A FAST 60 kV RESONANT CHARGING POWER SUPPLY FOR THE LHC INFLECTORS

M.J. Barnes, G.D. Wait, TRIUMF
E. Carlier, L. Ducimetière, U. Jansson, G.H. Schröder, E.B. Vossenberg, CERN.

Abstract

The injection kicker systems for the two LHC beams will each consist of four magnets and four pulse forming networks (PFNs), discharged by thyratron switches. Fast resonant charging systems (RCS) are used to charge the PFNs within 1 ms to 60 kV: fast charging minimises the number of unwanted erratically thyratron discharges. The stability and pulse to pulse reproducibility of the PFN voltage must be maintained to a precision of $\leq \pm 0.1\%$. Each RCS consists of a 2.4 mF primary capacitor bank, connected via a Gate Turn-Off thyristor (GTO) and a 1:23 step-up transformer to two PFNs, each with an effective capacitance of 0.96 μF. The PFNs are discharged 400 μs after the end of the charging period into the kicker magnets. The RCS include novel features such as a GTO used in Gate Assisted Turn-off (GAT) mode and a low-leakage inductance, high voltage, step-up pulse transformer. This paper presents a basic design for the RCS, and the optimisation of the electrical circuit using PSpice. The RCS are designed, constructed and tested at TRIUMF in collaboration with CERN as part of the Canadian contribution to the LHC project.

1 INTRODUCTION

The European Laboratory for Particle Physics (CERN) is designing a Large Hadron Collider (LHC) to be installed in an existing 27 km circumference tunnel. The LHC requires Injection Kicker Systems, devices for fast deflecting the incoming particle beams onto the accelerator's circular trajectory. Two pulsed systems, of 4 magnets and 4 PFNs each, are required for injection[1,2]. The injection sequence, during normal operation, consists of 12 pulses with a period of 16.8s. However the RCS will be tested at 0.2 Hz, continuous. Fig. 1 shows a schematic of the RCS and the notation utilised for component names.

The RCS will simultaneously charge two 5 Ω PFNs, which are connected in parallel (Fig. 1), to 60kV before the thyratrons are triggered. The stability and pulse to pulse reproducibility of the PFN voltage must each be maintained to a precision of better than $\pm 0.1\%$[3]. Each RCS will have a 2.4 mF storage capacitor bank ($C_{storage}$) charged up to 2.5 kV. The storage capacitor bank is connected to the primary of a 1:23, low leakage inductance, step-up transformer, via a GTO and series diode. Each of two 5 Ω PFNs is connected to the secondary of the transformer via a cable, a charging resistor (R_{charge}) and a diode stack (D_{charge}). Each 5 Ω PFN can be considered to be a 0.96 μF capacitor during the charge cycle. The PFNs are discharged through a kicker magnet using thyratrons.

When the GTO is gated-on, a resonance is excited between the storage capacitor bank, the PFN capacitance and the leakage inductance of the pulse transformer. Energy is transferred from the storage capacitors to the PFNs. When the PFN voltage has reached its maximum value the high voltage diode stack, connected in series with each PFN, stops the resonance and electrically disconnects the charged PFN from the transformer. The GTO switch turns-off, and the storage capacitor bank is recharged, at constant current, in a few seconds.

Fig. 2 shows typical GTO current, PFN voltage, and the secondary voltage associated with the pulse transformer. The period of time when the positive voltage across the transformer secondary is increasing in magnitude is referred to as the *charge time*; the period when the positive secondary voltage is reducing in magnitude is referred to as the *backswing time*. The *effective charge time* (ECT) is the sum of the *charge time* and *backswing time*.

RCS's are used to charge the PFNs in order to reduce as much as possible the number of erratic thyratron turn-ons.

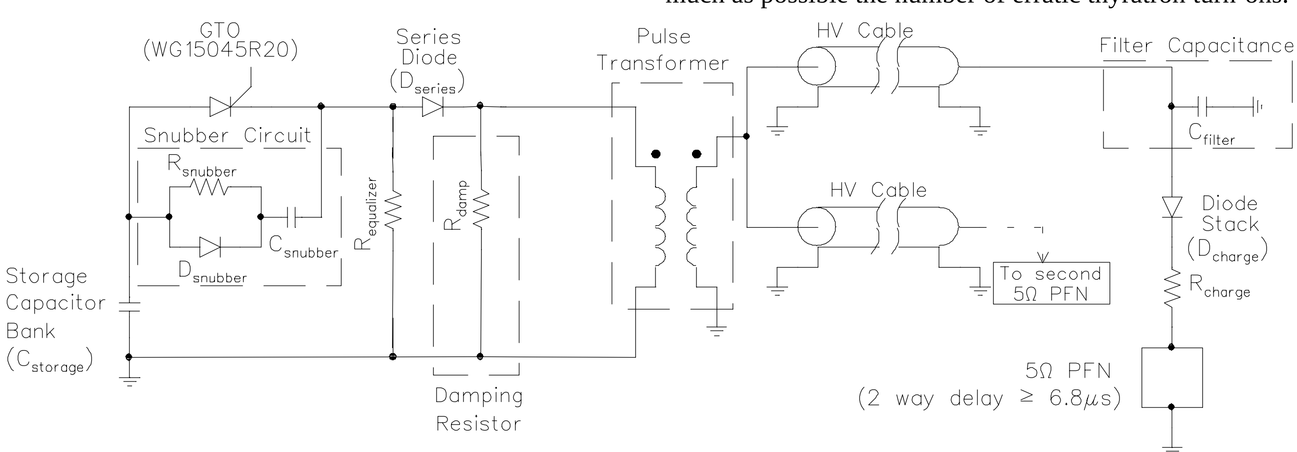

Figure 1. Schematic of Resonant Charging Supply

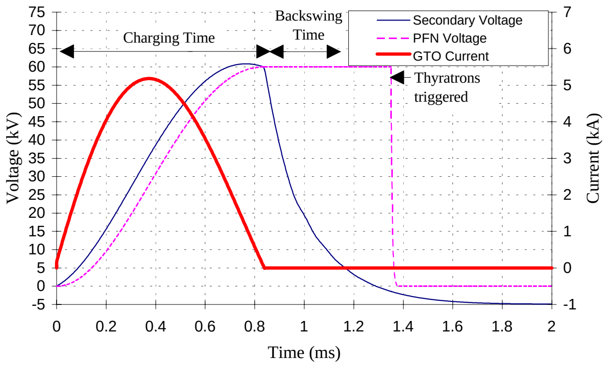

Figure 2. Typical secondary voltage, PFN voltage and GTO current waveforms

This number is dependent upon the time period that there is high voltage across the thyratrons, hence it is advantageous to minimise the ECT of the RCS.

2 POWER SEMICONDUCTOR SWITCH

If a thyratron turns-on erratically, during the recovery period of the power semiconductor switch, the semiconductor can be subjected to a forward dV/dt of 90 V/µs[4]. An SCR with suitable ratings for use in the RCS has a turn-off time (t_q) of typically several hundred microseconds. During the recovery period, forward voltage cannot be applied across the semiconductor switch without it turning on, and an SCR has a limited capability to withstand positive dV/dt when forward voltage is reapplied. A GTO used in GAT mode, with suitable ratings for use in the RCS, would have a t_q time of typically 10 µs. In GAT mode negative voltage is applied to the GTO gate just before the main current falls to zero. A suitable GTO is the WG15045R20[5].

3 SNUBBER COMPONENTS

The purpose of the snubber circuit is to limit the dV/dt across the GTO to an acceptable value. During normal operation, the ECT is increased at a rate of 32 µs/µF of the snubber capacitor value, and thus it is desirable to minimise the value of the snubber capacitor. A detailed consideration of several abnormal operating conditions resulted in the choice of a snubber capacitor with a nominal value of 2 µF. The 2 µF limits the maximum predicted dV/dt across the GTO, when a thyratron turns-on erratically during the recovery time, to 90 V/µs[4] which is believed to be a safe value for the WG15045R20.

The snubber resistor limits the magnitude of discharge current, from the snubber capacitor, into the GTO. The value of the snubber resistor is a compromise between a large value to limit this discharge current, and a small value for a relatively short time-constant for discharging the snubber capacitor. If the time-constant is too long, the snubber capacitor may still have a significant voltage across itself following the normal loop of conduction current through the GTO. A nominal snubber resistor value of 50 Ω represents a reasonable compromise.

4 DAMPING RESISTOR

The purpose of the damping resistor is to reduce the ECT and therefore the size of the transformer too. Without a damping resistor the ECT is 2100 µs, and the transformer volt-time integral (VTI) approaches 79 V.s., referred to the terminals of the secondary winding.

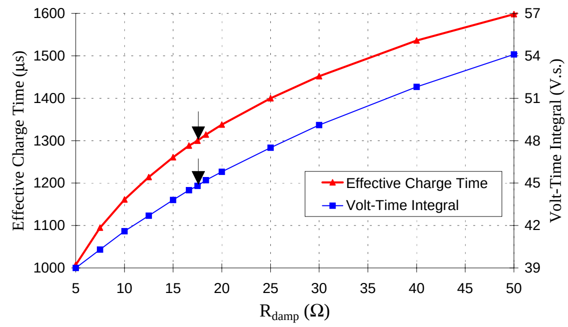

Figure 3. ECT and VTI as a function of the value of the damping resistor

Fig. 3 shows plots of ECT and the transformer VTI as a function of the damping resistor value (R_{damp}). Reducing the resistance increases both transformer reset time and the initial current into the GTO at turn-on: the reset time is the elapsed time at which the transformer core is reset to its initial value. In addition, dissipation in the damping resistor increases significantly with low resistance values (Fig. 4). The peak negative secondary voltage, following backswing, reduces as the resistance value is decreased. A low amplitude of negative voltage reduces the electrical stress on the secondary components.

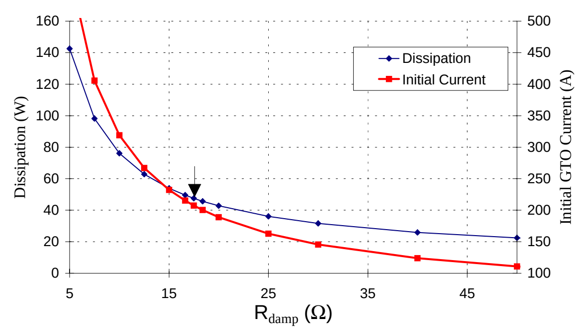

Figure 4. Damping resistor dissipation and initial GTO current as a function of the resistor value

A damping resistor value of 17.5 Ω±5% gives a reasonable compromise: 17.5 Ω results in a conservative value of initial current through the GTO immediately following turn-on (230 A), a transformer VTI of 45 V.s., an acceptable ECT (1300 µs), a minimum secondary voltage of –6 kV, a damping resistor dissipation of 48 W, and a reset time of 60 ms.

5 TRANSFORMER TURNS RATIO

The charge time is determined approximately by the leakage inductance of the transformer and the effective capacitance. The effective capacitance during the charge time is approximately equal to the series sum of the PFN capacitance, referred to the primary, and the value of the storage capacitor bank. The capacitance of the PFN is determined by the impedance of the PFN and its delay. Choosing a maximum storage capacitor voltage minimises the capacitance of the storage capacitor bank, and the charge time. A single WG15045R20 GTO is used for the RCS; Westcode recommend that the GTO be used with a DC blocking voltage of not more than 2.8 kV in the RCS. The transformer turns-ratio influences the ECT for the PFN. To evaluate the optimum, PSpice[6] simulations have been carried out[7,8]. For the optimisation it has been assumed that the value of the leakage inductance referred to the primary of the transformer reduces in inverse proportion to the square of the turns ratio, which can be true over a limited range[9]. However the value of the PFN capacitance referred to the primary of the transformer increases in proportion to the square of the turns ratio. The backswing time is dependent upon the sum of the parasitic capacitance of the secondary winding, and the capacitance of each of the HV cables and filters. This capacitance referred to the primary winding increases in proportion to the turns ratio squared: hence the backswing time increases with increasing turns ratio. Hence the optimum value for the turns ratio is dependent upon the effective capacitance during the backswing time. Fig. 5 shows a plot of both storage capacitance value and ECT as a function of turns-ratio. To limit the nominal value of the storage capacitor bank to 2.4 mF, a turns ratio of 1:23 is chosen.

6 CHARGING RESISTOR

The purpose of the charging resistor is to both limit fault current if the thyratrons erratically turn-on during the charging cycle and, together with the filter capacitors,

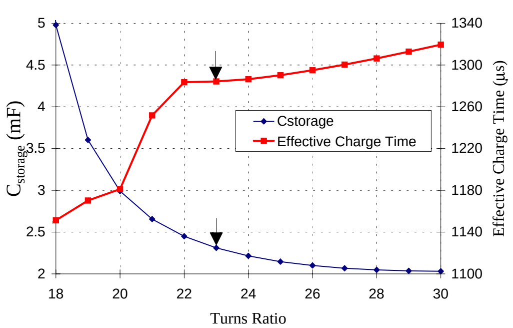

Figure 5. Storage capacitor value and ECT as a function of transformer turns-ratio

limit maximum dV/dt across the transformer secondary if the Dump Switch (DS) thyratrons turn-on erratically.

Without filter capacitors, the secondary dV/dt would be almost four times greater than that recommended for the transformer[7,8]. A time-constant of approximately 360 ns, for the charging resistor and filter capacitor, limits the maximum dV/dt across the transformer secondary, when both DS thyratrons turn-on simultaneously from maximum PFN voltage, to below 120 kV/µs[7,8]: this dV/dt is safe[9]. The optimum value of charging resistor has been determined using PSpice. The storage capacitor bank pre-charge voltage was selected to give the required PFN voltage. The time-constant of the charging resistor and filter capacitor was kept as 360 ns. The pre-charge on the storage capacitor bank is below 2.7 kV for charging resistor values of less than 100 Ω.

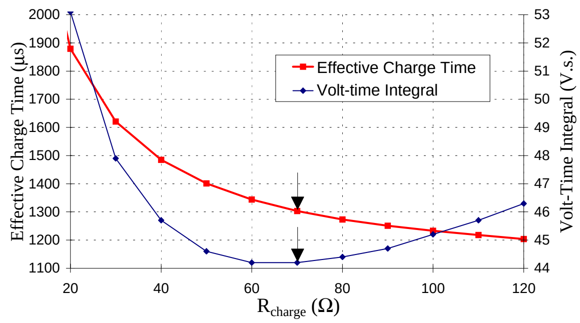

Figure 6. ECT and VTI versus the value of the charging resistor (C_{filter} x R_{charge} = 360 ns)

Fig. 6 shows a plot of ECT and VTI versus the value of charging resistor. A minimum VTI is required for a value in the range of 60 Ω to 70 Ω, and the VTI curve climbs less steeply for values greater than 70 Ω. In addition the ECT decreases for increasing values of charging resistor. Thus a nominal value of 70 Ω has been selected.

7 CONCLUSION

This paper has described the process employed for optimising component values for a 60 kV RCS for the CERN LHC inflector system. The often conflicting requirements have been considered in selecting component values.

REFERENCES

[1] L. Ducimetière, U. Jansson, G.H. Schröder, E.B. Vossenberg, M.J. Barnes, G.D. Wait. "Design of the Injection Kicker Magnet System for CERN's 14 TeV Proton Collider", Tenth IEEE International Pulsed Power Conference, Albuquerque, 1995, pp1406-1411

[2] M.J. Barnes, G.D. Wait, L. Ducimetière, U. Jansson, G.H. Schröder, E.B. Vossenberg, "Kick Stability Analysis of the LHC Inflectors", EPAC96, June 1996, Barcelona. pp2591-2593.

[3] Technical Specification SL/Tech.Spec.96-6(BT), "Resonant Charging Power Supply For LHC Injection Kicker Prototype", Prévessin, 11 May 1996

[4] M.J. Barnes, G.D. Wait, L. Ducimetière, E. Carlier, U. Jansson, G.H. Schröder, E.B. Vossenberg, "Operation Modes of the Fast 60 kV Resonant Charging Power Supply for the LHC Inflectors", Proc. of 11th IEEE Pulse Power Conference, Baltimore, June 1997.

[5] Westcode Semiconductors, "Gate Turn-Off Thyristor (Symetrical blocking type.) Types WG15026Rxx to WG15045Rxx", August 1996, Rat.Rep.96G9, Issue-3.

[6] MicroSim Corporation, 20 Fairbanks, Irvine, California. CA 92718. Tel (714) 770 3022.

[7] M.J. Barnes, G.D. Wait, "Design and Optimization of the 66 kV Resonant Charging Power Supply for the LHC Injection Kickers", Design note TRI-DN-96-22, December 1996.

[8] M.J. Barnes, G.D. Wait, "Design and Optimization of a 60 kV Resonant Charging Power Supply", Design note TRI-DN-96-16, August 1996.

[9] Private communication with Magne Stangenes, Stangenes Industries Inc., 1052 East Meadow Circle, Palo Alto, California 94303