TESTING OF A HOMOPOLAR GENERATOR, ENERGY STORAGE INDUCTOR,
OPENING-SWITCH RAILGUN SYSTEM

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Abstract - The first homopolar-fired railgun system was operated in Canberra in 1972 [1,2]. Since that time two additional systems have been tested, the EMACK homopolar generator (HPG) built by Westinghouse and operated by Army Research and Development Center (ARDC) [3] and the joint effort by The Center for Electromechanics of The University of Texas (CEM-UT) and General Dynamics in 1982 [4]. This paper describes the homopolar railgun system operated by CEM-UT in 1985. The aspect that makes this system different from the previous experiments is the design of a fast opening switch (10 to 20 μ s) that will allow operation of the HPG into hypervelocity launchers.

SYSTEM COMPONENT DESCRIPTION

All system components have been designed and constructed by CEM-UT. The specification of the compact HPG is given in Table 1 [5]. This generator has been developed for compactness and high energy density. The pulse forming for the railgun experiment is accomplished with a five-turn coaxial inductor. The inductor parameters are listed in Table 2 [6]. The opening switch is a single shot two-stage device and is shown in Fig. 1. The first stage is constructed with galvanic sliding contacts and the second stage is a lightweight explosive design. The switch parameters are given in Table 3 [7].

Table 1. Dimensions and performance parameters of the compact homopolar generator.

Stored energy	6.2 MJ at 6,245 rpm
Terminal voltage	50 V at 6,245 rpm
Effective machine capacitance	4,960 F
Internal resistance	7.5 $\mu\Omega$
Internal inductance	30 nH
Rated discharge current	750 kA
Total generator weight	1,545 kg (3,400 lb _m)
Peak discharge torque	61,000 N·m (45,000 ft·lb _f) (at rated current)

Table 2. Predicted performance of inductor.

Parameter	Nominal Value	Units
Resistance (dc, cryogenic)	2.04	$\mu\Omega$
Resistance (charging frequency, cryogenic)	3.14	$\mu\Omega$
Total inductance	6.2	μ H
Internal inductance	1.74	μ H
Peak current	1.02	MA
Energy stored	3.2	MJ
Energy transfer efficiency (HPG to inductor)	51.5	%
Discharge losses	0.61	MJ
Energy available to load	2.59	MJ
Inductor energy available/mass	1.73	kJ/kg
System energy available/mass	0.77	kJ/kg

Fig. 1. Two-stage opening switch.

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The launcher used in this testing was built and tested at Los Alamos National Lab and was brought to CEM-UT for expediency in testing. The gun was a round bore parallel rail design of copper and G-10, reinforced with a Kevlar® wrap and shrunk into a steel tube (Fig. 2). The geometry of the gun was very simi-

lar to a gun developed by General Dynamics. The L' and R' of the General Dynamics railgun were carefully measured at CEM-UT. The gun parameters are listed in Table 4 and are assumed to be representative of the characteristics of the round-bore gun used in this testing.

Table 3. Two stage opening switch parameters.

Mechanical switch resistance	6 $\mu\Omega$
Mechanical switch inductance	16.9 nH
Mechanical switch I^2t capacity	$1.2 \times 10^{11} \text{ A}^2\text{s}$
Mechanical switch commutation time to second stage	750 μs @ 350 kA
Explosive switch resistance	34 $\mu\Omega$
Explosive switch inductance	48.3 nH
Explosive switch I^2t capacity	$1 \times 10^{10} \text{ A}^2\text{s}$
Explosive switch commutation time into closely coupled fixed resistance load	14.2 μs

Table 4. Railgun parameters.

length	0.6 m (23.6 in.)
diameter	1.9 cm (0.75 in.)
L'	0.52 $\mu\text{H}/\text{m}$
R'	167 $\mu\Omega/\text{m}$

These components were assembled into the experimental system shown in Fig. 3.

Fig. 2. Parallel rail round-bore launcher.

Fig. 3. Compact HPG, coaxial inductor, two-stage opening switch and railgun system.

SYSTEM OPERATION

Steps necessary to perform an HPG/I driven experiment are listed below:

1. Prepare homopolar auxiliaries for test
2. Prepare mechanical opening switch
3. Test integrity of bridgwire detonator circuit
4. Connect explosive to detonator chassis
5. Motor HPG to speed
6. Discharge HPG (Fig. 4)
7. Use delay timers to predict peak current
8. Actuate mechanical switch which will break primary circuit for 3 ms (Fig. 5)
9. Detonate explosives after current commutation to explosive switch elements (Fig. 6)
10. Detonate explosives to crowbar breech of railgun after acceleration time interval (Fig. 7)
11. Mechanical switch remakes to remove residual energy from HPG (Fig. 7)

During actual testing, steps 9 and 11 were identified as the problem areas. In operation, the contacts in the mechanical switch slide from a copper armature onto a ceramic insulator to interrupt current. After the current has gone to zero in the mechanical switch and risen to full value in the explosive switch, the explosives may be detonated to force current into the railgun. Deriving a noise immune signal to realize this goal turned out to be a major problem. Four candidate trigger systems were implemented and tested before a satisfactory system was identified.

Signal and Operation

Problem

1. The signal from a linear displacement transducer connected to the armature would be delivered to a comparator with a position reference voltage equivalent to the voltage corresponding to the contacts being midway on the ceramic interruption	The arcing associated with the initial commutation would impose a noise signal on the linear displacement transducer and the comparator would trigger early

Fig. 4. Charging circuit

Fig. 5. Commutation to explosive stage

Fig. 6. Commutation to railgun

Fig. 7. Railgun crowbar followed by remake of mechanical switch

2. A rigid post was attached to the armature surface and a photo interrupter was fixed to the stationary switch body. The two were positioned to give an output signal when the contacts of the mechanical switch were midway on the ceramic interruption
 3. The photo diode holder was rebuilt to hold a graphite rod that could be used as a break switch. The post on the armature would break the graphite and provide a signal to the explosive switch when the contacts of the mechanical switch were in a favorable location
 4. The final system that has proven to be reliable is well shielded Rogowski loop measuring current commutated into the explosive switch loop. Upon current commutation to the second-stage switch the Rogowski loop voltage would go high and trigger a time delay. Upon time out of the delay a signal would trigger the explosive chasis
- Enough light was given off by the commutation arc that the photodiode was triggered on first current break. This would lead to early interruption of the explosive elements and potential damage to the mechanical switch contacts
- The holder was inaccessible and loading and verifying integrity of the graphite break switch was too difficult to be reliable. This system was also susceptible to vibration
- The problem with this system is that it relies on knowing the speed of the armature. The time delay multiplied by the armature speed is the displacement which is trying to be resolved accurately. As the current in the switch increases the downforce of the contacts goes up and the velocity of the switch may vary
- The last system reviewed has worked well enough to allow proper operation of the system.
- Potentially a more serious problem associated with step 9 is that a large voltage is developed when the explosive gaps rapidly commutate current to the railgun. The interrupting gap in the mechanical

Switch has only had a millisecond to recover before the high potential is applied. Several successful rapid commutations were performed into fixed resistive and inductive loads, but the first attempt to rapidly commutate into a sliding fuse element in a railgun required more developed voltage. In this test, the mechanical switch restructured to the breaking surface. A continuous annulus of Nomex® paper was mounted in a rigid holder just outboard of the breaking contacts of the mechanical switch. The continuous tight-fitting ring would collect arc debris away from the arcing gap and block the line of sight of the contact back to the break surface. This scheme worked for one successful railgun test, but on successive tests, the switch flashed over to the remake surface.

The second problem area (step 11) has been the remake of the HPG. If the generator is discharged from a high speed into a room temperature inductor, there is appreciable rotor speed at peak current. If the railgun is then fired, the open circuit voltage of the generator cannot sustain current in the circuit as the arc leaves the end of the launcher. At this point, current extinguishes in the circuit and the homopolar is stopped with mechanical friction from the brushes. It was not considered good practice to stop the HPG with its brushes after the test for fear of damage to the machine.

For this reason, the mechanical switch actuation was designed to move from the ceramic interruption back onto the armature surface and therefore continue discharge of the HPG. The residual energy would then be dissipated electrically instead of in mechanical friction. Since the time that this scenario was formed and the opening switch constructed, an explosive crowbar has been added to the breech of the gun to cut current off to the gun and to stop damage to the end of the launcher and downrange diagnostics.

The magnetic energy trapped between the remake contacts of the mechanical switch and the explosive crowbar is of great enough magnitude and discharges with a short enough time constant to cause pitting of the remake surface. This pitting causes molten copper to be wiped under the remake contacts and the resistance of the interface goes up. The continued discharge of the homopolar into the switch then causes intolerable damage.

These problem areas have been addressed in a recent rebuild of the switch. The remake feature has been eliminated, thus removing the narrow window of actuation defined by mechanical switch break and remake. Therefore, the Rogowski trigger system should be reliable now that the armature speed need not be known. Also, with the remake eliminated, the contacts will not be damaged and a surface that has been a sight of switch restrike has been eliminated.

With the removal of the remake function from the mechanical switch, it is anticipated that the railgun breech crowbar switch (Fig. 8) may also be used to maintain the HPG under electrical load. In Fig. 7, it is seen that if the current path in the mechanical switch is disallowed, the parallel path through the explosive crowbar remains. Future testing of the explosive crowbar with heavier armatures will increase its I^2t rating, allowing residual HPG energy to be removed through electrical dissipation throughout the discharge circuit as opposed to brush friction within the HPG.

Fig. 8. Explosively driven breech crowbar switch

THE EXPERIMENT

Data from two experiments are discussed in this section. Results of the first experiment is shown in Fig. 9. The test was a 135 kA commutation of the two-stage switch into a fixed 50-nH load. The first picture (Fig. 9a) shows the current profile of the HPG charging the inductor. (See Fig. 10 for signal identification.) At the time-of-peak current, 220 ms, the mechanical switch actuates and commutates current into the second-stage explosive switch. The transfer time is marked with the Nicolet cursor in Fig. 9b and 9c. The current dwells in the explosive switch for just over a millisecond, a time interval programmed to allow the arcing gap in the mechanical switch to recover to high insulation strength. The explosive switch actuates and transfers current to the load in 14.2 μ s as shown with the Nicolet cursors in Figs. 9d and 9e.

Fig. 9. Commutation data for transfer into a fixed load.

Fig. 10. Signal identification.

The second experiment was a railgun test and the experimental results of the commutation from the explosive switch to the railgun are shown in Fig. 11. There was not a design effort to construct a low impedance bus to connect the explosive switch to the railgun. An existing busbar used with a high voltage capacitor bank was used for expediency. The inductance from the switch to the railgun breech was 420 nH. Also, the electrical contact in the gun was a

copper foam element with light contact pressure against the rails. These two experimental conditions, high inductance and high resistance in the commutation path, make this experiment a near worst case effort for an attempted commutation. It can be seen that the commutation time is drawn out to 100 μ s because of the high inductance commutation path. The four parallel explosive gaps have problems achieving complete commutation until 400 μ s, but show no indication of restriking for the total 500 μ s event.

Fig. 11. Commutation data from a railgun test.

The test was a successful commutation and railgun shot. Attention to bus design and a clamped low resistance element in the railgun will greatly enhance performance of the system.

CONCLUSIONS

A very fast commutation 14.2 μ s has been demonstrated with the two-stage opening switch. Even under very demanding conditions, transfer into a high inductance and resistance commutation path, the switch has been able to provide the power conditioning for a railgun experiment. Modifications to the switch which include removing the remake feature in the mechanical switch and relocation of the explosive elements to reduce energy deposition in the mechanical contacts will be tested to establish further reliability of the design.

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