PULSE DISCHARGE CONTROL AND MACHINE PROTECTION
FOR A MULTI-DISCHARGE COMPULSATOR

Robert F. Thelen

Presented at the
4th Symposium on Electromagnetic
Launch Technology
Austin, Texas
April 12-14, 1988

Publication No. PR-62
Center for Electromechanics
The University of Texas at Austin
Balcones Research Center
EME 1.100, Building 133
Austin, TX 78758-4497
(512)471-4496

PULSE DISCHARGE CONTROL AND MACHINE PROTECTION FOR A MULTI-DISCHARGE COMPULSATOR

R. F. Thelen

Center for Electromechanics
The University of Texas at Austin
Austin, TX 78758-4497

Abstract

The Center for Electromechanics at the University of Texas at Austin (CEM-UT) has designed and built a compensated pulse alternator (compulsator) to power railgun research experiments. The compulsator power unit is intended to deliver a precisely timed train of nearly 1 megamp current pulses for a repetitive firing sequence. This paper presents the control design considerations and strategies used in the control of proper output pulses and the detection and clearing of faults. Since the compulsator is designed for limited pulse duty, particular emphasis is placed on reliability and redundancy in the fault control system to avert potentially massive generator damage.

Introduction

This paper sets forth the logic and circuitry employed in the fast sequence control of the compulsator rapid discharge, and the detection and clearing of discharge circuit faults. The controls developed should be applicable to any similar machine, but the specifics of this paper are the result of work on the rapid-fire, iron-core, compulsator developed at CEM-UT.[1,2,3,4] That machine is supported by auxiliary supplies which provide for the hydrostatic bearing system and hydraulic motoring of the compulsator to desired speed. An industrial programmable logic controller (PLC) is used to properly sequence the compulsator support systems and provide fault contingency logic. The PLC brings the overall system to the point of compulsator discharge and then enables the firing control circuitry briefly. The PLC is limited to a 10 to 30 ms input/output (I/O) and scan time and is, therefore, inappropriate for control within the firing window, which lasts from 10 to 170 ms for 1 to 10 shots, respectively.

The compulsator incorporates a horizontal shaft, six pole rotating field on a solid AISI 4340 steel rotor. Passive compensation is achieved by the 7050-T75 aluminum shield, thermally assembled onto the rotor. The stator armature has, likewise, six poles which are wired as three in-phase circuits and paralleled by buswork external to the machine (fig. 1). The rotor has a total mass of 4,555 kg (10,020 lb) which, at design speed of 4,700 rpm, stores a total of 38.6 MJ. The design output of the compulsator is 10 pulse pairs (a low level injector pulse followed by full current into the main railgun) delivered at 60 Hz (fig. 2a). The major current pulse is a 2.1 ms duration current wave of 0.94 MA peak and approximately 1 MJ energy. The nominal open circuit voltage is 2 kV peak at 235 Hz (4,700 rpm) in a rounded triangle waveform (fig. 2b).

The Firing Control Problem

The strategy of gun firing control is based on a switched injector railgun of repeatable performance which fires a shorting projectile into a "hot-rail", or directly connected main gun (fig. 3). Using the known operation of the injector gun, a firing angle is determined such that the projectile will move from

Figure 1. Compulsator circuit schematic showing armature field hook-up

injector to main gun near a current zero and then be accelerated down the main gun during the follow-on pulse (fig. 4a). If the projectile leaves the injector early, the main gun utility is wasted as the current alternates polarity (fig. 4b). A late injector gun exit can result in destructive arcing at the injector-main gun interface, and once again the main gun efficiency is compromised, due to delayed current rise and wasted arc energy (fig. 4c).

The control circuit must trigger off the phase angle of the armature voltage or, equivalently, the rotor position. Since the compulsator slows at each discharge, small changes in the firing angle are anticipated, and since the gun system is designed for 10 shots, the controller must select the correct setting

Figure 2. a) Typical discharge pulse pair
b) Open circuit voltage

Figure 3. Compulsator railgun circuit schematic

for each and trigger the appropriate output circuit. Using ± 100 kA as a desirable exit current limit at the main gun, a minimum accuracy of approximately ± 100 μ s in the gun control timing was decided upon. This corresponds to $\pm 3^\circ$ mechanical rotation, at the design speed of 4,700 rpm. The determination of rotor position was approached in a two-prong manner: direct rotation measurement and signal phase angle measurement. This was done as a hedge against the possibility that either approach proved to be less than successful when the machine was finally assembled.

Figure 4. a) Injector and main gun currents: ideal compulsator railgun shot
b) Early injector gun exit
c) Late injector gun exit

The direct measurement of rotor angular displacement was complicated by several factors. The two shafts of the rotor were kept short and tightly coupled to a hydraulic drive system on each end. Because of rapid rotor decelerations during discharges, shaft extensions were considered undesirable, and a shaft encoder would have to successfully handle the rotational decelerations as well as the pulsed magnetic fields resulting from a discharge. An attempt was made to develop a retro-reflective optical encoder using the side face of the rotor. The operation of this system became unreliable at higher operating speeds due to both lack of good optical edge detection and inadequate sensor electronics in quadrature for frequencies above 7 kHz.

An alternative was to use the phase angle of a voltage signal on the compulsator output. The main consideration here was the integrity of such a system following the first compulsator discharge. The distortion of the input signal must have no effect on the phase angle determination. To achieve this immunity and provide electrical isolation from the armature-railgun circuit, an instrumentation coil was embedded in the stator. This was comprised of a single turn of magnet wire, spanning from one armature pole-center to the next (fig. 1). Two coils, IC-1 and IC-2, were installed so that a backup coil would be available. This coil generates a square-wave, 90° out of phase with the terminal voltage, and experiences equal but opposite magnetic flux from the two adjacent armature coils during discharge (fig. 5). A signal conditioning circuit protects against high potential at full machine speed and excitation, while allowing operation even at the low voltage induced by the iron residual field (fig. 6). The signal conditioner output is a highly stable TTL-type signal which definitively keys the rotor position. The plot in figure 7 shows the stability of this signal during a 590-kA discharge.

Figure 5. Stator instrument coil signal with reference to armature voltage signal

The Cycle-Portion Encoder

The accurate determination of the firing angle is achieved by the so named "cycle-portion encoder" developed for this purpose (patent pending). This control is a hybrid analog/digital circuit designed to select a point in a signal's cycle based upon a high resolution clock/counter rate and the period of the immediately preceding cycle. Given a reliable cyclic input signal, the cycle-portion encoder scales the period of each cycle and steps into the current cycle the desired portion, or firing angle. Because of the

Figure 6. Stator coil signal conditioning

10-shot requirement, this control was constructed with 10 independent set point adjustments and outputs which are sequentially enabled. The control output is allowed or disallowed by appropriate gate logic so that the discharge occurs during the desired machine cycle (fig. 8).

The scaling of each cycle provides a dynamic adjustment to the sudden change in the compulsator speed upon discharge. At full speed and a 60 Hz firing rate, the instrument can fully adjust to the new rotor speed, since discharges are once every 4 cycles. A 12-bit digital architecture (4,096 count) was selected so that a minimum 1,000 counts/cycle could be maintained over a range of rotor speed changes. During operation, the cycle-period measurement is converted to an analog value and applied to the set point potentiometers and a 5 Vdc meter. A demultiplexer routes the current channel set point via an analog-to-digital (A/D) converter to a digital magnitude comparator, which monitors the clock count into the new cycle. The comparator output is combined with control logic so that if:

1. the controller is enabled by the PLC (i.e., it is time for the discharge sequence),
2. the appropriate dead time between shots is timed out,
3. the controller is not in the test mode, and
4. the last shot has not been fired,

then the output is presented to the output driver. The controller output pulse is used by an ignitron triggering circuit [5] to close the appropriate injector switch (fig. 3). After each output, a shot counter advances the demultiplexer circuit to the next set point selection and starts a dead-time timer to provide a delay (16 ms) between shots. This operation repeats until the shot counter matches the selected maximum number of shots.

A test mode enables the operator to adjust and confirm the set points at a signal frequency matching the planned machine speed. The set points are indicated on a digital panel meter with a 0.1% resolution while the set point potentiometer is adjusted. The clock rate is also selected such that, at the simulated speed, the counter will reach between 1,600 and 3,200 counts, or 2 to 4 V on the front panel indicator.

Figure 7. Stator instrument coil signals during 590-kA discharge (note armature voltage distortion)

The Fault Control Problem

In the fast sequence operation, a failure can take one of two forms: the circuit can fail to close or it can fail to open. In the former, the failure is inherently safe, and though the experiment has failed, no damage is realized. In the latter case, however, the failure can quickly damage the machine beyond repair.

It is estimated that 15 short-circuit pulses in a 235 Hz burst would deposit sufficient heat in the compulsator windings to soften the epoxy in which they are potted.[1] This softening would allow the armature winding to move and rapid mechanical destruction of the machine interior would follow. Fifteen pulses

Figure 8. Cycle portion encoder block diagram

at 235 Hz takes only 64 ms. For this reason, the compulsator output circuit is equipped with an explosive opening switch (EOS), which is able to cut the output bus within 4 μ s. Since the compulsator is an alternating current machine, it is possible and very advantageous to open this switch at a current zero and thus avoid having to dissipate the up to 1 MJ inductively stored energy in the output circuit ($\frac{1}{2}LI^2$ at the time of switch opening). The potential for severe machine damage, however, makes it imperative to detect a short circuit fault condition and to definitely activate the explosive opening switch, even if not at current zero. To achieve these goals, two steps were taken: an interface was built to the Reynolds Industries' Explosive Bridgewire Controller (EBW controller) and a fault control monitor was designed and built.

Interface to the EBW Firing System

The Reynolds Industry model FS-10 EBW firing system was purchased as the detonation system for the explosive opening switch. This control is provided with a jack for remote triggering as well as the switch for manual detonation. The arming circuit is wired only to the manual switch on the panel and, it was noted, the "Ready" status light is merely a timed delay on the charging circuit and does not actually test the high voltage capacitor in the firing module. In order to assure the readiness of this circuit and safeguard the compulsator control, several changes were determined.

- 1) The arming of the EBW firing system should be done by the PLC before motoring the compulsator.
- 2) The "Ready" state should be prerequisite to the enabling of the discharge sequence, and should abort the discharge or application of field current upon its loss.
- 3) The "Ready" state should include sampling of charge voltage on the FS-10 firing module capacitor.
- 4) A 4 kV isolation level should be established between the FS-10 firing circuit and any electrical connections to it.

The last requirement is due to the fact that the detonator output wires are common with the control circuitry. The detonators are mounted on the severable bus in the explosive opening switch, so contact with the compulsator output circuit (± 2 kV) is very plausible. The FS-10 is battery operated, so the unit is unplugged and operated in the screened control room as a floating (i.e. ungrounded) circuit. The control signal from the PLC to arm the FS-10 is isolated by an opto-electric, solid-state relay, which is wired to parallel the "arm" toggle switch. The power to the FS-10 "Ready" light is used to drive a comparator circuit which tests the output capacitor voltage (a meter is provided for visual confirmation). The comparator output, in turn, drives an optically isolated solid-state relay back to a PLC input. PLC logic controls the arming and ready-feedback interlocking. Finally, the trigger pulse to the FS-10 is isolated through a pulse transformer (figs. 9a and b).

The triggering pulse to the FS-10 is a 40 V capacitive discharge. The integrity of the trigger pulse circuit is maintained by building this circuit with internal back-up and diagnostics. The 40 Vdc supply has capacitor back-up for 20 s after power failure and the battery-backed diagnostics test the ac power, the capacitor charge, and the output connection through the pulse transformer to the FS-10 control.

Figure 9a. EBW firing system isolation and PLC interface

Figure 9b. FS-10 and interface box

Fault Control Monitor

The circuits for fault detection and explosive opening switch activation are constructed with reliability and redundancy in prime consideration. The fault control monitor's "Ready" status is combined with the trigger pulse circuit "Ready" and the FS-10 firing control "Ready" to provide the PLC with an "Explosive Switch Ready" input status.

Input to the fault control monitor is from four Rogowski coils [6] on the compulsator output. One coil each is installed on the three output terminals of the compulsator. These are potted in epoxy and slipped over the bus, both for the electrical isolation and for a mechanical support relative to the bus. A fourth, or total current, coil is mounted on the inner coaxial bus conductor after the bus "spider" connection and before any load hookups (fig. 1). These signals are passively integrated in a 50 ms resistor-capacitor (RC) network and then buffer amplified into the follow-on circuitry. A buffered output is provided at this point for data acquisition recording of the four currents. The amplifiers are calibrated to supply a 100, 100, 100, and 300 kA/V output for the four currents. This provides a 1.2 MA range, given the 4 V swing of the amplifiers.

The fault control monitor was constructed on an Augat Corporation #8136 socketed, wire-wrap board. The circuits for the four circuits were segregated on board by integrated circuit (IC) chip and physical location. The power supply was line powered with a back-up battery to supply the +5 Vdc bus. A -5 Vdc was supplied via a Reliability type SB-5 dc/dc converter from the +5 Vdc supply. The 74HC logic family and LM324/LM319 linear components were chosen for their wide power supply tolerance. A "Ready" diagnostic circuit confirms that both the line powered supply and the battery voltage are within tolerances.

Three independent tests are run on the integrated Rogowski coil signals (fig. 10).

Figure 10. Fault control logic schematic

The signal from the "A-terminal" current is fed to a pulse count circuit which separately counts the positive and negative current output pulses (above a 90 kA threshold) and compares it with a switch selected maximum output count. It is reasoned that a shorted bus or railgun will produce a stream of output current pulses, which are then counted until the planned discharge count is achieved. A count error sets a fault latch within the fault control monitor and a front panel annunciator light.

The signal from the "B-terminal" current is fed into a comparator and trips a fault latch if the output current exceeds approximately 40% in the negative polarity. The negative current pulse is used to power the injector railgun which always operates on less than 300 kA (limited by its internal impedance). In a short-circuit fault condition the positive current pulse may be indistinguishable from a railgun shot, but a full negative current pulse will be detected as a fault. The comparator sets a fault latch and a front panel annunciator light.

The "C-terminal" current signal is fed to a voltage-to-current source amplifier, the output of which goes to a RC integrator network by way of a full wave rectifier. The result is an analog representation of the total coulombs passed by the compulsator. This circuit ends in a comparator to limit the total discharge to less than the equivalent of 10 full level discharge sequences. The comparator output sets a fault latch and lights the front panel annunciator.

A fourth circuit checks for an imbalance between the sum of the three terminal currents and the total current. This circuit effectively detects any problem in the Rogowski coil hook-up (provided at least one coil is connected), and can detect a fault occurring before the total current Rogowski location (e.g., an internal compulsator short). If the fault is located before the explosive opening switch, one can only turn off the field excitation current and hope for the best. On the chance that the fault is located between the opening switch and the total current Rogowski, the current imbalance comparator sets a fault latch to operate the explosive opening switch. Any fault condition drops the "Ready" output to the PLC which turns off the field excitation. The field power can be de-energized within 30 ms, but takes nearly 1 s to decay, due to shield eddy currents.

A first-out circuit indicates on the front panel which of the fault detectors latches up first. When any fault latch is set, it starts a 7 ms timer at the end of which the fault output is triggered. In the meantime, two current zero monitoring circuits try to trip the fault output before the 7 ms, one based on the "A-terminal" current and one based on the total current signal. The current zero threshold is about 9 kA. Since passive integrators are used, an offset of about 8% of peak between true zero and apparent current signal zero may occur (fig. 2a). The fault output is a TTL-compatible high (>4.0 Vdc) for the no-fault condition and drops low (<0.7 Vdc) for the fault condition. In this way, a board power supply bus short circuit (which defeats the circuit redundancy) will cause an apparent fault and detonation of the explosive opening switch.

The protective circuitry redundancy is reduced to one path through the FS-10 EBW firing control and out to the two detonator caps which are wired in series. To secure this portion of the circuit a "Test" switch on the fault control monitor is used to manually set a fault latch. The 7 ms timer triggers the output; a flash lamp (to simulate the detonator load) at the FS-10 output indicates that all circuits are operational. The detonator circuit is measured with a blasting galvanometer as the connection is made to the FS-10 output. As a matter of procedure, the FS-10 flashlamp test and the detonator cap continuity test are performed before the initiation of an experiment run.

Testing Results

Discharge Control

The cycle-portion encoder was first tested on the bench with a function generator input signal. This confirmed the basic operation. The "total shot" inhibit was then removed and the unit was allowed to run continuously. In this way, a 25 μ s jitter was observed for any given set point. The jitter is consistent with the uncertainty introduced by the D-to-A and A-to-D conversions. The A-to-D conversion requires a 25 μ s delay but this only affects the time to update the setpoint value presented to the comparator. In other words, there is some time around the cycle zero point (00.1% for instance) when the setpoint value may be based on the cycle period before the last, rather than the immediately preceding, period.

At the time of this writing some preliminary discharge tests have been conducted at half speed, or 2,400 rpm. From this experience, the firing angle was

found to vary an average of 0.16% from the programmed setpoint ($\sigma = 0.19$) when there was either one gun fired or on the first shot of two guns fired. In three 2-gun shots the second shot was early by 2.1, 2.4, and 3.0 percent-of-cycle. This relatively large error led to the revision of the stator instrumentation coil signal conditioning to that shown in figure 6. The plot in figure 7 shows the improved signal into the cycle-portion encoder during a 590 kA discharge current. No discernible perturbation is evident in the zero-crossing region of either IC-1 or IC-2. Figure 11 shows the alignment of the instrument coil signals with the valley of the armature voltage signal and the discharge at time zero corresponds precisely to 59.7% of cycle (as measured from the armature voltage peak).

Figure 11. Plot showing stator instrumentation coil alignment with armature voltage and compulsator discharge at 59.7% of cycle

Fault Testing

Each function of the fault control monitor was demonstrated in bench tests using function generators as inputs. Upon installation, the various amplifiers were calibrated to give the proper span. A recent revision was made to correct a slight amplifier offset which biased the negative count of pulses for low level restrike currents. During normal operation an amplified RC offset of about 8% of peak affects the signal in the opposite direction. The offset is self-cancelling in a continuous short. Figure 12 shows the current trace during a short-circuit test in which the pulse count limit was set to 3. It can also be seen that the opening switch operated nicely at current zero. The current zero threshold is set at about ± 9 kA.

Conclusion

Control circuits have been devised to precisely control the time of discharge for a rapid-fire compulsator-railgun system. The circuit has provided reliable performance through the system testing to

Figure 12. Short circuit test showing 3 pulse count fault control and explosive opening switch operation at current zero

date. Other circuits, designed to protect the compulsator from short-circuit fault damage, have also been successfully implemented. The circuits and control strategies described are useful for any pulse power and rotor position dependent applications.

Acknowledgements

This work was funded under U.S. Army Armament Research, Development, and Engineering Center contract number DAAK10-83-C-0126.

The fault control monitor was built by Deen Engineering of Austin, Texas. Other circuits were constructed in-house at CEM-UT.

References

1. M. L. Spann, S. B. Pratap, and M. R. Vaughn, "Research and Development of a Compensated Pulsed Alternator for a Rapid-Fire Electromagnetic Gun," Interim Report #RF45, U.S. Army ARDEC Contract #DAAK10-83-C-0126.
2. S. B. Pratap, W. L. Bird, G. L. Godwin, and W. F. Weldon, "A Compulsator Driven Rapid-Fire EM Gun," presented at the Second Symposium on Electromagnetic Launch Technology, Boston, Massachusetts, October 10-13, 1983.
3. S. B. Pratap, M. L. Spann, W. G. Brinkman, M. D. Werst, and M. R. Vaughn, "A Compulsator-Driven Rapid-Fire Railgun System," presented at the IEEE 5th Pulsed Power Conference, Washington D. C., June 10-12, 1985.
4. M. L. Spann, S. B. Pratap, W. G. Brinkman, D. Perkins, and R. F. Thelen, "A Rapid-Fire, Compulsator Driven Railgun System," *IEEE Transactions on Magnetics*, vol MAG-22, no. 6, Nov. 1986.
5. EG & G Incorporated, Electro-Optics Division, data sheet #K5500B-1, "Krytons--Cold Cathode Switch Tubes," EG & G Incorporated, Salem, MA.
6. K. E. Nalty, R. C. Zowarka, and L. D. Holland, "Instrumentation for Electromagnetic Launcher Systems," *IEEE Transactions on Magnetics*, vol MAG-20, no. 2, March 1984, pp 328-331.