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HIGH VOLTAGE POWER CONDITION SYSTEMS POWERED BY FLUX COMPRESSION GENERATORS*

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Abstract

Compact, high-gain magnetic flux compressors (FCGs) are convenient sources of substantial energy for plasma-physics and electron-beam-physics experiments, but the need for high-voltage, fast-rising pulses is difficult to meet directly with conventional generators. While a variety of novel concepts employing simultaneous, axially-detonated explosive systems are under development, power-conditioning systems based on fuse opening switches and high-voltage transformers constitute another approach that complements the fundamental size, weight, and configuration of the small helical flux compressor. In this paper, we consider first a basic inductive store opening switch circuit and the implications associated with, specifically, a fuse opening switch and an FCG energy source. We develop a general solution to a transformer opening switch circuit which also includes (as a special case) the direct inductive store opening switch circuit (without transformer) and we report results of one elementary experiment demonstrating the feasibility of the approach.

Basic Opening Switch Circuit

We recall the fundamental behavior of a current interrupting switch, limiting our consideration to the case where the load is switched across the opening switch and storage inductor at the time when the voltage across the opening switch reaches a peak. Thus, the behavior of the circuit up to the time of peak voltage is independent of the load. For purposes of analysis we consider a switch whose resistance rises linearly from $R = 0$ at $t = t_c$ in Fig. 1, thus

$$R(t) = R' t' ,$$

where we use primed time coordinates to measure time from the end of the "conduction time," t_c , ($t' = t - t_c$). The circuit equation for the circuit in Fig. 1, before the output switch closes,

$$L(dI/dt) + IR(t) = 0$$

has the solution

$$I(t) = I_0 e^{-R' t' / 2L} \quad (1)$$

where I_0 is the current in L before the start of interruption.

It is convenient to identify a "switching interval," t'_{sw} , during which the current has been virtually interrupted, falling to $I(t'_{sw}) = I_0 e^{-R' t'_{sw} / 2L} (11\% I_0)$ and from Eq. (1) we identify

$$t'_{sw} = 2\sqrt{L/R}$$

Furthermore, we can write the voltage across the switch

$$V(t) = R(t) I(t) = R I_0 e^{-R' t' / 2L}$$

We can find the time, t'_{vm} , of maximum voltage by taking $dV/dt = 0$

$$t'_{vm} = \sqrt{L/R} = 0.5 t'_{sw}$$

and at t'_{vm} the current is

$$I(t_{vm}) = I_0 e^{-1/2} = I_0 e^{-0.693} (61\% I_0)$$

which is a consequence of assuming a linear rise in the switch resistance. At t'_{vm} the resistance and voltage are:

$$R(t_{vm}) = \sqrt{RL} = 2L/t'_{sw}$$

$$V(t_{vm}) = 1.2 LI_0 / 2\sqrt{L/R} = 1.2 \Phi_0 / t'_{sw}$$

where $\Phi_0 = LI_0$ is the flux in L prior to the start of interruption. The energy dissipated in the switch up to the time t'_{vm} is

$$E_{min}(t'_{vm}) = 0.5 L(I_0^2 - e^{-1} I_0^2) = 0.63 E_0 \quad (2)$$

where E_0 is the energy in the circuit at t_c . We see that E_{min} , which is the minimum energy that any switch displaying a linear resistance profile must dissipate, is independent of the details of the switching mechanism and of the circuit parameters.

FIG. 1. Opening switch circuit with ramp resistance

When the switching mechanism is, more specifically, a fuse, we follow convention (which is well supported by more than 20 years of experiments conducted worldwide) and assume that the fuse vaporizes and undergoes a large increase in resistance when the accumulated specific action reaches a value determined only by the nature of the material.

$$\frac{1}{A^2} \int_0^{t_v} I(t)^2 dt = g_v \quad (3)$$

where $t_v = t_c$ is the time of vaporization, g_v is the "burst" specific action and A is the cross section of conductor presented to the current. Since different current waveforms deliver action to the fuse in dramatically different ways (e.g., capacitor bank compared to flux compressor waveforms), it is useful to introduce an "equivalent action time scale" t_{eq} .

$$t_{eq} = 1/I_0^2 \int_0^t I(t)^2 dt \quad (4)$$

where $I_0 = I_c$ is the current in the circuit at the time of the onset of vaporization. Thus, using Eqs. (3) and (4) we establish a criterion on the area the fuse must present to the current

$$g_v A^2 = I_0^2 t_{eq}$$

* This work was conducted by the US Department of Energy

Because a switch (displaying a linear resistance increase) must dissipate energy, ΔE , which lies between E_{min} and the total circuit energy E_0 ,

$$\Delta E = \alpha E_0 \quad 0.63 < \alpha < 1.0 \quad (6)$$

a criterion on the fuse length, L , is defined by the requirement to bring the fuse of mass (ρLA) to vaporization energy density using only a total energy ΔE ,

$$\Delta E = \epsilon_v \rho LA = \alpha E_0$$

Defining $\Phi_0 = LI$, and using Eqs. (2), (5), and (6):

$$L_0 = \frac{\Delta E}{\epsilon_v \rho A} = \alpha^2 \frac{1}{2} \frac{g^{1/2}}{\epsilon_v \rho} \frac{\Phi_0}{\tau_{eq}^{1/2}} = \alpha k_2 \Phi_0 \tau_{eq}^{1/2} \quad (7)$$

Using Eqs. (5) and (7) we arrive at the initial resistance of the fuse:

$$R_0 = \alpha \eta_0 \frac{k_2 \Phi_0}{k_1 I_0 \tau_{eq}} = \alpha \eta_0 \frac{k_2 L}{k_1 \tau_{eq}}$$

where η_0 is the initial resistivity of the fuse material. Upon vaporization, the resistance of the fuse rises (linearly) by a ratio M_f and all the details of EOS, hydrodynamics, tamping and quenching can be combined, at least for first order, into the parameter M_f . Thus, the fuse resistance at t'_{sw} is $R_{vm} = M_f R_0$, but from circuit considerations we recall $R_{vm} = 2L/t'_{sw}$, therefore,

$$R_{vm} = M_f \alpha \eta_0 k_2 L / k_1 \tau_{eq} = 2L/t'_{sw}$$

which provides an expression for the switching speed of the fuse

$$t'_{sw} = \frac{2k_1}{\alpha \eta_0 k_2} \frac{\tau_{eq}}{M_f} = \frac{1}{\alpha} k_0 \frac{\tau_{eq}}{M_f} \quad (8)$$

and finally the voltage and electric field produced by the fuse are

$$V_m = \frac{1.2 \alpha M_f \Phi_0}{k_0 \tau_{eq}}$$

$$E_m = k_3 \frac{M_f}{\tau_{eq}^{1/2}}$$

Equation (8) provides an expression for the current interruption time in terms of material parameters, k_0 , the resistance multiplication ratio and the parameter τ_{eq} . Material parameters for copper and aluminum fuse materials are summarized in Table I and are, of course, independent of circuit or source parameters. Thus, the parameters that can effect the current interruption time are the equivalent action timescale and the multiplication. Equation (4) for τ_{eq} can be evaluated analytically for the case of a sinusoidal current waveform (such as a capacitor bank) and for an exponential current waveform (which approximates the waveform of most flux compressors). For a sinusoidal waveform with a quarter period τ_q we find $\tau_{eq} = \tau_q/2$. While for an exponential waveform $I(t) = I_0 e^{-t/\tau}$, where τ is the exponential factor and τ_r is the full operating time (run time) of the generator, we find $\tau_{eq} = \tau_r/27$. The τ_r

Fig. 2. Action time scale for three FCGs.

of flux compressors can vary from 10 μ s to several hundred microseconds, and the exponential factor from 1 to about 5. We calculate the action timescale from experimental waveforms of three flux compressors in Fig. 2. All are helical flux compressors with the explosive charge initiated at one end. The first is a relatively compact high current-gain configuration, the second is a similar small generator consisting of a helical section and a coaxial section designed to produce larger currents and the third is a very large (relatively slow) generator designed to produce very large energies. The curves show similar general behavior and all contain a relative minimum in τ_{eq} near the end of the run but not necessarily at peak current. For minimum current interruption time Eq. (8) shows that a fuse should be designed to burst at this minimum in the τ_{eq} profile.

Circuit Analysis

With this general description of fuse opening switch performance, we next explore two circuit concepts outlined in Fig. 1. In one, the energy is stored in the primary inductance of a transformer and released by an opening switch, and in the other, the transformer degenerates into a simple storage inductor. We first develop the general solution for an energy storage transformer with an opening switch in the primary loop and a resistive load in the secondary loop. The general circuit is shown in Fig. 3a where $L_g(t)$ is the variable inductance of a flux compression generator, $R_g(t)$ is the resistance of the opening switch in the primary loop, L_{xp} is the total inductance in the primary loop that is "external" to both the generator and the transformer, and L_p is the primary inductance of the transformer. Similarly, L_s is the secondary inductance, L_{sx} is the inductance in the secondary loop external to the transformer (including the inductance of the load) and R_L is the load impedance. M is the mutual inductance coupling L_p and L_s .

When the generator completes its operation, $L_g(t)$ approaches zero, and by replacing the transformer with the familiar "T Equivalent" we describe the circuit as shown in Fig. 3b.

Fig. 3. Transformer (a) and equivalent circuit (b).

Table I

		Aluminum	Copper
k_0	$4\rho\eta_0/\eta q$	57	68
L_0	$q/\eta^{1/2}$	3.9×10^{-4}	2.4×10^{-4}
k_1	$\frac{1}{2} \frac{g^{1/2}}{\rho}$	4.9×10^{-4}	3.9×10^{-4}
k_2	$0.6\eta q^{1/2}$	4.3	4.5

at the instant just prior to current interruption. The transformer is described by the physical quantities L_p , L_s , and M . Following convention, we define the coupling, k , and the quantity N , which we associate with the physical turns ratio in simple geometries,

$$k = M / \sqrt{L_p L_s} \quad N = \sqrt{L_s / L_p}$$

For convenience, we rewrite the circuit in Fig. 3b by combining inductances in the primary and secondary loops and arrive at the circuit in Fig. 4 where we define:

$$L_1 = L_{T1} + L_p \quad L_2 = L_{T2} + L_s$$

$$k_{eq} = M / \sqrt{L_1 L_2} \quad N_{eq} = \sqrt{L_2 / L_1}$$

So that the effect of external inductances is included in k_{eq} and N_{eq} —reducing the coupling and making N_{eq} possibly quite different from the physical turns ratio.

FIG. 4. Circuit for general solution.

At this point, we observe that the circuit in Fig. 4 can also be used to describe the transformerless approach by setting $L_1 = L_s = M = L_{store}$. Then

$$L_1 = L_{Tp} + L_{store} \quad L_2 = L_{Ts} + L_{store}$$

and for L_{Tp} , $L_{Ts} \rightarrow 0$

$$k_{eq} = 1 \quad N_{eq} = 1$$

For analysis, we define the switching action as an instantaneous transition in R_s from $R_s(t_{vm}) = 0$ to $R_s(t_{vm}^+) = R_s$. The transition occurs at $t = t_{vm}$, and at t_{vm}^+ $I(t)$ has fallen to I_{vm} . This allows a general solution of the circuit equations to be written as

$$I_2 = I_p e^{-t/\tau_f} (1 - e^{-t/\tau_r})$$

where

$$I_p = I_{vm} k_{eq} N_{eq} (1 + r) Q \quad I_{vm} = 617 I_s$$

$$\tau_r = \tau_s (1 - k^2) 2Q$$

$$\tau_f = \tau_s (1 - k^2) / (1 - Q)$$

where r is the dimensionless ratio of load resistance to switch resistance scaled by the equivalent turns ratio N_{eq} , and τ_s is a characteristic time scale,

$$\tau_s = R_s / R_s N_{eq}^2$$

$$\tau_s = 2 L_1 (R_L + N_{eq}^2 R_s)$$

$$Q = \sqrt{1 - 4r(1 - k^2) / (1 + r)}$$

We observe that for $k \rightarrow 1$, $Q \rightarrow 1$, independent of r . Thus, the ratio of the rise time to the fall time of the secondary current

$$\tau_r / \tau_f = (1 - Q) / 2Q > 0$$

FIG. 5. Normalized current in secondary loop

We observe that for $r \rightarrow 1$, $Q \rightarrow k$ and

$$I_p \rightarrow 0.5 I_{vm} / N_{eq}$$

Figure 5 shows the magnitude of current in the secondary loop (normalized to I_{vm}/N_{eq}) as a function of r with k as a parameter. The figure shows that for small r , $I_p \Rightarrow k I_{vm}/N_{eq}$; and for large r , $I_p \rightarrow k I_{vm}/r N_{eq}$.

Figure 6 shows the values of the rising (τ_r) and the falling (τ_f) time constants, normalized to τ_s , as functions of r with k as a parameter. The figure shows that τ_r peaks at $r = 1$ (but not sharply) and that τ_f has a minimum at $r = 1$. τ_r approaches zero (a step rise in current) independent of r for $k \rightarrow 1$.

From the solution, we can also write the voltage across R_L :

$$V_{lp} = R_L I_p = I_{vm} k R_L N_{eq} / Q (N_{eq}^2 + R_L / R_s)$$

Figure 7 shows $V_{lp}/R_s N_{eq} I_{vm}$ as a function of r with k as parameter.

Frequently, we would like to choose the transformer design to maximize the voltage impressed across a load assuming a given performance for the opening switch. We find the value of N_{eq} for which V_{lp} is a maximum by finding where $\partial V_{lp} / \partial N_{eq} = 0$. For case of relatively good coupling $1/Q \rightarrow 1$, we find that

$$N_{eq}^2 = R_L / R_s (1 + r)$$

Fig. 8. Load voltage
the maximum occurs where

$$R_L = N_{eq}^2 R_s \quad (\text{i.e., for } r = 1)$$

Furthermore when $r = 1$, we see that $Q = k$ and the voltage across the level and power to the load are:

$$V_{lp} = \frac{1}{2} \frac{I_{vm} R_L}{N_{eq}}$$

$$P_{lp} = \frac{1}{4} R_s I_{vm}^2$$

Performance Estimates

As an example of applying the results of the previous sections to a flux compression generator power-conditioning system, we consider a 50- μ H flux compressor operating into a 500-nH storage inductor (L_{store}) with a series current interrupting fuse. We explore first the performance to be expected for a 10- Ω load coupled across the fuse at the time of peak voltage. We then explore the improvement in performance to be expected by introducing an optimized transformer with a 500-nH primary inductance.

For illustrative purposes we consider the flux compressor to be initially loaded with 20-kA current, resulting in 1.0 Weber initial flux. We assume 50% flux efficiency, $\tau_r = 100$ - μ sec, $\gamma = 5$ and $\tau_{eq} = 10$ - μ sec, resulting in a current of 1 MA in the storage inductor and 610 kA at t'_{vm} . For the switch, we assume aluminum conductor, a multiplication of $M = 300$, and we find $R_{vm} = 333$ m Ω .

For a direct store/switch configuration in coaxial geometry with the load coupled across the fuse we take $L_{sp} = 0$, $L_{ss} = 25$ nH, $R_L = 10$ Ω . Thus, with $L_s = L_p = 500$ nH, we find $k_s = 0.98$, $N_{eq} = 1.025$, and $r = 28.6$, which results in $V_{lp} = 197$ KV, $\tau_r = 2.4$ ns, and $\tau_f = 1.6$ μ s.

$$P_{lp} = 1.4 \times 10^6 \text{ (4, 10, 25 OHM)}$$

According to this analysis, N_{eq} should be selected to achieve $r = 1$, i.e., $N_{eq} = 5.5$. For the assumed generator and switch performance, $L_s = 15.13$ μ H, $M = 2.20$ μ H and $k = 0.8$ we find $V_{lp} = 556$ KV, $\tau_r = 337$ ns, and $\tau_f = 2.7$ μ s.

In Fig. 8 we plot the voltage predicted across 4, 10, and 25-ohm levels for the representative flux compressor and fuse as a function of the physical turn ratio N with $k = 0.8$. For each case we mark $r = 1$ and observe that a 4- Ω load experiences a peak voltage of 350 KV and the power to all loads is about 30 GW.

Experiment

To demonstrate the feasibility of a flux compressor, fuse, and transformer power-conditioning system, a 0.5-MH class flux compressor was operated into the primary of a rudimentary (non-optimized) transformer coupled to a 60-k Ω load. The generator initial inductance was 50 μ H, initial current was about 25 kA. The copper fuse was 40-cm long, 52-cm wide, and 0.35-mil thick. The fuse material was bonded between two layers of 0.010 Mylar making the package self supporting. The fuse was mounted coaxially with the small helical flux compressor. The helical transformer consisted of a 1.5-turn primary of about 270-nH and a 10-turn secondary, coupled with a $k = 0.70$. The load was a high-resistance liquid resistor of about 60 k Ω in series with the secondary without a series isolation switch. As shown in Fig. 9, the current in the transformer primary rose to about 800 kA and was interrupted in about 3 μ s. The voltage in the transformer secondary, was about 1.3 MV.

Fig. 9. Simple Transformer Experiment

Fig. 9. Simple Transformer experiment

Conclusions

Simplified analytic analysis shows that for powering resistive loads with an FCG/Fuse combination and a transformer, the turns ratio should be selected to match fuse to load impedances ($r = 1$). Using matched transformers, loads at a few ohms can be driven to a few-hundred KV and loads of a few 10's of ohms can be driven to about 1 MV. Direct fuse power conditioners can be useful for voltages up to 300-500 KV but transformers are required for higher voltages. FCG/Fuse/Transformer systems are viable energy sources for a variety of experiments.