HELICAL EXPLOSIVE FLUX COMPRESSION GENERATOR RESEARCH AT THE AIR FORCE RESEARCH LABORATORY

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Abstract

The inherent high energy density of explosives make them an obvious choice for pulsed power systems requiring high peak power and energy in compact packages. Ongoing research at the Air Force Research Laboratory's Directed Energy Directorate into helical explosive flux compression generators is discussed. These generators provide the initial pulsed power drive for a high voltage, long pulse system, which is the subject of a companion paper. The helical generator research described here centers on experiments utilizing two distinct generator designs, based on 7.6 cm. and 15.2 cm. diameter aluminum armatures, respectively. Experiments using several different stator coil winding schemes with these armatures are described.

I. INTRODUCTION

High explosives provide extremely high energy density (~4 MJ/kg) and discharge times which are suitable for many pulsed power systems (often with further conditioning). Helical explosive flux compression generators (FCGs) generally provide high current and energy gain. However, they are low impedance current sources and require power conditioning to match the generator to high voltage, high impedance loads. Additionally, while the discharge time of helical FCGs is of the order of microseconds to tens of microseconds, many loads require fast rise times and somewhat shorter, high fidelity pulses. Thus the pulse conditioning system often must provide both temporal and impedance matching between the FCG and the load.

In an ideal FCG the magnetic flux is conserved, that is,

$$\frac{d}{dt}(\Phi) = \frac{d}{dt}(LI) = 0 \Rightarrow L_f I_f = L_i I_i \qquad (1)$$

where Φ is the magnetic flux, L_i and I_i are the initial FCG inductance and current, respectively, and L_f and I_f are the final inductance and current after generator burnout. Thus, the ratio of final to initial current (often called the current gain) is simply given by the initial to final inductance ratio. In actual generators, some magnetic flux is dissipated by various mechanisms. In a circuit sense, the dissipation is often lumped into an equivalent resistance, R, which results in the output current being given by [1]

$$I(t) = I_i(L_i / L(t)) \exp\left[-\int_0^t (R / L(\tau)) d\tau \right] \qquad (2)$$

where $I(t)$ and $L(t)$ are the instantaneous current and inductance, respectively.

In many applications of interest, the output magnetic flux from the helical FCG into the load is the key parameter, and thus the important figure of merit for compact helical generators is the flux conservation, i.e., the ratio of final to initial magnetic flux. The flux conservation in a real generator is always less than one.

Flux loss mechanisms in FCGs include flux which is trapped and cannot be compressed, such as when the armature skips one or more turns. Flux which diffuses into either the stator or armature conductor cannot be compressed and is thus lost to the generator. At current levels generally found in FCGs, nonlinear diffusion and proximity effect are often at play. Nonlinear diffusion results from Joule heating of a conductor causing the resistivity to increase, resulting in increased magnetic diffusion, further Joule heating, and higher resistivity. As the conductor temperature approaches the melting point, the resistivity increases sharply during the phase change and the diffusion increases with it. Proximity effect occurs when the large magnetic field surrounding one conductor (due to large currents flowing in the conductor) influence the distribution of currents in adjacent conductors. Proximity effect can cause local current concentrations in conductors resulting in enhanced nonlinear diffusion.

Therefore, the detailed design of helical FCGs involves to a great extent minimizing the heating of conductors to keep conductor in the solid phase. This involves controlling the current density in the stator conductor by controlling the diameter of the conductor. As the generator burn progresses, the stator current increases exponentially and thus the conductors are often bifurcated and/or increased in diameter to keep the current density (or, equivalently, magnetic flux density at the conductor surface) below a critical value. Such current density

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14. ABSTRACT
The inherent high energy density of explosives make them an obvious choice for pulsed power systems requiring high peak power and energy in compact packages. Ongoing research at the Air Force Research Laboratorys Directed Energy Directorate into helical explosive flux compression generators is discussed. These generators provide the initial pulsed power drive for a high voltage, long pulse system, which is the subject of a companion paper. The helical generator research described here centers on experiments utilizing two distinct generator designs, based on 7.6 cm. and 15.2 cm. diameter aluminum armatures, respectively. Experiments using several different stator coil winding schemes with these armatures are described.

15. SUBJECT TERMS

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control may obviously be repeated numerous times along the length of the generator. However, the current density may not be made arbitrarily small, as doing so generally drives the inductance gradient of the generator down (the inductance gradient, dL/dz, coupled with the axial burn velocity of the explosive in the armature, v_z, results in the IdL/dt voltage which drives the load). Thus the design of a helical generator involves, among other things, a tradeoff between minimized flux loss and efficient driving of the load.

In addition to the heating mechanisms outlined above, several others have been identified, including shock heating of the armature by the explosive pressure and heating due to plastic work done on the armature conductor. These additional heating sources are discussed in [2].

The voltage developed across the generator can result in electrical breakdown between the stator and the armature, resulting in lost output to the load. Additionally, the LdI/dt voltage across the stator can lead to turn to turn breakdown, which is a flux loss mechanism similar to turn skipping. Magnetic forces can be great enough to cause deformation of the stator conductors, leading to local electric field enhancement and premature insulation failure. Thus, the design of all practical FCGs must take all of these factors into account.

II. COMPUTATIONAL EFFORTS

Several computer codes are used or are in development in support of the Air Force Research Laboratory (AFRL) explosive pulsed power program. These include circuit codes such as Microcap and circuit-based, generator-specific design and modeling codes such as CAGEN [3]. CAGEN models helical and coaxial explosive flux compression generators as circuit elements containing conducting armatures driven by high explosives. Being primarily a modeling code, CAGEN requires some empirical feedback. Specifically, the flux loss term discussed above is primarily lumped into a resistance called the contact resistance, which is a free parameter which may be adjusted to match experimental results.

Material interface tracking and explosive detonation capability have been incorporated into MACH2, a 2 1/2 dimensional magnetohydrodynamic code [4]. MACH2, and MACH3, the fully three dimensional version under development, are well suited to detailed studies of areas such as armature expansion and stator/armature interactions.

III. EXPERIMENTAL FACILITIES

The AFRL explosive pulsed power facility is located in a remote canyon and can accommodate experiments of up to 1000 lb of high explosives. The experimental facility includes a 200 kJ, 10 kV capacitor bank for providing seed flux for FCGs. The output of this bank is fed through fifty low inductance coaxial cables to a detonator driven switch located near the explosive pad. The current is then fed to the explosive firing point on the pad. Capacitor discharge units (x-units) for driving detonators are located in concrete culverts near the firing point. Diagnostic coaxial and fiber optic cables terminate in a small diagnostic shed on the pad. Another shed located on the pad houses a Beckman and Whitely 189 high speed framing camera, which is used for optical diagnosis of explosive events. Electrical and optical signals are fed to a screen room located in the explosive facility. This screen room houses controllers for the capacitor bank and x-units, 28 digitizer channels, timing and delay systems, and a computer control and data acquisition system. A streak camera records signals from a crushed fiber optic diagnostic system, which is used to provide a temporal record of the armature impact with the generator stator.

Another explosive site (Chestnut) has recently been developed and is presently being used for the bulk of our experiments. It can handle up to 750 lb of HE and has seed capacitor bank and diagnostic capabilities similar to those described above.

IV. EXPERIMENTS

Explosive pulsed power experiments began at the Air Force Research Laboratory in the summer of 1995 with joint pulsed magnetohydrodynamic experiments with Sandia National Laboratory. These experiments, which are described in [5], spurred the development of explosive experiment infrastructure at the AFRL. Early explosive flux compression generator experiments centered around the use of simple helical explosive generators. These experiments drove further development of explosive experiment infrastructure and diagnostic techniques, and provided benchmarking data for design and analysis codes. These experiments are detailed in [6].

The next experiments were performed using 7.6 cm. armature-based generators. These generators were wound with various bifurcated winding schemes for limiting current density and, therefore, conductor surface magnetic flux density. These generators used aluminum armatures with hand packed C4 explosive systems. These experiments were primarily designed to provide empirical benchmarking data for the CAGEN generator modeling code. Later experiments utilized these generators with PBXN-110 explosive systems to test various concepts individually. Due to space limitations, these experiments will not be discussed in detail here and will be the subject of a future publication.

Numerous experiments were done using 15.2 cm. armature-based generators, i.e., twice the armature and stator diameter of the 7.6 cm. generators. The goal of these experiments was primarily the attainment of the ultimate required output current and magnetic flux to the load. Numerous changes were made to the 15.2 cm. armature based generators (relative to the 7.6 cm. generators) more or less simultaneously. While ideally such changes would be made incrementally so their effect on generator performance could be determined, this was not possible due to schedule and cost constraints (the 7.6 cm generator experiments mentioned above were designed to assess the effects of the changes in half scale tests). The major changes include:

-Cold cast PBXN-110 explosive in place of hand loaded C4.

-Greater aluminum armature wall thickness

-Concrete tamping (inertial confinement) of the stator winding

-Two parallel generator windings

-550 nH load inductance (*vs.* 250 nH)

-Low mass crowbar tabs.

The PBXN-110 explosive is energetically similar to C4. The ability to cold cast the explosive gives much more uniform density than the hand packed C4. Voids and other density variations in the C4 are believed to lead to erratic armature behavior and jetting.

The thicker armatures came about as a scale up from the 7.6 cm. armatures. The wall thickness of the 15.2 cm. armatures was determined to keep the Gurney expansion angle [7] the same as in the 7.6 cm. case. The resulting armature thickness was 0.95 cm., 1.5 times the thickness of the 7.6 cm. armatures. This had the effect of increasing the magnetic flux diffusion time relative to the seed flux loading time, as detailed below. This is important, as any flux which diffuses into the armature represents flux which cannot be compressed, and therefore contributes to the overall flux loss in the generator.

The diffusion time for the 15.2 cm. armature, t_d', is related to the diffusion time for the 7.6 cm. armature, t_d, by

$$t_d' / t_d = (d_r' / d_r)^2 = (1.5)^2 = 2.25, \qquad (3)$$

where d_r', d_r are the wall thickness of the 15.2 and 7.6 cm. armatures, respectively. The seed current loading time for the 15.2 cm. armature based generator, t_s', is related to that for the 7.6 cm. armature based generator, t_s, by

$$t_s' / t_s = (L_g' / L_g)^{0.5} = (2)^{0.5} = 1.4, \qquad (4)$$

where L_g', the initial inductance of the 15.2 cm. generator, is approximately twice L_g, the inductance of the 7.6 cm. generator. Thus, the increase in the magnetic diffusion time is approximately 1.6 times greater than the flux seeding time for this increase in armature dimensions.

These generators had two windings in parallel (displaced 180 degrees in azimuth) to take advantage of inherent feed and load symmetry. The low mass crowbar tabs were designed to provide substantial crowbar switch action at the generator input while minimizing perturbation of the expanding armature.

Within the general framework outlined above, numerous stator winding schemes have been examined, including multiple bifurcations of the windings, increases in wire diameter toward the load end of the explosive generator, and expanded stator pitch (i.e., stator turns not close packed).

The bifurcations and changes is stator wire diameter has created high current joints within the FCG, i.e., connections, which, toward the end of the generator run, are carrying megamperes of current. It is suspected that molten copper, and perhaps vapor and plasma as well, is being ejected from the joints into the volume of the generator, where it could contribute to stator to armature breakdown. An FCG was built with clear windows covering critical current joints so the joints could be imaged with a high speed framing camera during the generator operation. Analysis of the photographs indicated that light, and thus likely some material, was indeed issuing from the current joints. Steps are being taken to eliminate, or at least delay, the onset of material ejection from the current joints.

Output (load) current traces for a typical 15.2 cm. generator are shown in Fig. 1. The seed current for this experiment was 12.6 kA. This represents a current gain of approximately 120. While current and energy gain are of great interest, the single most important parameter for the AFRL explosive generator effort is the output magnetic flux delivered to the load. Figure 2 shows the dramatic increase in the output flux we have obtained as the experiments have progressed.

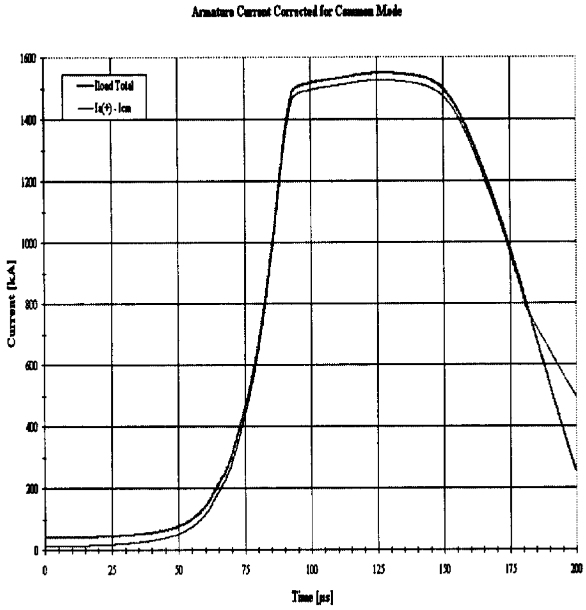

Figure 1. Explosive generator output current

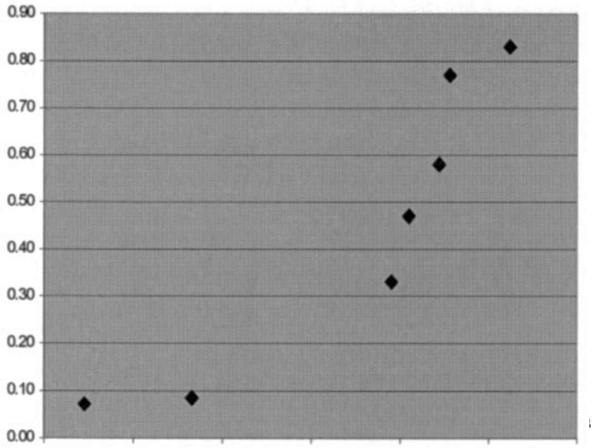

Figure 2. FCG output flux as a function of experiment date

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