An ultrafast prefire detector for a 300T single turn magnet system

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For the Single Turn Project initiated at the Los Alamos site, an efficient method for monitoring the magnet's capacitor bank was needed. In operation, 24 capacitors are all charged in parallel to 60 kV before they are dumped through a large coaxial cable that carries the current into the experimental tank and through the single turn of copper. In order to avoid the need for an external source to power the capacitor monitoring system, Rogowski coils were designed to themselves drive a small fiber-optic transmitter.

Introduction

In the single turn magnet of the Single Turn Project, 24 capacitors are charged up to 60 kV in parallel. A custom spark-gap switch is mounted on the top of each capacitor and each capacitor is individually triggered when the bank is properly charged. Out of the spark gap switch come 4 large coaxial cables. All 96 coaxial cables feed into a large custom coaxial assembly that carries the current to a slip disk. A 1/4" thick copper plate is bent into a single-turn and fitted into the slip disk. When all of the spark-gap switches are triggered, each coaxial cable coming out of the top of switch carries approximately 40 kA, totaling over 3.8 MA all traveling through the copper turn in a pulse that is approximately sinusoidal, with a rise time of 2 μs.

This amount of current destroys the copper turn about a 10-20 μs after the pulse. The turn is intact for the duration of the pulse when measurements would be made, but then expands explosively outward.

Carefully monitoring the capacitor bank and the switches is important because even the current from one of the capacitors, 160 kA, will destroy the copper turn creating an open circuit. Thus, if one of the spark-gap switches triggers errantly and its capacitor pre-fires, all of the other capacitors would be dumped into an open circuit if the pre-fire were not detected and the shot aborted. If 23 charged capacitors were fired into an open circuit, damage could occur to the capacitors and/or to the switches. With the capacitors mounted on the top of the tank and not in any sort of reinforced enclosure, monitoring the capacitors is essential.

The solution to monitoring the capacitors was to use a Rogowski coil. A Rogowski coil is a toroidal coil of copper wire placed around a conductor. It is not wound around the conductor, but rather, the coil turned around the conductor so that the circular turns of the Rogowski coils are normal to the circumferential field lines produced by the current. The coaxial cables that carry the current from the switches to the center coaxial assembly are true coaxial cables with a center conductor and an outer shielding so that no magnetic

field exists outside the conductor. However, inside the spark-gap switch, the outer shielding is connected to the case of the switch and the inner conductor is inserted into the interior of the switch casing. Thus, by wrapping the Rogowski coil around the inner part of the coaxial cable inside the spark-gap switch, the field lines produced by the current pass through the loops of the Rogowski coil. When there is a pulse of current there are changing magnetic field lines, which will then induce a voltage across any load connected to the Rogowski, and only this power generated by the induced voltage will be used to create an optical pulse to be detected in the screening room.

Theory

We can estimate the electromotive force produced by the Rogowski coil with relationship

$$\mathscr{E} = -\frac{d\Phi}{dt} \qquad \textbf{Eq. 1}$$

where Φ is the magnetic flux

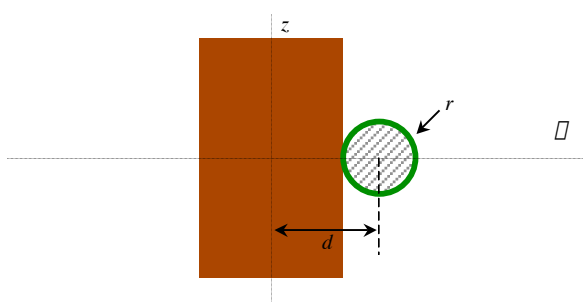
$$\Phi = \int_S \mathbf{B} \cdot d\mathbf{a} \qquad \textbf{Eq. 2}$$

found by integrating the normal component of the field over the surface created by the loop of current. The field produced by a straight current-carrying conductor is easily found with Ampere's law to be

$$\mathbf{B} = \frac{\mu_0 I}{2\pi r}\hat{\phi} \qquad \textbf{Eq. 3}$$

Since the field lines will all be approximately normal to the surface created by the coils, the dot product in Eq. 2 is dropped and we only need to express magnitudes.

If we look down on a length of the conductor, we have the following geometry (in cylindrical coordinates and the z-direction being along the axis of the conductor)



The green circle represents one turn of the Rogowski coil and the dashed region is the region of integration to find the flux. To integrate $1/r$ over that circle, d is used to transform to a coordinate system with the circle centered yielding the complete expression for Φ

$$\Phi = \mu_0 I\left[\mathrm{d} - \sqrt{(d-r)(d+r)}\right] \qquad \textbf{Eq. 4}$$

Noticing that during a pulse of current, only I varies, so the time derivative in Eq. 1 is trivial. For a sinusoidal pulse with an amplitude of 40 kA, the maximum value reached by the time derivative is simply 40 kA times the characteristic angular frequency, ω. For a rise time of 2 μs, a complete period of the sinusoid would take 8 μs, so that $\omega = 2\pi/8$ MHz. With d = 1.0625" and r = .0625", a total electromotive force of approximately 1.8

V is induced per turn in the Rogowski coil. For the 16 turn Rogowski coil employed in these spark-gap switches, we should expect an induced voltage that peaks at about 30 volts, more than enough to drive the fiber-optic transmitters with some basic pulse-shaping.

Design and Results

The actual pulse created by the Rogowski coil looks like the gray trace in Figure 1

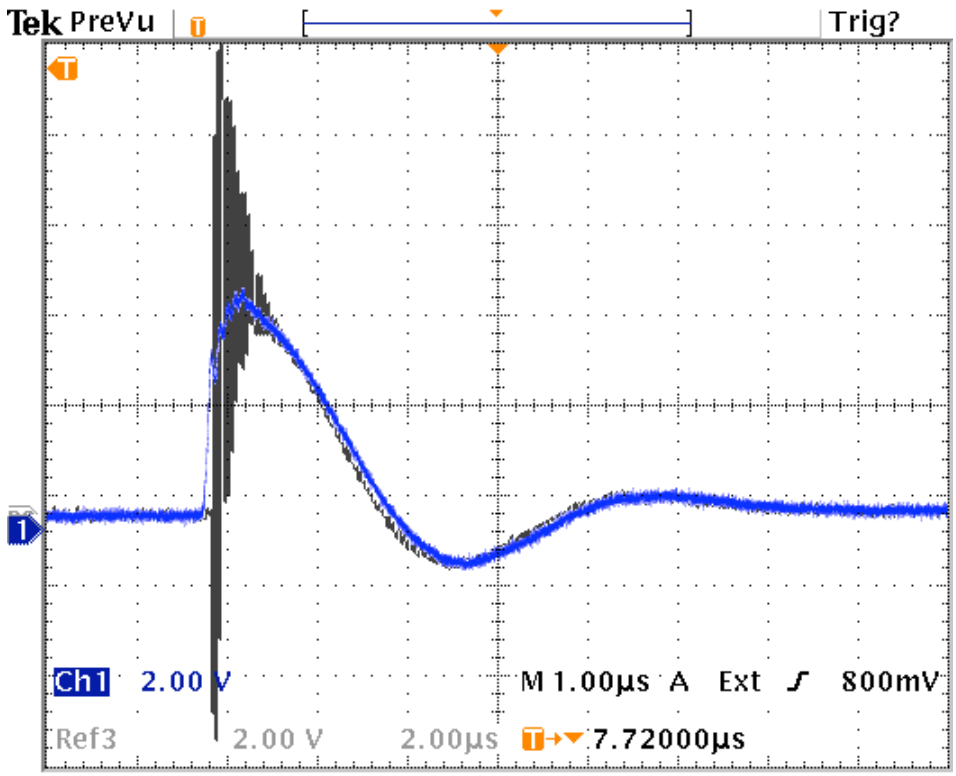


Figure 1 - Actual pulse (gray) and simulated pulse (blue)

and was obtained during the testing and calibration of the switch-mounted capacitors. In order to avoid having to use the high-voltage equipment every time I want to test the circuit, the waveform was programmed into an arbitrary waveform generator. The blue trace above shows the output of the arbitrary waveform generator. The number of points recorded by the oscilloscope was too great for the generator, thus, every 5 points were averaged and then programmed in. There is clearly a good deal of ringing in the system, and though the averaging has reduced the magnitude of these oscillations, they are still visible at the peak of the pulse. The ringing is in the sensor circuit and not in the actual high-voltage shot. A diode in the high-voltage circuit prevents any current from flowing back into the capacitor, so the oscillations are moist likely due to the inductance and capacitance of the Rogowski coil and the oscilloscope circuit. The oscillations occur with a frequency around 25 MHz. For our solenoidal coil of wire, the inductance is

$$L = \mu_0 N^2 \pi r^2 / l \qquad \textbf{Eq. 5}$$

where N is the total number of turns, and l is the length of the solenoid. Plugging in .0625" for the radius, 16 turns making a coil about .5" long, we get an inductance of .2 μH. With the resonant frequency of an LC circuit given by

$$\omega_0 = 1/\sqrt{LC} \qquad \textbf{Eq. 6}$$

the Rogowski coil would need to see a capacitance of approximately 200 pF. The RG223 coaxial cable used has a listed capacitance of 94 pF/m, so with a few feet of cable and also the 15 pF load inside the oscilloscope, the oscillations can be understood with good certainty to be caused by LC oscillations in the Rogowski coil circuit.

The first design issue was to eliminate the oscillations so that a good pulse could be shaped for the fiber-optic transmitter. The simplest solution given the current Rogowski coil already in place in all of the spark-gap switches was to use a low-pass filter. For a 1 μs rise time (the current from the capacitor has a 2 μs rise time, but the Rogowski is a measure of the time derivative of this current, the Rogowski coil peaks in half the time), the pulse has a characteristic frequency of 250 kHz. By setting the corner frequency of the low-pass filter to around 1 MHz, we can obtain approximately 20 dB attenuation on the 25 MHz oscillations with only a small amount of attenuation on the main pulse. And with a 30 volt pulse, a small amount of attenuation is fine since the fiber optic transmitter diode requires only a few volts.

Another solution would have been to design a new Rogowski coil that could be fitted in all of the spark-gap switches that would still provide sufficient voltage but avoid oscillations with the coaxial cable. Looking at Eqs. 4 and 5, we see that if we decrease the radius, the inductance will drop like r^2 while the induced voltage will *increase* like r. Similarly, if the length of the coil could be increased by simply spacing out the number of turns, a different inductance could be achieved, but it would be important to make sure that the coils were still approximately normal to the field lines to get the most flux.

At this point, the low-pass filter seems like the most reasonable solution since the attenuation of the main pulse is very small, and the Rogowski coils are already in place. Furthermore, different cables and geometries will be in place in the actual single turn magnet than with the test setup, and resonant frequencies would probably change. The corner frequency of the low-pass filter can be changed quite easily by changing the resistor and/or capacitor value once the circuit boards are printed up.

The low pass filter did an effective job of eliminating the small oscillations, even in the simulated waveform.

The next design issue was to shape a pulse in a way that was simple, required no external power source, and could drive the fiber optic transmitter. It was important that external power not be brought in since it would have been a challenging task. The spark-gap switches were custom built with only a BNC connector on the top for a Rogowski coil, and so no power could be brought inside the switches. Bringing power to the outside of the switch is possible, but it just complicates things, and with 3.8 MA being fired all around, the possibility for interference and subsequent failure of the sensors is great.

The most effective, passive, pulse-shaping component was a 3.6 V zener diode connected across the low-pass filter. The rising edge of the Rogowski pulse is very sharp up until it gets to about 4 or 5 volts, so limiting the voltage to 3.6 volts created a very square leading edge. The trailing edge of the pulse is more rounded, but one really clean edge is ideal for something like an edge-triggered flip-flop. The fiber optic transmitters being used are designed for short- to medium-haul transmission and when driven with 60-70 mA, can transmit several kilometers. For this application, detectable transmission over no more than 40 meters was necessary, and thus the transmitter can be driven with as little as 10 mA. A simple series resistor was used after the zener diode to limit the current to 10 mA.

Figure 2 shows a number of relevant traces.

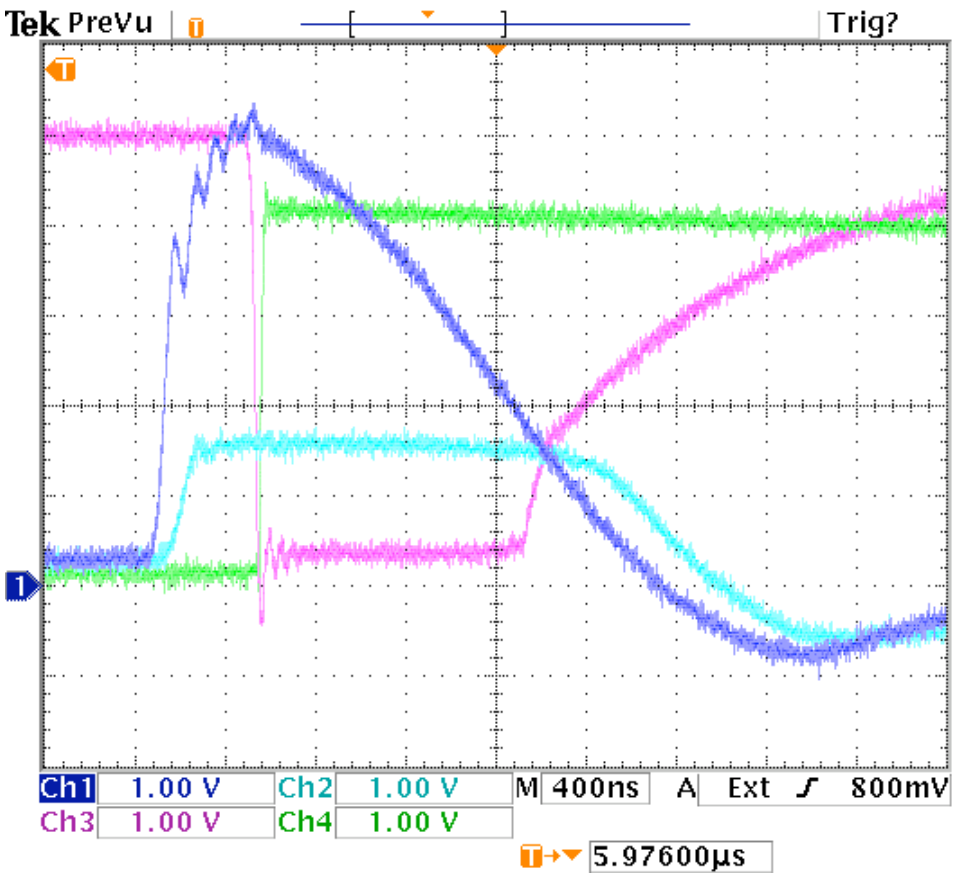


Figure 2 - Logic traces

CH1, the blue trace, shows the output of the arbitrary waveform generator with a little more detail than before. This is before the low-pass filter, so no filtering is done. Notice the 25 MHz oscillations. CH2, the light blue trace, shows the forward voltage on the fiber optic transmitter's diode, about 1.6 V. With 400 ns per division, the rise time on the leading edge of the pulse is less than 100 ns, perfect for logic circuits that are doing the detection. CH3, the pink trace, shows the output of the fiber optic receiver on the other end of a 25-foot long, 62.5 µm diameter cable. The receiver is hooked up in an active low configuration so that when detecting light, the receiver's transistor can sink current. The leading edge of this pulse is very sharp and designed for high-speed TTL circuits, and is

ideal for a negative edge-triggered flip-flop. CH4, the green trace, shows the Q output of a J/K negative edge-triggered flip-flop. This output is used to drive a 15 V pulse sent to a National Instruments Field-Point I/O device for monitoring the capacitors with a computer. The $\overline{Q}$ output is used to sink the current of an LED for monitoring in the rack. The trace shows that the flip-flop is triggered less than 400ns after the capacitor fires.

Conclusion

The solution presented here offers an effective way to independently monitor all 24 capacitors in the capacitor bank. Whenever the capacitor fires, the field induced in the Rogowski coil created a pulse that can be shaped to drive a fiber optic transmitter which then activates a flip-flop notifying the user that the capacitor has fired, and the flip-flop must be reset either manually on the rack, or with the computer. Further design of the computer program could prevent recharging the capacitors until the flip-flops have been reset as an added safety measure. By using very minimal components that still produce a reliable result, these pulse-shaping circuits can be nicely packaged into a Pomona box only .8” □ 1” □ 1.5” in size, with a BNC connector on one side to receive the pulse from the Rogowski coil, and a fiber-optic transmitter coming out the other side to send the pulse to the screening room. The control circuitry in the screening room is not complex and easily interfaces with the computer for total computer control of the capacitor bank. And for a system that effectively monitors 24 capacitors without the need to bring an external power supply into the capacitor bank, this solution is relatively low-cost, with the fiber-optic components being the most expensive.

The actual circuit boards have not been printed and the final control box not fabricated, but testing on true prototypes of these sensor circuits shows promising results for monitoring the single turn capacitor bank.