AN INTRODUCTION TO THE PROPELLANT-DRIVEN
MAGNETIC FLUX COMPRESSION GENERATOR

by

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Abstract

An introduction to the concept of a propellant-driven magnetic flux compression generator is presented, together with the theory of its operation. The principles of operation of the propellant flux compression generator combine generator principles, derived from lumped parameter circuit theory, and interior ballistic principles.

I. INTRODUCTION

Explosive magnetic flux compression generators have been designed, tested, and discussed in the literature for nearly thirty years. More recently, large conferences have been held focusing on research using these generators. Many applications have been found. Explosive flux generators can generate large internal voltages when large current gains are sought. One method of reducing internal generator voltages is to use slower detonation explosives. There is a lower limit to the detonation velocities one can obtain. If, on the other hand, one were to design a propellant-driven flux compression generator, which uses the motion of a projectile in place of the detonating explosive, the design incorporates the flexibility of velocity that is found in interior ballistic design. Such a design would allow large current gains, and hence large inductance changes, without necessarily creating excessive internal generator voltages.

This report presents some elementary generator and interior ballistics theory to provide background for the propellant-driven generator. Complete coverage of either field is not intended. An excellent discussion of the basics of explosive generators can be found in the Los Alamos National Laboratory Report LA-5890-MS titled "An Introduction to Explosive Magnetic Flux Compression Generators" by Fowler, Caird, and Garn. A good discussion of the interior ballistics of guns is given in J. Corner's Theory of the Interior Ballistics of Guns (John Wiley & Sons, Inc., New York, 1950).

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II. EXPLOSIVE-DRIVEN MAGNETIC FLUX COMPRESSION GENERATORS

A. Basic Generator Concept

In an explosive-driven magnetic flux compression generator the chemical energy released from the detonation of the explosive is used to compress an already established magnetic field. Explosives drive a conductive surface which acts as containment for the magnetic flux. Work is done when the conductors move against the magnetic fields, resulting in an increase in the electromagnetic energy. This additional energy comes from the energy stored in the explosives, a part of which was transferred to the moving conductors. The explosive-driven conductors are generally called armatures, in reference to the usual rotating generators. The nondriven elements are sometimes referred to as stators. The whole device is normally called a flux compression generator, or simply a generator.

Figure 1a shows the basic components of spiral generators. The propellant-driven generator belongs to this type of generator. The load coil has a fixed inductance, L_1 , which is to be powered by the generator. The generator itself consists of the external

Figure 1a. Spiral generator before explosive initiation

spiral winding and the explosive-loaded conductive cylinder. An initial magnetic flux is supplied to the generator and the series-connected load coil from an external source, usually a capacitor bank, but in some cases a battery. The conductive cylinder, the armature, serves as part of the circuit. When the explosive is detonated, the armature expands, causing a conical metal front to move with the explosive detonation velocity. The first contact between the armature and the stationary coil, stator, shorts out the initial field source, removing it from the circuit and trapping the initial current in the generator. After this closure of the current input, the conical front proceeds down the armature, contacting the spiral turns in a continuous wiping fashion. Figure 1b depicts the generator after the explosive has been initiated and the armature has closed the current input circuit. The inductance of the generator is roughly proportional to the square of the number of turns in the spiral, and inversely proportional to the remaining length over which the turns are spaced. The generator inductance, L_g , thus varies continuously from its initial value L_0 to zero after the armature has shorted out the last turn.

Figure 1b. Spiral generator after explosive initiation

The generator inductance may be taken as a function of time in most cases. If this is the case, Figure 2 is a schematic of the generator circuit. The generator inductance is a variable inductance $L_G(t)$, and the external load to be powered is L_1 . Allowance for source or waste inductance (from various external leads to the load, residual generator inductance, etc.) is indicated by L_0 , and circuit resistance is shown as R . The equation governing the performance of this circuit is then:

$$-\frac{d}{dt} [(L_G + L_0 + L_1)I] + IR = 0; \text{ with } I(0) = I_0. \quad (1)$$

Time is measured from the instant that the armature shorts out the input current source; at this initial moment the current is I_0 and the initial generator inductance is $L_G(0) = L_{G0}$.

If the circuit is perfectly conducting ($R = 0$), the well-known electrodynamic result of flux (LI) conservation is obtained. Under this condition the conservation of flux leads to the result:

$$I = \frac{(L_{G0} + L_0 + L_1)}{(L_G + L_0 + L_1)} I_0. \quad (2)$$

Under burnout conditions, $L_G = 0$, the final current becomes

$$I = \frac{(L_{G0} + L_0 + L_1)}{(L_0 + L_1)} I_0. \quad (3)$$

Figure 2. Schematic of generator circuit

The resistance (R) in an actual circuit is usually related to the generator action in a complex way. Among the significant factors affecting the resistance are changes in conductor skin depth, temperature, and path length as generator action proceeds. For illustrative purposes, however, we shall only consider the case where R is a constant. If the inductances in the generator circuit are functions only of time, the solution for Eq. (1) is

$$I(t) = I_0 \left[\frac{L_T(0)}{L_T(t)} \right] \exp \left[- \int_0^t \frac{R}{L_T(g)} dy \right] \quad (4)$$

where the total circuit inductance $L_T = L_G + L_0 + L_1$.

If Eq (1) is expanded it reads

$$I \frac{dL_G}{dt} + L_G \frac{dI}{dt} + L_0 \frac{dI}{dt} + IR + L_1 \frac{dI}{dt} = 0. \quad (5)$$

In terms of the circuit of Figure 2, the second to fifth terms represent voltage drops across the load inductance, the resistance, the source inductance, and the residual inductance in the generator. The first term is the potential across the moving armature and, in fact, is the source voltage for the rest of the circuit. In the term dL_G/dt is analogous to a resistance and is sometimes referred to as such. Resistance, multiplied by the current I, gives the armature voltage. Thus, the armature voltages produced by a generator with a large inductance, L_{G0} , may quickly become very large when the generator is driven by explosives.

B. Transformer Use

Resistance reduces generator currents. However, there are many instances where it is desirable to drive resistive loads, such as an x-ray diode or a laser cavity. By coupling transformers to low inductance loads, it is possible to power a wide range of impedances with generators. Resistive loads as well as loads with inductances far greater than the inductance of the generator itself can be included. Figure 3 shows the schematic of a generator coupled to a load with a load inductance L_l and a load resistance R_l . The generator, or primary circuit, is assumed to have negligible resistance. The equations governing this circuit are

$$\frac{d}{dt} [(L_G + L_0 + L_p)I_p + MI_s] = 0, \quad (6)$$

$$\frac{d}{dt} [(L_s + L_l)I_s + MI_p] + I_s R_l = 0,$$

$$M^2 = k^2 L_p L_s.$$

Figure 3. Schematic of generator circuit when a transformer is used

III. PROPELLANT-DRIVEN MAGNETIC FLUX COMPRESSION GENERATOR

A. Basic Generator Concept

The basic components of the propellant-driven magnetic flux compression generator do not differ significantly from those of the explosive-driven spiral generator. The components of a propellant generator are shown in Figure 4a before firing. The primary difference between the propellant and the explosive generators is the manner in which the armature is driven down the spiral coil. In the case of the explosive generator, the armature is driven down the spiral coil by the detonation of the explosive expanding the conductive cylinder. In the propellant generator, the expanding gasses behind the projectile drive the projectile, and hence the armature, down the coil. This is depicted in Figure 4b. The lengthwise conductor in the center of the coil of the propellant generator is as necessary in the electrical circuit as is the unexpanded portion of the conductive cylinder in the explosive generator.

The propellant generator circuit has the same schematic as the explosive generator (Figure 2). Therefore, the same equations which govern the explosive generator also govern the propellant generator. The major difference in the two generators is the time dependence of the inductances. In the explosive generator, the velocity of the armature down the coil is the detonation velocity of the explosive and is a constant. For the propellant generator the armature velocity is the projectile velocity and is a complicated function of time. The velocity of the projectile is controlled by the interior ballistics of the generator, together with the armature reaction upon the projectile.

Figure 4a. Propellant generator before firing

Figure 4b. Propellant generator during firing

B. Elementary Interior Ballistics

Interior ballistics are made up of four major relationships: how the propellant burns (law of burning of propellant), the pressure effects on burning the propellant (rate of burning), how the energies are related (energy equation), and how the pressure produces acceleration of the projectile (equation of motion).

The law of burning of propellant is defined as

$$\phi = (1 - f)(1 + \theta f); 0 \leq f \leq 1 \quad (7)$$

where f is the percent of propellant left unburnt and is zero at "all burnt". θ is generally referred to as the form factor and is a measure of the propellant grain shape.

The rate of burning of the propellant is given by

$$\frac{df}{dt} = -(\beta/D) P \quad (8)$$

where D is a measure of the web of the propellant and β is a measure of the rate of burn.

The energy equation is

$$\phi C \left[\frac{RT_0}{\gamma - 1} \right] = \frac{1}{2}(1 + \chi)(1 + C/3W)W V^2 + \frac{P(1 + C/3W)}{(\gamma - 1)(1 + C/2W)} [A(\ell + x) + C\phi \left(\frac{1}{\gamma} - \eta \right)] \quad (9)$$

The term on the left of equation 8 is the energy released by burning the propellant. The first term on the right is the kinetic energy of the projectile and the burnt gasses, including the energy loss due to heating of the barrel. The second term on the right is the energy that remains in the gas. Additional definitions of variables involved are: C = weight of propellant charge, W = weight of projectile, χ = heat loss in barrel as a percent of kinetic energy of projectile, V = projectile velocity, P = breech pressure, γ = thermodynamic gas constant, R = ideal gas constant, T_0 = initial temperature, A = bore area, $A\ell$ = initial breech volume, x = projectile travel down barrel, η = propellant co-volume, ϕ = propellant specific volume.

The equation of motion is given as

$$W \left(1 + \frac{C}{2W}\right) \left[\frac{dv}{dt}\right] = AP \quad (10)$$

After all the propellant has been burnt and the projectile is still in the barrel the pressure is given by

$$P = P_B r^{-\gamma}$$

$$\text{where } r = \frac{x - \ell(1-b)}{x_B + \ell(1-b)} \quad (11)$$

$$b = \frac{(\eta-1/\gamma)C}{A\ell}$$

Here x_B is the projectile travel at the point "all burnt".

A solution of this system of equations can be made fairly easily by numerically integrating Eq. (8). Experience gained by using this system of equations in designing a number of experimental devices has shown that accuracies of 1% to 5% may be achieved.

C. Generator Theory

The theory governing the operation of a propellant-driven magnetic flux generator is a combination of interior ballistics and electromagnetic theory. In essence, the combination involves accounting for the electromagnetic energies in the energy equation of Eq. (9) and accounting for the retardation force of the armature reaction in the equation of motion of Eq. (10). The new energy equation becomes

$$\begin{aligned} \phi C \left[\frac{RT_0}{\gamma-1} \right] &= \frac{1}{2}(1+\chi)(1+C/3W)W V^2 + \frac{1}{2}[L_{PT}(t) - L_{PT0}]I_{P0}^2 \\ &+ \frac{1}{2}[(L_S+L_L) I_S(t)^2 - (L_S+L_L) I_{S0}^2] + \int_0^t R_P I_P(y)^2 dy \\ &+ \int_0^t R_L I_S(y)^2 dy + \frac{P(1+C/3W)}{(\gamma-1)(1+C/2W)} [A(\ell+x) + C\phi \left(\frac{1}{\gamma} - \eta \right)] \end{aligned} \quad (12)$$

The term on the left is still the energy released by the burning propellant. The first term on the right is the kinetic energy in

the gasses and the projectile plus the energy loss through heating of the barrel. The second term on the right is the energy stored in the inductances of the primary circuit. The third term on the right is the energy stored in the inductances in the secondary circuit. The fourth and fifth terms on the right are respectively the resistive losses of the primary and secondary circuits. The last term is the energy remaining in the gas.

The equation of motion, which includes the armature reaction retardation force, is

$$W (1 + C/2W) \left[\frac{dV}{dt} \right] = AP + I_p(t)^2 \left[\frac{dL_p(x)}{dx} \right] \quad (13)$$

where the last term on the right gives the armature reaction retardation force.

The system of equations which governs the operation of the propellant flux generator includes Eqs. (6), (7), (8), (12), and (13).

IV. PROFLUX

A propellant-driven magnetic flux compression generator has been designed to power an x-ray diode. This design has been referred to as the Proflux generator. The components of the Proflux are shown in Figure 5. The breech portion of the generator provides enough distance for the projectile to be accelerated to a reasonably high velocity before it enters the barrel coil. The breech is equipped with a side-firing ignitor, because the required center conductor rules out a center-fired ignitor. The barrel consists of a coil of heavy square copper wire potted inside a steel or aluminum barrel. The spacing and number of turns in the barrel are determined by the application; for the x-ray diode all of the turns, except the last, are of one spacing. The last turn is given a very different spacing in order to produce a particular pulse shape. The generator is coupled to the load through a transformer in order to achieve the high voltage required to drive the x-ray diode while maintaining a reduced generator voltage to prevent internal arcing.

In this design, the initial magnetic field is set up with current from a battery. The secondary of the transformer is initially shorted through an explosively opened switch which allows current to build up in the secondary circuit during the build up of current in the generator. As a result energy is stored in the inductance of the transformer secondary. When the explosive shorting switch is opened the energy stored in the transformer secondary is immediately coupled to the load. This additional energy, available after opening the shorting switch, adds a great

Figure 5. Elements of the Proflux

deal to the energy that can be supplied by the generator. Another potential advantage of an explosive shorting switch in the secondary of the transformer is to assure a rapid voltage rise on the x-ray diode to achieve proper ionization of the tube.

The heavy center conductor serves two functions. First, and most obvious, it provides a part of the electrical circuit both before the projectile enters the barrel coil and after shorting of the coil turns has begun. Second, the center conductor provides important projectile guidance.

It is essential to keep resistances at a minimum in the generator. This means care must be exercised in all aspects of the design to reduce resistance. Unwanted resistance may quickly appear in the sliding contact between the center conductor and the projectile shorting disc, or between the shorting disc and the coil turns. The resistance of the sliding contact between the disc and the center conductor may be reduced by using a conductive lubricant. To ensure minimum resistance of the sliding contact between the shorting disc and the coil turns, two design changes have been made. First, the inside diameter of the coil is slightly tapered so that the diameter of the turns decreases as the disc proceeds down the barrel coil. The outside diameter of the shorting disc is smaller than the minimum inside diameter of the barrel coil and then is knurled to a diameter only slightly larger than the maximum inside diameter of the barrel coil. In this fashion, the diameter of the disc may be decreased by sliding on the barrel coils without forcing the coil turns out of the potting material. The action of the knurled disc also works well to sweep

clean any corrosion build-up on the turns and to prevent an increase in sliding resistance.

The second feature of the design that reduces sliding resistance is placing the potting material between the coil turns so that its surface is at a greater diameter than that of the inside of the turns themselves. In this manner, the potting material does not have contact with the sliding disc, and no wearing of the disc occurs nor can any of the material get between the disc and the coil turns.

Because of this difference in the surface level of the coil turns and the potting material between the turns, coupled with the need for the diameter of the shorting disc to be slightly larger than the rest of the projectile, the projectile cannot depend upon the sliding contact of the shorting disc alone to guide it down the barrel. The center conductor provides the necessary guidance for the projectile down the barrel coil.

The difference in the diameters of the coil turns and the potting material between the turns makes it impossible for a gas seal of any usual gun design to be used to keep gasses from the burning propellant from passing through this small opening and getting in front of the projectile. If these ionized gasses get in front of the shorting disc they offer an increased potential for internal generator arcing. To prevent the gasses moving head of the disc, the design of the Proflux includes a breech-to-barrel adapter with escape ports for the gasses before they get around the projectile. This has a secondary advantage in that the relief of pressure prior to the projectile rear seal entering the barrel means that the barrel does not need to withstand the full amount of pressure that is exerted on the breech. A great weight reduction results because the barrel can be made of significantly lighter material.

D. Some Practical Design Considerations

1. Timing

Propellant-driven devices have an inherently large jitter in the time when the projectile reaches a given barrel position. This jitter is due to several factors. At early times the propellant burn rate is very low due to the low initial pressure making small variations in pressure become large variations in time to achieve a specified projectile travel. Most propellant ignition methods include mechanical devices with considerable inertia providing another source for considerable time jitter.

Whatever the source of the time jitter in propellant-driven devices, the designer of a propellant generator must keep timing in mind. This difficulty might be avoided by using the position of the projectile to initiate other events. Thus, any uncontrollable jitter in the time for the projectile to reach a

certain position becomes immaterial. This method is used in the Proflux design to drive an x-ray diode, discussed later.

2. Projectile velocity

The action of the flux compression generator depends upon trapping the magnetic flux in an initial field and compressing the field by the motion of a conducting surface. In the case of the propellant generator the conducting surface is the face of a projectile sliding down the center conductor and shorting out the spiral coils. If the velocity of the projectile is too slow, the magnetic field may not be effectively trapped. Therefore, the projectile must be allowed some time, or travel, to acquire sufficient velocity for flux compression prior to its entry into the coil. Using an extended breech provides this time.

3. Pressure release

A good method is needed to keep the burnt propellant gasses from moving ahead of the projectile while it travels through the coil. Releasing pressure before the projectile rear seal enters the coil is a solution to the problem. This pressure release ensures that there will be no ionized gasses in front of the projectile to potentially cause breech and barrel to release the pressure. This pressure release has the further advantage of allowing reduced barrel weight because it does not need to withstand higher pressures.

4. Coil turn spacing

Generally, even coil turn spacing is the easiest to fabricate. However, the uncertainty associated with propellant-driven devices and the very high increases in current near the end of the coil necessitate a deviation from even coil spacing in the x-ray diode application. The uncertainty of propellant devices means that precise timing of events cannot be done reliably from propellant ignition time. Rather, one must time precise events from the position of the projectile in the barrel coil. Placing a pin switch near the end of the barrel to initiate the explosive in the shorting switch in the secondary of the transformer is one way of using position instead of ignition time. If even turn spacing is used, the slope of the current versus projectile position becomes very large near the end of the barrel coil. Therefore, an uncertainty in positioning the pin switch is correlated with a large uncertainty in the current at the time of opening the shorting switch.

One way of reducing the uncertainty in the current at switch opening is to extend the spacing of the last turn in the coil, which will reduce the increase in current as a function of projectile travel. The extension of the spacing of the last turn in the barrel coil works to very good advantage in the x-ray diode application. The extended spacing not only reduces the uncertainty in selecting operating voltage, but may also be used as a parameter in shaping the x-ray pulse.

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