A 40 KV, 3.1 Ω PFN FOR THE MAIN INJECTOR ABORT KICKER

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Abstract

The Main Injector abort kicker system has been run at full voltage. The system was required to operate with a PFN to meet specifications. The system was designed to operate in air to allow for easier maintenance. The topology chosen has the thyratron cathode grounded, a grounded PFN and a floating pulse transformer. The system is also required to have low EMI because of the proximity of low level controls. Several problems related to the pulse transformer and to operation in air are addressed and some solutions are presented.

1 CIRCUIT DESIGN

Siting constraints have forced the abort kicker modulator to be located ~100 m from the kicker magnet itself, much further than the existing distance of ~12 m in the Main Ring and ~40 m in the Tevatron. At the same time, the rise time of the field has been decreased from 1.8 µs in the Main Ring to 1.0 µs in the Main Injector. To meet specifications, a pulse forming network is required in place of the circuit used in the Main Ring [1] and Tevatron. The Main Injector Abort Kicker specifications are shown in Table 1. A more detailed explanation on the requirement for using a pulse forming network is given in [2].

The circuit function is straight forward with the possible exceptions of the transformer secondary snubber circuit and the 0.05 µF capacitor added to the high voltage bus connection. This capacitor is added where the high voltage bus connects to the pulse transformer. It is used to compensate for the added inductance of the bus.

The transformer secondary snubber circuit is required because the load time constant is longer than the rise time of the PFN. It provides a mechanism to control the initial voltage applied to the magnet, and then damp the reflections that come back from the magnet to the modulator. There is an optimum value of capacitance that makes the current at the magnet rise rapidly but not overshoot by more than 5%. The value depends on the cable length between the magnet and the modulator, on the transformer leakage inductance, and on the load time constant.

Table 1, Main Injector Abort Kicker Specifications

Field rise time (10% – 70 %) (10% – 90 %)	700 ns 1 µs
Field flat top duration	>9.8 µs
Flatness (ΔB/B) during pulse	± 10%
Field fall time	NA
$\int$B dl (Total kick/2 Magnets)	0.37 kG m (8 GeV) to 2.51 kG m (150 GeV)
Repetition Rate	0.7 Hz
Magnet Inductance	5.05 µH
Magnet Current	2700 A

2 IMPLEMENTATION

The original design for the abort modulator had all components assembled in a single 24" x 30" x 75" high relay rack. Due to partial discharge problems with several components, a more spacious layout was implemented. Six commercial EMI/RFI shielding enclosures, Schroff® Eurorack HF 1, were purchased for the two modulators. Three enclosures were then joined together to form a final cabinet that is 79" long x 34" wide by 61" high. Each section contains a major pulse power component and is arranged for easy and rapid maintenance.

2.1 PFN Cabinet

The first cabinet contains the PFN, shorting safety relay and end of line termination. The PFN consists of 13 capacitors and 12 inductors. These inductors may be tuned approximately ±5% by changing the length of the coil. This can be done with the system energized. The capacitors are double ended Maxwell capacitors rated for 10^8 pulses at 40 kV charge voltage. The inductor coils are placed parallel to each other and alternately wound right handed and left handed. This positioning of the coils adds coupling between sections to achieve a flatter pulse response.

There is only one connection to frame ground in the

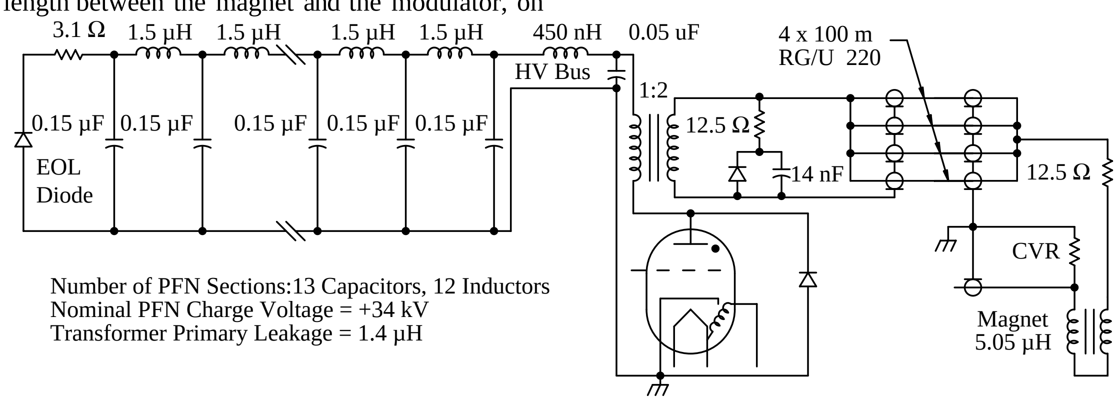

Figure 1, Schematic of Main Injector Abort Kicker System modulator and this is done at the thyratron. This location was chosen because of the multiple number of connections required between ground and the thyratron. The return bus at the PFN then rings up to about 1 kV during the pulse. The PFN is constructed in a polycarbonate housing which is isolated from the enclosure by standoffs rated for 1 kV_{rms}.

The safety shorting relay and end of line clipper diode and resistor are also in the PFN cabinet. The shorting relay is mounted for gravity return. A modified wire wound resistor from Ohmite, rated at 1 kW average power, is used as the load dump. The modification was to replace a metal frame that runs the length of the resistor with a G–10 frame. This allows the part to be rated for 20 kV pulse voltage and two are used in series. The end of line clipper resistor is made from a stack of 15 ceramic composition resistors, HVR Inc. #W0825A0R2J, rated at 5 kV each. The end of line diode is an assembly from CKE Inc., C03–1689, rated at 60 kV and 11 kA for 10 μs.

2.2 Thyratron Cabinet

The next cabinet contains the thyratron, the thyratron support electronics, and the modulator interlocks. The thyratron trigger circuit, support electronics and interlocks are contained inside a shielded enclosure inside the thyratron cabinet. Initially, a Litton L–4988 thyratron was purchased for the switch. Subsequently, six excess ITT, now Triton, F-241 thyratrons became available. The F-241 has shown acceptable service life under similar conditions in the modulators for the SLAC linac. The Fermilab operating conditions have a much lower repetition rate, but a slightly higher A•s rating per pulse. Two parallel stacks of inverse diodes, 9 pieces Micro–Semi UDD–7.5 per stack, were connected across the thyratron to further ease the operating conditions. These provide a low loss path for reverse currents through the thyratron.

Triggering requirements for this thyratron could be met with the trigger system already designed for the Main Injector Proton Injection Kicker [3]. A 1:3 transformer was used at the output of the trigger circuit to get an open circuit voltage of 2100 V.

In the bottom of this cabinet is mounted a 1.48 m long high voltage bus that connects the PFN, the pulse transformer and the thyratron. Fermilab has successfully used a low inductance stripline bus in air at 12 kV DC for another modulator project [4] so extending the operating voltage to 40 kV DC was reasonable. Several 2D electric field models were made with Opera-2D software from Vector Fields. This was the basis for the bus design. Two tall narrow insulators are used to provide sufficient spacing between the high voltage conductor and two ground conductors. This reduces the electric field stress enough to prevent partial discharge in the air. A thin wide insulator is used between the tall insulator and the ground conductor to get sufficient tracking distance. The insulating material used is polycarbonate because of its excellent electrical and good mechanical properties. Initial testing of the entire bus structure has resulted in a 19 kV_{rms} 60 Hz corona extinction level. The source of the partial discharge appears to come from high voltage connections at the ends. For long life, an extinction level of 25 kV_{rms} is desired and will require further improvements.

2.3 Pulse Transformer Cabinet

The last cabinet contains the pulse transformer, the secondary snubber circuit and the output cable connectors. Free space is required in this section to maneuver the pulse transformer in and out of the cabinet.

The prototype pulse transformer had severe corona problems. The insulation was a cast epoxy that gave sufficient voltage holdoff, however the lifetime of the transformer was in question because of a low corona extinction voltage. The subsequent transformer for the system was specified to use oil as insulation. A solid barrier between primary and secondary windings was also required because the transformer primary will be at 40 kV for 2 seconds during accelerator flattop. Also, 60 kV DC bushings, Isolation Design Model 404, were specified to reduce corona from the connections.

The manufacturer of the first production transformer ordered under the new specification experienced several additional problems. First, the primary windings required additional bracing to protect against shifting during shipment. Second, the leakage and magnetizing inductance were both out of specification. After winding repairs were made, the leakage inductance met specifications but the magnetizing inductance was still small by a factor of two. However, during testing the transformer passed 5000 pulses at 200% nominal operating voltage. It was decided to accept the transformer in order in continue to make progress with modulator development.

The 60 Hz corona extinction level was measured at Fermilab to be approximately 6 kV rms. This level seems inconsistent with long lifetime, however the corona extinction level for the transformer was not specified. It is not obvious that the 60 Hz corona levels are indicative of life for this pulse application. The slow 0.5 second charging time and the fast discharge are definitely not AC operating conditions. Fermilab has many high voltage cables that last 10^8 pulses with a slow charge to 60 kV and pulse discharge, but they also have had measured corona extinction voltages of less than 25 kV_{rms}.

3 TEST RESULTS

Preliminary tests at low voltage indicated that all magnet current specifications had been met. However, after running at full voltage, the magnet current rise time (10 % – 90 %) has increased from 1.0 μs to 1.3 μs. Upon returning to low voltage, the increased rise time is still present. The cause is unknown for certain, but a change in leakage inductance of the transformer is suspected given the problems the vendor had with bracing. Another more experienced vendor has been contracted for the next transformer and that unit has just been tested successfully and shipped.

The measured PFN voltage and current are shown in Fig. 2. The voltage is measured on the primary high side of the transformer with a Northstar VD-60 probe and the current is measured at the thyratron anode with a Pearson 3025 CT. The magnet current is measured with a 2.5 mΩ CVR and shown in Fig. 3. The flat top specification for ripple and length have been met. The ripple is under ±5% and the 90% – 90% pulse length is now 9.7 µs. The pulse length can be further extended by approximately 700 ns because the design allowed for the addition of one more PFN section. However, this should not be necessary when the rise time specification is met.

4 CONCLUSIONS

The modulator has run at rated voltage. The problem of pulse transformer leakage inductance has been solved with the new manufacturer.

The cost of each finished modulator is approximately 130k$ for parts and materials, 800 hours for shop labor and 3000 hours for assembly and testing labor. While the parts cost is substantially more than the old Main Ring abort kicker system, an increased cost was anticipated because the specifications ruled out the technique used for that kicker system.

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This work is supported by the U.S. Department of Energy under contract No. DE-AC02-76CHO3000.

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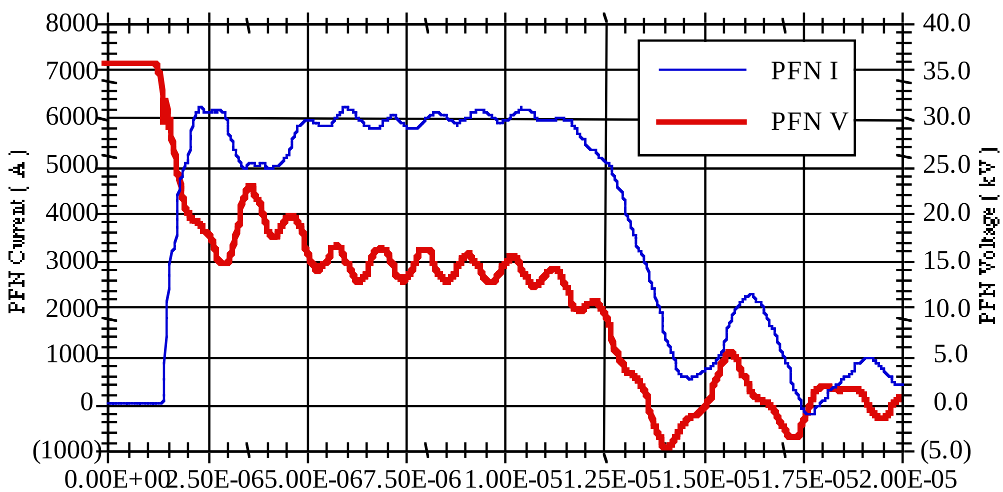

Figure 2, Measured PFN Voltage and Current Waveforms at Nominal Operating Level

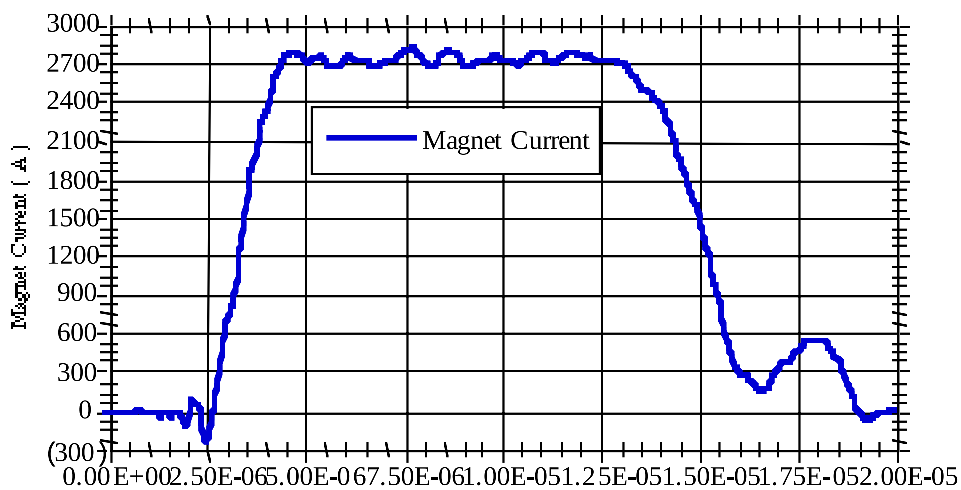

Figure 3, Measured Magnet Current Waveform at Nominal Operating Level