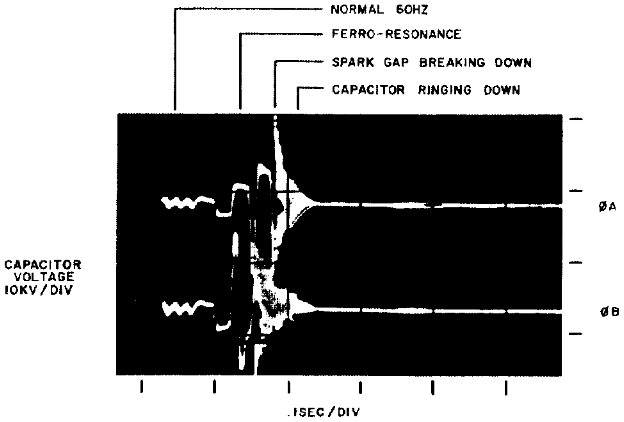

Fig. 4. Undamped Ferroresonance.

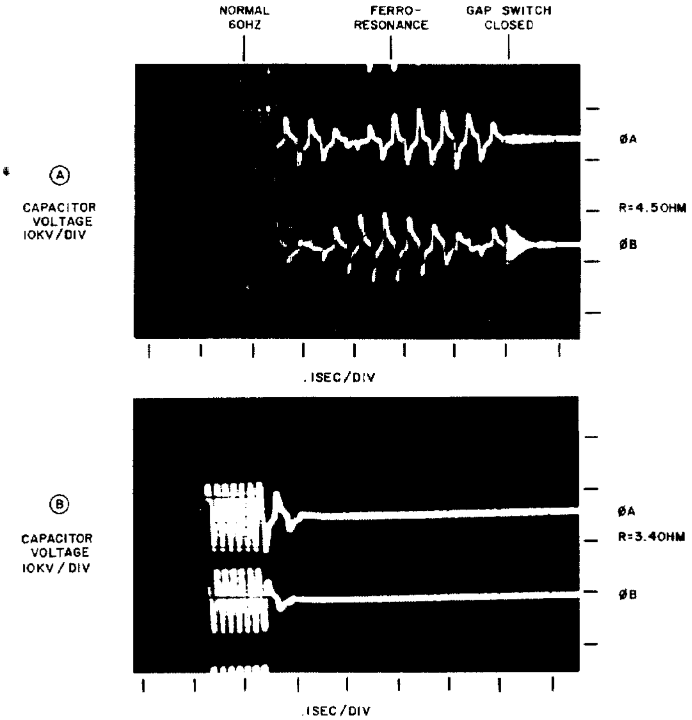

Fig. 5. Partly damped and critically damped ferroresonance.

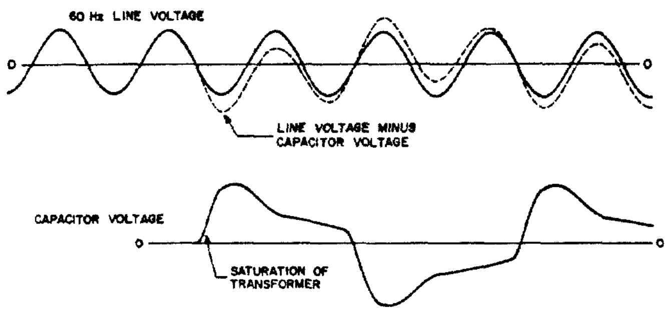

Fig. 6. Single phase ferroresonance.

Our damping resistors are high-conductivity water columns, which we set to 3.5Ω by adding the proper concentration of sodium sulphate and by maintaining a 110°F operating temperature. An air heat-exchanger in the system can dissipate up to 1 MW of power generated in the resistors.

The Resistor Switching System

The water resistors are not designed to dissipate the 3 MW that would be generated if they were employed throughout the power supply cycle. If they were so used, the wasted power would also be very expensive. Damping, however, is only routinely needed during the invert of the ramp, when the load is dropping quickly and perturbations are generated by the rapidly slewing power supplies. Damping must also be available whenever ferroresonance is caused by unexpected transients.

To switch the resistors in and out of the circuit, we use a series SCR switch, capable of holding off 18 kV peak, and of conducting 1500A RMS. The switch configuration is shown in Fig. 7. The SCR gating is controlled via two isolation transformers; the first generates 25 volts dc at the cathode potential, and the second triggers a transistor gating card which applies the 25 volts to the gate resistor. Separation of the power and trigger functions of the gate circuitry enables us to trigger all of the series SCR's simultaneously to within 100 ns, and to fire each one with a fast leading edge (20 V/70 ns into 10Ω). The transistor gating card is a flip/flop circuit which holds the gate voltage on until a negative trigger pulse turns it off.

Figure 8 shows the damping resistor current during a 400-GeV ramp. Note that in addition to invert, we also leave the switches on during low ramp levels for extra ferroresonance protection.

Operation

The Captree has been in operation since May, 1976, when it helped achieve 500-GeV acceleration. Subsequent operation has been basically at 400 GeV. At this energy level, the Captree is not crucial to operation, but it increases the allowable ramp repetition rate 15% by reducing the current in the feeder cables. Operation is also smoother because fewer power supplies are needed.

Problems in the Captree itself have included water leaks in the SCR switches, noise in the switch control system, blown capacitor fuses, salt precipitation in the water system, and several others. The system has been out of operation for approximately 3 weeks since last May for repairs. Improvements are in progress for various Captree elements.

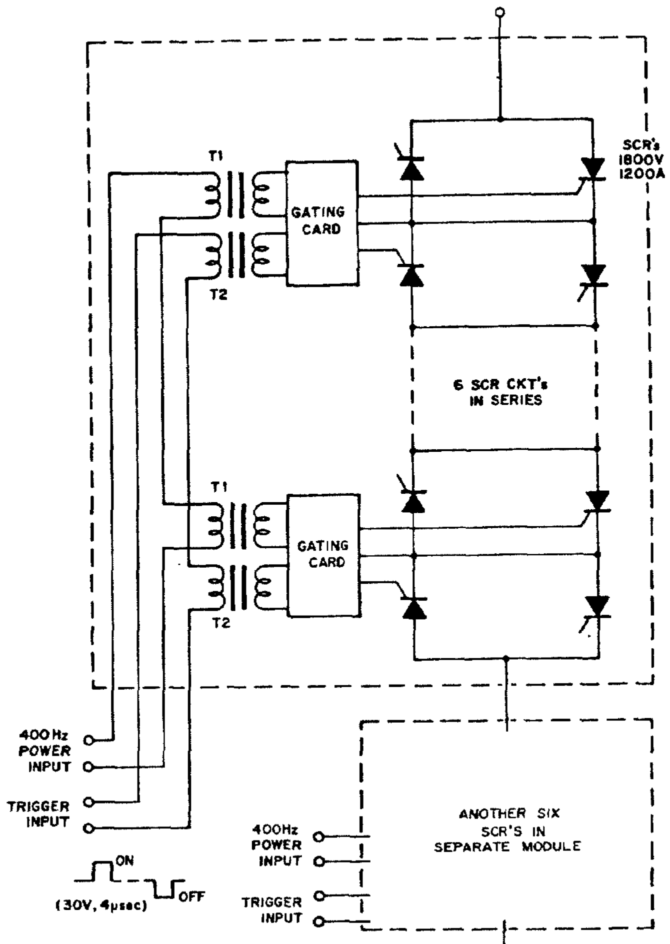

Fig. 7. SCR switch schematic.

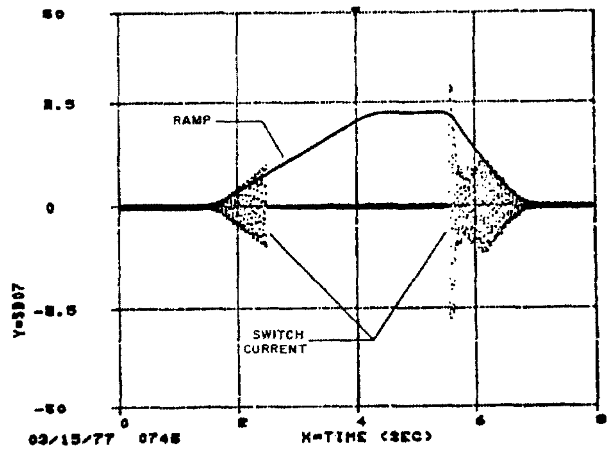

Fig. 8. Switch operation during ramp.

Acknowledgement

The Capacitor Tree was designed, supervised, and brought very close to operation by Dick Cassel, presently at Princeton's Tokomak. The authors have followed his guiding concepts in completing the project.