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CONCEPTUAL DESIGN FOR A SHORT-PULSE EXPLOSIVE-DRIVEN GENERATOR*

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ABSTRACT

A design is described for a short-pulse explosive-driven generator. The initial flux is provided by a side-fed one-turn coil that is crowbarred at peak field. This field is then compressed by the axially uniform expansion of a cylindrical armature inside the coil. A multistrand helical coil is used to convert the changing flux to voltage at the coaxial output. The circuit is completed by the impact of the armature against contact rings connected to the helical coil and output. An approximate circuit model is derived. The analysis indicates that several megajoules can be delivered to an inductive load in 0.5 to 5.0 μs.

INTRODUCTION

Conventional explosive-driven generators deliver a current pulse at the output that rises from zero to peak in times ranging from ten to hundreds of microseconds. Many applications, however, require a risetime of one microsecond or less. The usual solution for overcoming this discrepancy is to use some combination of opening and closing switches at the generator output to shape and compress the pulse. The opening switches are difficult to design and fabricate and add greatly to the complexity of the experiment. This paper describes a generator design that should make it possible to eliminate the external time compression circuitry. The approximate circuit model indicates that this short-pulse generator should deliver 20 to 30 MA to a 10 nH load in 0.5 to 2 μs without further pulse compression.

DESCRIPTION

A cross-sectional schematic drawing of the short-pulse generator is shown in Fig. 1. The initial magnetic flux for the generator is provided by a one-turn coil encircling the rest of the generator components. A capacitor bank powers this primary coil, although a booster generator could be used if more energy is required. At peak field, the input to the primary coil is crowbarred by firing the detonators shown in Fig. 1.

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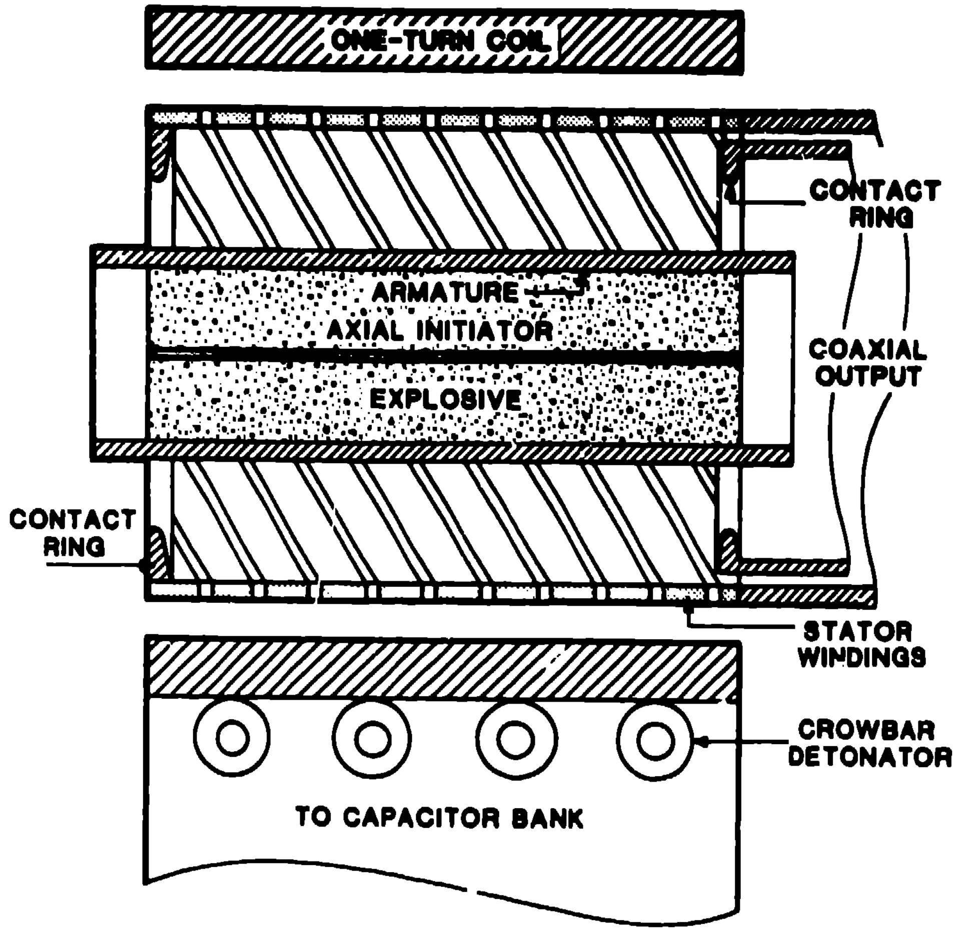

Fig. 1. Schematic cross-section of short-pulse generator.

The initial flux is then trapped between the shorted one-turn coil and the cylindrical armature during the remainder of the generator action.

A simultaneous axial initiation system detonates the cylinder of explosive within the armature along the axis to produce a cylindrically expanding detonation front. The timing is arranged so that the outside surface of the armature starts to move when the one-turn coil is crowbarred. The armature then expands radially in a close approximation to a circular cylinder as it is driven by the pressure of the explosive reaction products. The trapped flux is compressed and the axial magnetic field increases correspondingly. However, no voltage appears at the generator output until the armature hits the contact rings shown in Fig. 1. This feature is the key to the operation of the short-pulse generator. No current has to flow through the generator output during the injection of the initial flux and early portion of the armature run. After impact with the contact rings, the flux trapped between the armature and the stator coil is pushed out into the load during the remainder of the radial expansion.

The stator coil is wound from many strands of insulated wire in a helix. For high current applications, the multi-strand helix will have typically a total turn-count of about one. The multi-strand arrangement gives a good fill-factor for carrying high currents and divides down the strand-to-strand voltage to the point where the wire insulation can handle the stress. There is an additional advantage in that the current distribution at the coaxial output is azimuthally symmetric.

A one microsecond pulse is produced by positioning the contact rings so that only one microsecond is required for the armature to travel from the contact ring radius to the inner stator radius. It is evident that the flux between the stator coil and the primary coil at the end of the armature run represents waste energy. We are not getting something for nothing in this design.

SIMPLIFIED CIRCUIT MODEL

Figure 2a shows the initial geometry of the short-pulse generator. Figure 2b shows the geometry after the armature has reached the contact rings. R_p and R_s are the radii of the one-turn primary coil and the stator coil, respectively. ℓ is the length of the primary coil, the stator coil and the moving portion of the armature. ρ_o is the initial radius of the armature; and ρ and v are the radius and velocity at a later time, t. ρ_c is the radius of the contact rings. N_s is the total turn count for the stator and I is the current flowing in it and the load.

We make the following assumptions to simplify the calculations:

(a) The conductors in the generator have infinite conductivity, i.e., the flux losses are zero.

(b) The current distribution in the coils and armature may be approximated by current sheets of zero thickness.

(c) The magnetic field does not vary axially within the generator volume.

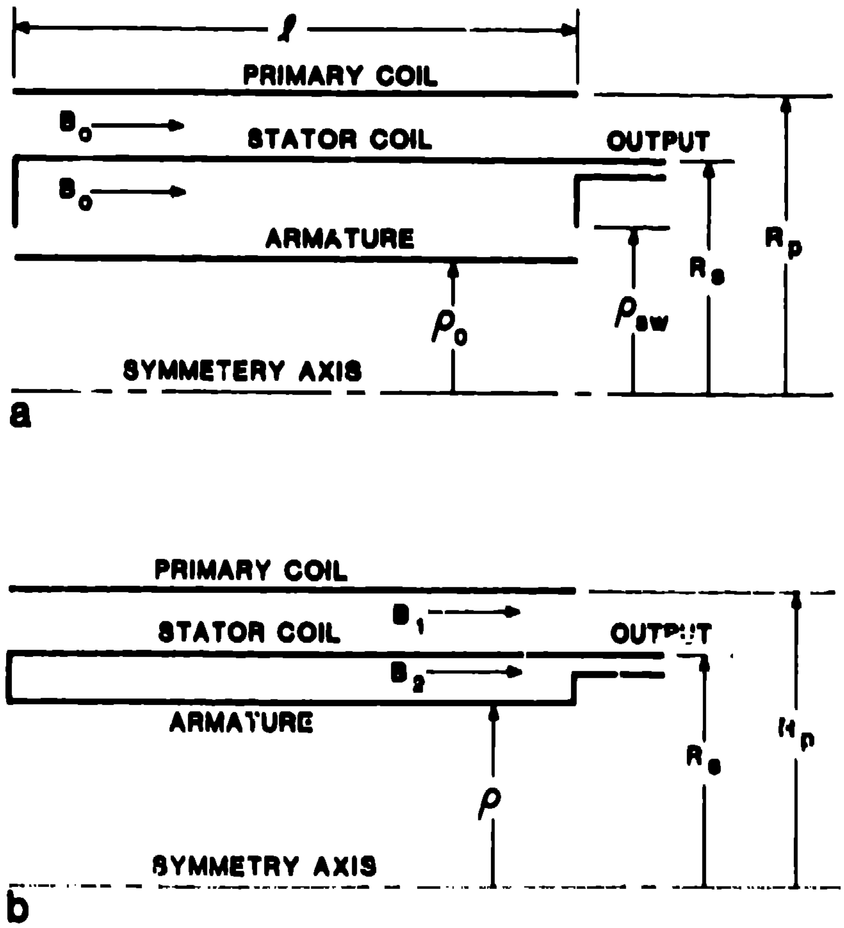

Fig. 2 (a) Initial geometry of short-pulse generator. (b) Geometry of generator after contact.

The initial flux, ϕ_o, between the armature and primary coil is

$$\phi_o = \pi(R_p^2 - \rho_o^2)B_o \quad , \tag{1}$$

where B_o is the axial initial field. Assumption (a) implies that the flux within the one-turn coil will remain constant during the armature run.

$$B_o(R_p^2 - \rho_o^2) = B_1(R_p^2 - R_s^2) + B_2(R_s^2 - \rho^2) \quad , \tag{2}$$

where B_1 is the field between the primary and stator coils and B_2 is the field between the stator and armature. A second equation for B_1 and B_2 can be obtained by invoking assumption (b) and applying the boundary condition across a current sheet.

$$\mu_o N_s I/\ell = B_2 - B_1 \quad , \tag{3}$$

where $\mu_o = 4\pi\times10^{-7}$ H/m. Solving for B_1 and B_2, we have

$$B_1 = B_o \; \frac{R_p^2 - \rho_o^2}{R_p^2 - \rho^2} - \frac{\mu_o N_s I_s}{\ell} \; \frac{R_s^2 - \rho^2}{R_p^2 - \rho^2} \quad , \tag{4a}$$

$$B_2 = B_o \; \frac{R_p^2 - \rho_o^2}{R_p^2 - \rho^2} + \frac{\mu_o N_s I_s}{\ell} \; \frac{R_p^2 - R_s^2}{R_p^2 - \rho^2} \quad . \tag{4b}$$

The flux, Φ_s, linking the stator coil is

$$\Phi_s = N_s \pi(R_s^2 - \rho^2)B_2 \tag{6}$$

We can define the following useful quantities:

$$\lambda = \mu_o N_s^2 \pi(R_p^2 - R_s^2)/\ell \quad , \text{ and}$$

$$\gamma(\rho) = (R_s^2 - \rho^2)/(R_p^2 - \rho^2) \quad .$$

Then, Eq. (6) can be rewritten as

$$\Phi_s = \gamma(\rho)(N_s\phi_o + \lambda I_s) \quad . \tag{6'}$$

The time dependence enters implicitly through $\rho(t)$.

We can now obtain the output voltage, V.

$$V = d\Phi_s/dt = o \qquad \text{for } \rho<\rho_c \tag{7a}$$

$$= V_g + L_g dI/dt + I dL_g/dt \text{ for } \rho_c < \rho < R_s \quad . \tag{7b}$$

Here,

$$V_g = N_s \phi_o d\gamma/dt \quad ,$$

$$L_g = \gamma\lambda \quad .$$

$$dL_g/dt = \lambda d\gamma/dt \quad , \text{ and}$$

$$d\gamma/dt = -2\rho v(R_p^2 - R_s^2)/(R_p^2 - \rho^2)^2 \quad .$$

Equation (7) gives us a complete circuit model for the short-pulse generator. It is made up of a voltage source in series with a time-varying inductor. This voltage is present even when the generator is operating into an open circuit.

It is useful to develop the formulas for the operation of the short-pulse generator into a fixed inductive load, L. Using assumption (a), we have

$$\Phi_s + LI = \phi_o(R_s^2 - \rho_c^2)/(R_p^2 - \rho_c^2) \quad . \tag{8}$$

Substituting for Φ_s from Eq. (6′) and solving for I, we have

$$I = (\gamma_c - \gamma)N_s\phi_o/(L + \gamma\lambda) \quad , \tag{9}$$

where $\gamma_c = \gamma(\rho_c)$. The load voltage, V, is

$$V = -LdI/dt = -\frac{N_s\phi_o(1 + \gamma_c\lambda/L)}{(1 + \gamma\lambda/L)^2}\frac{d\gamma}{dt} \tag{10}$$

A straight-forward variation on this design is to use a stator with a greater radius at the output end than at the other end. This change would be desirable in any event to preclude shorting out the output end of the stator prematurely. It also has the virtue of decreasing the peak voltage considerably with only a slight loss in energy. We must modify assumption (c) to say that the axial field between the conductors is a function of axial distance only; i.e., $B_1 = B_1(z)$ and $B_2 = B_2(z)$. We define the taper, δ, by taking the stator radius as $R_s + \delta$ at the output and R_s at the other end. We shall not go through the entire derivation, but simply state the final formulas. The current and voltage formulas remain the same, but the expressions for γ and $d\gamma/dt$ are different. The primary coil is assumed to have the same taper as the stator coil so that the spacing, Δ, between them is constant

$$\gamma(\rho) = 1 - \frac{\Delta}{\delta}\left\{\ln\left[\frac{(1+a)(1+b)}{ab}\right] - \frac{\Delta}{2\rho}\ln\left[\frac{a(1+b)}{b(1+a)}\right]\right\} \quad , \tag{11}$$

for $\rho_c < \rho < R_s$ and

$$\gamma(\rho) = (1-\xi) - \frac{\Delta}{\delta}\left\{\ln\left[\frac{(1+a)(1+b)}{(\xi+a)(\xi+b)}\right] - \frac{\Delta}{2\rho}\ln\left[\frac{(1+b)(\xi+a)}{(1+a)(\xi+b)}\right]\right\} \quad ,$$

where $\xi = (\rho - R_s)/\delta$ and $R_s < \rho < R_s + \delta$.

$$\frac{d\gamma}{dt} = -\frac{v}{\delta}\left\{\frac{\Delta}{\delta}\left[\frac{1-\Delta/2\rho}{b(1+b)} - \frac{1+\Delta/2\rho}{a(1+a)}\right] + \frac{\Delta^2}{2\rho^2}\ln\left[\frac{a(1+b)}{b(1+a)}\right]\right\} \quad , \tag{12}$$

for $\rho_c < \rho < R_s$, and

$$\frac{d\gamma}{dt} = -\frac{v}{\delta}\left\{1 + \frac{\Delta}{\delta}\left[\left(1 + \frac{\Delta}{2\rho}\right)\left(\frac{1}{1+a} - \frac{2}{\xi+a}\right) - \frac{1-\Delta/2\rho}{1+b}\right] + \frac{\Delta^2}{2\rho^2}\,\ell n\left[\frac{(1+b)(\xi+a)}{(1+a)(\xi+b)}\right]\right\},$$

for $R_s < \rho < R_s+\delta$.

We have made the simplifying assumption that $\delta \ll R_s$. The expressions for γ and $d\gamma/dt$ are continuous at R_s.

COMPUTATIONAL RESULTS

The predicted behavior of the short-pulse generator into a 10 nH load has been calculated for the following geometry: R_s = 16.51 cm, ρ_0 = 8.255 cm, Δ = 0.5 cm, ℓ = 30 cm, and v = 0.4 km/s. The initial field is 10 T and corresponds to an initial magnetic energy of about 850 kJ. In order to add plausibility to the calculations, the total turn count, N_s in each case has been adjusted to keep the peak linear current density in the stator windings down to 100 MA/m.

The effect of tapering the stator on the energy output can be seen from Fig. 3, which shows the energy in the 10 nH load as a function of time for a generator with τ = 0.5 μs, where τ is the total energy delivery time. The peak energy is about 24% greater for the untapered design. Figure 4 shows the voltage vs time plot for the same parameters. The peak voltage for the untapered stator is almost twice that for a 1 mm taper. It is evident that a slight taper is very desirable for reducing the voltage stresses on the generator. For this reason, all the remaining calculations assume a 1 mm taper.

Figures 5 and 6 show the current and voltage vs time curves, respectively, for delivery times of 0.5, 1 and 2 μs. N_s is 1.33, 0.986, and 0.809 for these three cases, respectively. The corresponding power and energy plots are shown in Figs. 7 and 8. For a 1 μs delivery time, the predicted performance is a peak current of 28 MA, a peak voltage of 607 kv, a peak power of 12 TW, and an energy of 4.1 MJ.

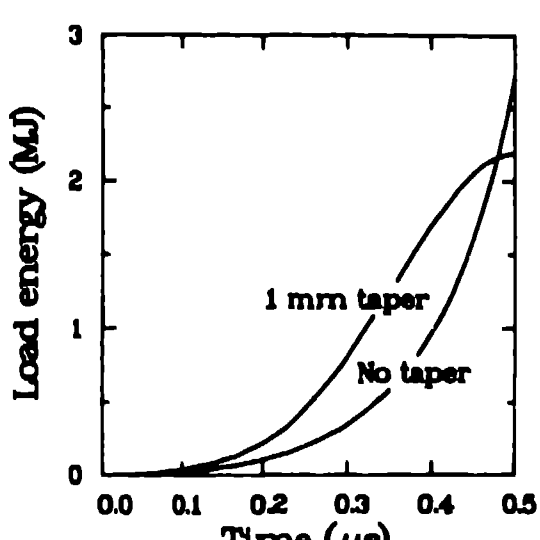

Fig. 3. Energy vs time curve for tapered and untapered stators.

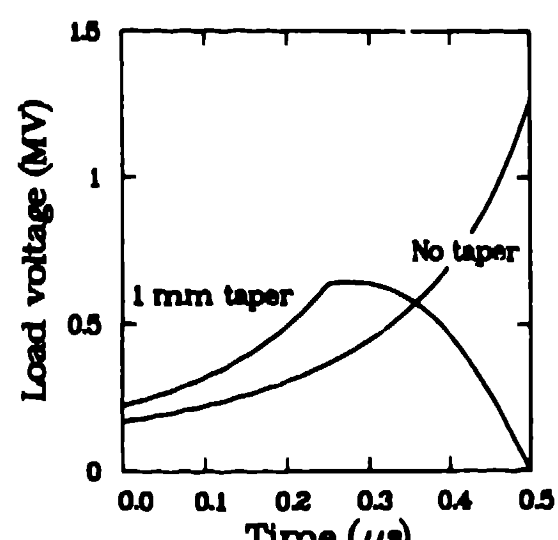

Fig. 4. Voltage vs time curves for tapered and untapered generators.

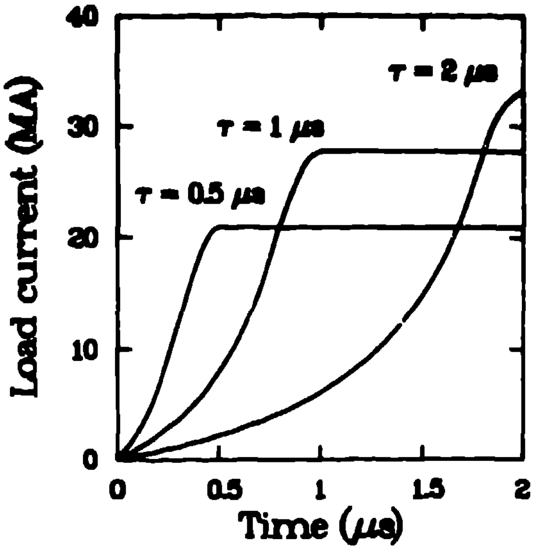

Fig. 5. Current vs time curves for three delivery times.

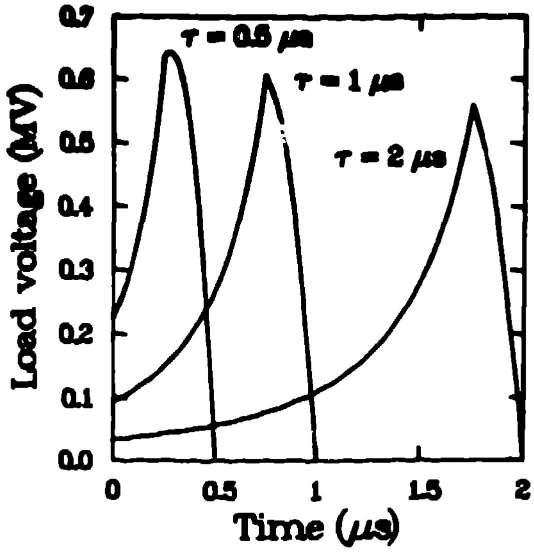

Fig. 6. Voltage vs time curves for three delivery times.

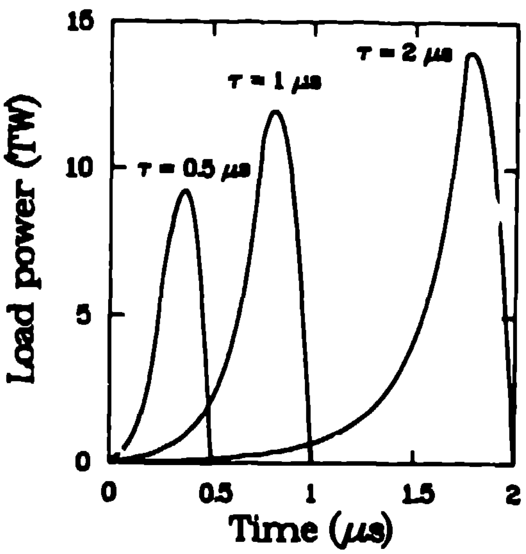

Fig. 7. Power vs time curves for three delivery times.

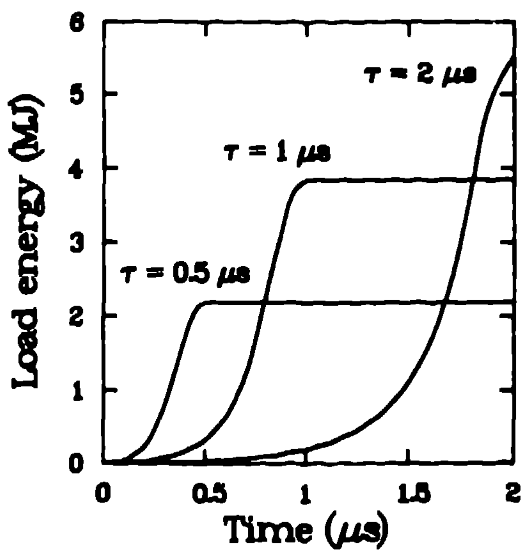

Fig. 8. Energy vs time curves for three delivery times.

DISCUSSION

The simplified circuit model predicts that the short-pulse generator should be able to deliver several megajoules at currents of close to 30 MA in one microsecond. Even a rather pessimistic assessment of the flux losses would indicate that a modest-sized generator could put out 1 MJ in 1 μs. The voltage stresses are unavoidably high within the generator volume. However, if the interior is evacuated, the high magnetic fields may provide magnetic insulation. We conclude that an experimental investigation of the short-pulse generator design is worthwhile.