INSTRUMENTATION FOR EM LAUNCHER SYSTEMS

K. E. Nalty, R. C. Zowarka, and L. D. Holland

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Center for Electromechanics
The University of Texas at Austin
Balcones Research Center
EME 1.100, Building 133
Austin, TX 78758-4497
(512)471-4496

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K. E. Nalty, R. C. Zowarka, and L. D. Holland
Center for Electromechanics
The University of Texas at Austin
Taylor Hall 227
Austin, TX 78712

Summary

This paper reviews the techniques found successful for the measurement of current, voltage and velocity in electromagnetic (EM) launcher experiments at the Center for Electromechanics at The University of Texas at Austin (CEM-UT). Current measurement methods using shunts, current transformers, and Rogowski coils are presented and discussed. Special attention is given to the construction and calibration of Rogowski coils and their integrators. Voltage measurements by means of high impedance voltage dividers and current transformers are reviewed. Finally, velocity measurements are presented, with attention to obtaining reliable measurements from time-of-flight velocimeters and ballistic sleds.

Introduction

Unlike conventional chemically powered guns, railguns allow fairly easy transient measurements of driving forces. From measurements of breech and muzzle voltage, rail current, and projectile velocity, the performance and efficiency of railguns can be determined. Problems encountered in electric gun research frequently center around making safe, accurate measurements of currents in hundreds of kiloamperes, voltages in the kilovolt range, and projectile velocities between 1 and 20 km/s. The purpose of this paper is to present the techniques for making these measurements that have been found to be successful at CEM-UT, in hopes of reducing the frustration and loss of time that newcomers to the electric gun research community will experience.

Current Measurement

Shunts

Railgun current levels are typically in the range of 100 kA to 2 MA. Rise times vary from approximately 0.3 s for HPG-charged inductive stores to less than 10 μ s for capacitive discharge stores. Common-mode voltages associated with the currents range from near zero to several thousand volts. The net result of these conditions is to discourage direct measurement of current via shunts or sampling resistors. Instead, indirect measurements of current by means of current transformers and Rogowski coils are used. The shunts used are empirically calibrated, low inductance sections of buswork. Low inductance in the shunt is necessary to prevent $L(di/dt)$ voltages from corrupting measurements of current. Buswork, rather than commercial shunts, is used because of the coulomb load and resultant heating effects. Finally, shunts require the use of voltage dividers on instrumentation to reduce common-mode voltage when those voltages are large (40 V or larger). These dividers, in turn, reduce the signal-to-noise ratio in the current measurement.

Current Transformers

Indirect measurement of currents by means of current transformers and Rogowski coils has the advantage of providing a measurement independent of common mode voltages. Current transformers provide a convenient

means for measuring low currents or very brief, high-amplitude currents, but are restricted by a coulomb limit. Once this limit is exceeded, the current transformer output becomes nonlinear due to saturation of the magnetic core. For example, the Pearson model 301X pulse current transformer is rated at 22 A.s. This means it can accurately measure only those current pulses whose integrated current-time product is below 22 A.s.

Rogowski Coils

Measurements of current without a saturation effect can be performed using air-core Rogowski coils and integrators. In its simplest form, a Rogowski coil is a spiral winding on a circular hoop. In practice, we usually use two layers of spiral winding, one of opposite pitch to the other, to help cancel the effect of stray magnetic fields upon the coil. Also, a shield is usually employed to reduce capacitive pickup.

The Rogowski coils used at CEM-UT are manufactured in-house. Two types of construction are used. The more accurate and suggested construction technique uses G-10 or a similar reinforced plastic to build a rigid hoop for the coil. Such a coil is illustrated in a cut-away display in Fig. 1. A second technique, which is easier to construct and install, but which is potentially less accurate, is a wrap-around Rogowski coil wound as a spiral on a BNC coaxial line (such as RG58 A/U), and covered with heat-shrink tubing for protection. The two leads of the coil are connected to the BNC cable shield and inner conductor, allowing the output of the coil to be taken in the BNC connector. The coil is wrapped around the conductor carrying the current to be measured.

Fig. 1. Construction of rigid Rogowski coils

The Rogowski coils made at CEM-UT are all non-self-integrating coils. That is, they are wound in such a manner as to cause the output of the coil to be proportional to di/dt , rather than to I itself. As a result, an integrator is needed to complete the current-measuring system. This integrator may be as simple as a passive RC circuit for moderately fast systems (1 μ s to 10 ms) such as railguns, or they may be feedback amplifier based integrators, as are used on long-pulse systems, such as homopolar generators.

For exceptionally fast systems, such as particle accelerators, the L/R characteristics of the coil itself may be used to make a self-integrating Rogowski.

The design equations for non-self-integrating Rogowski coils which follow assume that negligible current flows in the windings of the Rogowski coil (i.e., the voltage measurement is made with a high-impedance device). Given this assumption, the induced voltage in one turn of the coil is

$$V_{\text{turn}} = \frac{d\phi}{dt} = A \frac{dB}{dt}$$

where

A = cross-sectional area of the coil winding form

B = flux density through the form

For a coil of n turns and a circular form with the current-carrying conductor centered in the form, each turn has the same induced voltage, and

$$V_{\text{coil}} = nA \frac{dB}{dt}$$

Again, assuming the current-carrying conductor to be centered in the form, we may express B as a function of the current and the radial distance as

$$B = \frac{\mu I}{2\pi r}$$

where

I = current to be measured

r = mean radius of the coil from the current-carrying conductor

Hence, we have for the induced voltage the Rogowski coil

$$V_c(t) = \frac{nA\mu}{2\pi r_0} \frac{dI}{dt}$$

When the output of this coil is integrated, we have a voltage signal that is proportional to the current in the conductor passing through the form.

In the design sequence, the physical dimensions for the form are first established, usually defined by the shape of the machine or buswork that the coil will be installed upon. A coil output voltage is chosen based on the sensitivity and voltage limits of the measuring instruments. Finally, given the value of dI/dt in the current waveform to be measured, the number of turns in the coil is chosen.

Sample Rogowski Coil Design

For the systems tester homopolar generator at CEM-UT, the available space in which to place a coil will allow a hoop of 85-cm (33.5-in.) inner diameter, 88.3-cm (34.77-in.) outer diameter, and 1.6-cm (0.625-in.) height. The actual size of the form was selected to be that of a hoop made of 0.95-cm (3/8-in.) G-10 glass fiber-filled epoxy with an inner diameter of 85.7 cm (33.750 in.), 1.6 cm² outer diameter of 87.6 cm (34.5 in.), and a cross-section of 1.6 cm² (3/8 in.²). The extra space allows room for windings, insulation, and clearances. In practice, the cross-section is not perfectly square, as we have broken all sharp edges with a file, but we will consider it square for calculation purposes. Estimate the maximum dI/dt of the system tester to be 15 MA/s. The active integrator requires signals between 10 mV and 10 V. Using a desired output of 0.5 V for the highest anticipated dI/dt, which gives a factor of safety of 20 for analyzing fault currents, the number of turns for the coil is calculated as follows:

$$\text{Area} = 9.073 \cdot 10^{-5} \text{ m}^2$$

$$r_0 = 0.433 \text{ m}$$

$$\mu = \mu_0 = 4\pi \cdot 10^{-7} \text{ H/m} = 4\pi \cdot 10^{-7} \frac{\text{V}\cdot\text{s}}{\text{A}\cdot\text{m}}$$

$$0.5 \text{ V} = \frac{n(9.073 \times 10^{-5} \text{ m}^2)(4\pi \times 10^{-7} \frac{\text{V}\cdot\text{s}}{\text{A}\cdot\text{m}})(15 \times 10^6 \text{ A/s})}{(2\pi)(0.433 \text{ m})}$$

$$0.5 \text{ V} = n(6.29 \times 10^{-4}) \text{ V} \quad \text{or} \quad n = 795 \text{ turns}$$

These turns will require two layers, since the form can accept roughly 400 turns per layer. The mean circumference of the coil is 272 cm (107 in.). A convenient procedure for construction of the coil is to wind one turn every 0.64 cm (1/4 in.), yielding 429 turns per layer.

The anticipated output of this coil will then be

$$\begin{aligned} V_c &= \frac{nA\mu_0}{2\pi r_0} \frac{dI}{dt} \\ &= \frac{(858)(9.073 \times 10^{-5} \text{ m}^2)(4\pi \times 10^{-7} \frac{\text{V}\cdot\text{s}}{\text{A}\cdot\text{m}})}{2\pi(0.433 \text{ m})} \frac{dI}{dt} \\ &= 3.596 \times 10^{-8} \frac{dI}{dt} \end{aligned}$$

For a 15 MA/s rise time, the output is

$$V_{c_{\text{max}}} = 0.539 \text{ V}$$

which is within the proper range for the integrators.

Sample Rogowski Integrator Design

The next task for making the current-measuring system is to build the integrator for the coil. Because of the long anticipated pulse times of the systems tester homopolar generator (~ 0.1 to 2 s), an active integrator will be used. A schematic of this integrator is given in Fig. 2. The integrator output can be written as

$$V_{\text{int}} = \frac{1}{RC} \int V_c dt$$

where R and C = components so labeled in Fig. 2.

Typical values for C range from 0.001 to 0.22 μF , typical values for R range from 1 to 100 k Ω . The output of the integrator, considering the form factor of the system testers coil, is

$$V_{\text{int}} = \frac{1}{RC} (3.506 \times 10^{-8}) I, \quad I \text{ in A}$$

or

$$= \frac{1}{RC} (3.596 \times 10^{-2}) I, \quad I \text{ in MA.}$$

Let C = 0.22 μF , then for an output of 1 V per 250 kA,

$$1 \text{ V} = \frac{1}{R(2.2 \times 10^{-7})} (3.596 \times 10^{-2})(0.25)$$

or

$$R = 40.9 \text{ k}\Omega$$

A 100 k Ω , 10-turn trim potentiometer is used for R. The value of R can be adjusted during the calibration process to obtain the desired output scale factor. The purpose of the relay shown in Fig. 2 is to minimize drift of the integrator and to ensure that integration begins from initial conditions of zero voltage.

Fig. 2. Rogowski coil active integrator

Rogowski Coil Calibration

After building the Rogowski coil and integrator, the remaining task is to calibrate the coil against a reference. This calibration step is necessary to account for errors due to the approximations used in calculations and to tolerances in manufacturing. Calibration consists of measuring a current with both the Rogowski coil and a reference, such as a commercially-available current transformer. One method used at CEM-UT for producing apparently high currents and dI/dt for the coil while simultaneously observing the coulomb rating of the current transformer is to pass multiple loops of a current carrying cable (4/0 welding cable) through the coil, but only a single turn through the current transformer. Both I and dI/dt as measured by the coil are scaled up by the number of turns through it, whereas the current transformer sees only the current in the conductor. If a capacitor of known value is charged to a known voltage, we can ensure that the $I \times t$ or coulomb rating of the current transformer is not exceeded, while achieving apparently high current and dI/dt in the coil.

Another method for calibrating Rogowski coils involves measuring the current flowing in an RLC circuit, when the resistance, inductance, capacitance, and initial capacitor voltage are known. The transient current in an underdamped RLC circuit where the initial voltage on the capacitor is V_0 and the initial inductor current is zero is

$$I(t) = \frac{V_0}{L} \left[\left(\frac{1}{LC} - \left(\frac{R}{2L} \right)^2 \right)^{-1/2} e^{-(R/2L)t} \sin \left(\sqrt{\frac{1}{LC} - \left(\frac{R}{2L} \right)^2} t \right) \right]$$

$$\text{Let } \omega = \sqrt{\frac{1}{LC} - \left(\frac{R}{2L} \right)^2}$$

The time to peak current is found by letting $dI/dt = 0$

$$t_{I_{\max}} = \frac{1}{\omega} \tan^{-1} \left(\frac{2L\omega}{R} \right)$$

The peak current is found by using the above value for $t_{I_{\max}}$ in the equation for current above. Given that V_0 , L , R , and C can be accurately measured,

which is usually the case with capacitively driven systems, a Rogowski coil can be empirically calibrated by discharging the above RLC system and measuring peak current and time to peak with the coil under test.

For a calibration when R is negligible, we can greatly simplify the above to obtain

$$I(t) = V_0 \sqrt{\frac{C}{L}} \sin \left(\sqrt{\frac{1}{LC}} t \right)$$

$$I_{\max} = V_0 \sqrt{\frac{C}{L}}$$

$$t_{\max} = \frac{\pi}{2} \sqrt{LC}$$

Voltage Measurements

In this section, a review of two techniques used at CEM-UT for measurement of voltages of the range 20 V to ~ 10 kV is presented. These voltages are encountered when measuring railgun breech and muzzle voltages and transients in capacitive store-driven guns.

The first technique is the use of high-impedance voltage dividers. These dividers reduce the signal-to-noise ratio and are potentially difficult to compensate properly for frequency.

The second technique is the use of a voltage sampling, low-inductance resistor with a current transformer. The advantage of this technique is differential measurement of voltage without common-mode voltage affecting the instrumentation. The disadvantage is that the use of a current transformer limits one to measuring only transient signals.

Projectile Velocity Measurements

The most important piece of information from an EM launcher is the velocity of the projectile. In ballistic research, a widely-accepted technique for measuring velocity has been the use of a two-stage flash x-ray unit. The advantage of the x-ray unit over other methods of measurement is its ability to verify the physical condition of the projectile as well as its velocity. One disadvantage of the x-ray unit is the time delay inherent in developing an image before a velocity measurement can be obtained. Further disadvantages include the high initial cost of flash x-ray units ($> \$100,000$) and the personnel protection and exposure documentation required for the use of high-power x-rays.

Time-of-Flight Velocimeters

The velocimeters used CEM-UT are of two types, time-of-flight velocimeters, and ballistic sleds. The time-of-flight velocimeters are clock-driven counters, which measure the time of flight of the projectile between two sensing positions. The most serious problem with time-of-flight velocimeters is false triggering due to electrical noise or acoustical shock. Our earliest velocimeters were of the breaking-switch type, in which pieces of pencil lead carrying small currents were broken by the projectile in flight. These switches were susceptible to electrical noise pickup. To eliminate the electrical pickup problems, a laser fence was next used, in which the projectile interrupted laser beams focused on fiber optic receiving ports. This provided a good solution to electrical pickup, but at higher projectile velocities the acoustic shock and mechanical vibration of the railgun generated false triggering and unreliable data. Three

trigger stations are used in the laser-based time-of-flight measuring system. If the measured velocity between the first two stations is less than between the latter two stations, or if the two velocities are not comparable to each other, then the data are suspect. False triggering due to acoustical and mechanical shock disappears when velocities begin to exceed the speed of sound in metal.

Our present solution, which seems fairly reliable, uses a making switch in conjunction with the lasers for triggering. The making switches consist of two sheets of brass shim stock separated by a 0.08-mm (0.003-in.) Mylar sheet. Before the projectile hits, the brass sheets are insulated from each other by the Mylar. As the projectile leaves, the torn edges usually contact and short out. To detect the shorting of the brass sheets, a voltage of 2.5 kV is applied across the Mylar. The value of 2.5 kV was chosen on the basis of the observed 50 V_{pp} noise picked up by the screens during a railgun shot. By using a 2.5 kV signal, the signal-to-noise ratio becomes good enough to provide an accurate trigger signal. A typical trace for the velocimeter output is shown in Fig. 3.

Fig. 3. Making switch trigger trace

Ballistic Sled Velocimeters

The velocity-measuring device used at CEM-UT that is least susceptible to noise is the ballistic sled, sketched in Fig. 4.

The ballistic sled is a lead shot-filled catch tank mounted on ball bearings and free to travel about 15 cm (6 in.). A tapered land on top of the sled is interrogated by an eddy-current displacement probe, with the distance between the land and the probe indicating the position of the sled.

Fig. 4. Simplified ballistic sled

Knowing the masses of the projectile and the sled, M_s and M_p , and having measured the velocity of the

sled, v_s , by means of displacement probes, we can obtain the projectile velocity, v_p , from the law of conservation of momentum.

$$v_p = v_s \frac{M_s + M_p}{M_p}$$

A typical trace for such velocimeter is shown in Fig. 5. The initial spike occurs as the unmachined part of the sled moves under the probe. The ramp occurs as the machined taper travels under the probe. The final flat area occurs when the sled comes to rest at the end of its track.

Fig. 5. Displacement probe trace looking at ballistic sled

The main advantage of the ballistic sled measuring system is that it is extremely noise-immune, since all measurements occur after the electrical pulse is over.

Conclusions

This paper has described the methods for making current, voltage, rotor speed, and projectile velocity measurement presently being used with EM launcher systems at CEM-UT. Some of these techniques will no doubt be further refined and replaced in the future as better methods become available.