EXPLOSIVE DRIVEN FERROELECTRIC GENERATORS

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Abstract

Explosive Driven Ferroelectric Generators (EDFEGs) are compact power sources that have been considered for use as seed sources for magnetocumulative generators, as well as prime power sources [1,2]. Shock waves generated by high explosives are used to shock depolarize ferroelectric materials, which results in a voltage pulse being delivered to a load. These generators have been experimentally investigated at Texas Tech University. Data from these experiments was used to benchmark a code developed at the Institute of Electromagnetic Research. In this paper, a description of the simulation and a comparison of the experimental and simulation results will be presented.

I. DESCRIPTION OF MODEL

As the shock wave passes through the polarized module, made of ferroelectric ceramics (in particular lead-zirconate titanate (PZT)), its volume is divided into two zones (Fig. 1) differing by such parameters as bulk polarization, permittivity, and conductance. These zones are referred to as the “compressed” and “uncompressed” zones, where the compressed zone is that through which the shock wave has already passed and the uncompressed zone is that through which the shock wave has not passed. The equivalent circuit diagram for the longitudinal EDFEG is presented in Fig. 1, where C_1 and C_2 are the capacitances of the uncompressed and compressed zones, respectively.

In building the model, the following assumptions were made:

- There is a single planar shock wave.
- Bulk compression of the ferroelectric (or to be more precise ferroceramic) material was not taken into account, since experimental results indicate that this value does not exceed 0.05.
- Shock polarization inherently bears an inertial characteristic; that is, domain rearrangement is a kinetic process.
- The ferroelectric material is a linear dielectric in both the compressed and uncompressed zones.

Taking these assumptions into consideration, the general set of ordinary differential equations for the current in the reactive load I_2 [A] and the charges on the load capacitor Q_2 [Cl] and PZT module Q_1 [Cl] in the EDFEG is

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14. ABSTRACT

Explosive Driven Ferroelectric Generators (EDFEGs) are compact power sources that have been considered for use as seed sources for magnetocumulative generators, as well as prime power sources [1,2]. Shock waves generated by high explosives are used to shock depolarize ferroelectric materials, which results in a voltage pulse being delivered to a load. These generators have been experimentally investigated at Texas Tech University. Data from these experiments was used to benchmark a code developed at the Institute of Electromagnetic Research. In this paper, a description of the simulation and a comparison of the experimental and simulation results will be presented.

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$$\begin{aligned} &\dot{Q}_1 + \dot{Q}_2 = I_0(t) - I_2 - I_{leak}(Q_1); && Q_1\big|_{t=0} = 0; \\ &L\,\dot{I}_2 = Q_2 C_L^{-1} - RI_2; && I_2\big|_{t=0} = 0; \\ &\dot{Q}_1 C^{-1}(t) - \dot{Q}_2 C_L^{-1}(t) = \dot{C}(t)\, C^{-2}(t)\, Q_1; && Q_2\big|_{t=0} = 0; \end{aligned} \qquad (1)$$

where R (Ohm), L (H) and C_L(F) are the resistance, inductance, and capacitance of the load.

The capacitance of the ferroelectric module $C(t)$ is described by using the standard model for a layered parallel plate capacitor, where one layer is the compressed zone and the other layer is the uncompressed zone. For this type of capacitor, the distance between the plates, l, must be less than the radius of the plates, $S^{1/2}\pi^{-1/2}$. Therefore, the capacitance of the ferroelectric module shown in Fig. 1 is:

$$C(t) = \begin{cases} \varepsilon_0\varepsilon_1\left[l + \left(\varepsilon_1\varepsilon_2^{-1}(p) - 1\right)V_S t\right]^{-1} & \text{for} \quad l \geq V_S t; \\ \varepsilon_0\varepsilon_2(p) S l^{-1} \quad \text{for} \quad l < V_S t; & \end{cases} \qquad (2)$$

where S (m^2) is the area of the end plates of the ferroceramic module, ε_1 is the permittivity of the uncompressed zone, $\varepsilon_2(p)$ is the permittivity of the compressed zone, ε_0 is the permittivity of free space, l is the total length of the ferroelectric module, r is the radius of the module, and V_S is the velocity of the shock wave in the ferroelectric material, which, in the absence of substantial changes in the state of the material, can be assumed to be equal to the velocity of sound in the material. The permittivity of the shock-compressed ferroceramic is a complex function of the pressure in the shock wave.

The total electric charge released at the end plates of the ferroceramic module during the time it takes for the shock wave to travel through the module is $Q_{tot} = \sigma(p)S$. Since the free charge surface density, $\sigma(p)$, released at the end plates is equal to the difference in the specific bulk polarization in the compressed and uncompressed regions of the material, $\sigma = P_1 - P_2$, the amount of charge released at any given moment in time, $Q_0(t)$, is proportional to the depolarized volume of the module and is described by the expression:

$$Q_0(t) = \sigma(p) V_S t l^{-1}. \qquad (3)$$

Taking the derivative with respect to time yields the depolarization current:

$$I_0(t) = \theta(t)\frac{d\sigma(p) V_S t l^{-1}}{dt}; \qquad (4)$$

where $\theta(t)$ takes into account the "switching on" of the polarization current at the origin, which corresponds to the moment at which the shock wave enters the ferroceramic module, and the "switching off" at the moment the shock wave exits the module ($t_f = lV_S^{-1}$) and is approximated by the expression:

$$\theta(t) = \frac{1}{4}\left(1 - \tanh\left[4t_{rel}^{-1}(p)(t - lV_S^{-1}) - 2\right]\right)\left(1 + \tanh\left[2t_{rel}^{-1}(p)t - 2\right]\right); \qquad (5)$$

which is convenient for numerical calculations, since it is a smooth function. Since the calculation of $t_{rel}(p)$ using kinetic theory is relative complex, experimentally measured values of 0.05 – 0.4 μs are used [3,4]. These values decrease significantly as the pressure in the shock wave increases.

The electric conductance of ferroceramics sharply increases under shock compression and part of the charge released at the end plates leaks through the compressed region of the module forming a leak current, $I_{leak}(p)$. In the case of a longitudinally driving force, the leak takes place over the entire surface of the module and, consequently, does not depend on time. The leak current can be found from the field strength in the shock-compressed region of the module by using Ohm's law:

$$j_{leak}(Q_1) = \lambda_2(p)E_2; \;\; I_{leak}(Q_1) = j_{leak}(Q_1)S = \lambda_2(p)Q_1\left[\varepsilon_2\varepsilon_0\right]^{-1} \qquad (6)$$

where λ_2 (Ohm m) is the specific conductance of the compressed ferroceramic material. The conductance increases, as the pressure in the shock wave increases, due to the increase in the number of free carriers because of electron tunneling, ionization, and other phenomena.

The set of ODE in Eq. (1) describes the operation of a longitudinally driven ferroceramic module, where the shock wave velocity and spontaneous polarization vectors are either parallel or anti-parallel, before the onset of bulk breakdown in the compressed region of the module. Generally speaking, breakdown can occur in both the compressed and uncompressed regions, but it starts first in the compressed region because the electric strength of the ferroceramics is less than that in the uncompressed region. This is related to the formation of local breakdown areas in the compressed zone due to the impact of the shock wave on powder grain boundaries, defects, dislocations, and air-filled cavities generated during the baking process. Thus, Eq. (1) is restricted to the time domain prior to the start of bulk breakdown in the compressed zone:

$$E_{br} > Q_1(t)\left[S\varepsilon_2(p)\varepsilon_0\right]^{-1}; \qquad (7)$$

where E_{br} [kV/m] is the electric strength of the ferroceramic material compressed by the shock wave.

Since the set of equations in Eq. (1) is stiff and cannot be efficiently solved with the required precision, they are normalized by introducing the reduced variables:

$$\tau = t/\tilde{t};\ q = Q/\tilde{Q};\ \text{and } i = I\tilde{t}/\tilde{Q}; \qquad (8)$$

where $\tilde{t} = lV_S^{-1}$ and $\tilde{Q} = \sigma(p)S$. After making the appropriate substitutions, Eq. (1) becomes:

$$\frac{dq_1}{d\tau} = \frac{1}{C(\tau)+C_L}\left[\frac{\dot{C}(\tau)}{C(\tau)}C_L q_1 + C(\tau)\left(i_0(\tau) - i_2 - i_{leak}(q_1)\right)\right]; \qquad q_1\big|_{\tau=0} = 0;$$

$$\frac{dq_2}{d\tau} = \frac{1}{C(\tau)+C_L}\left[-\frac{\dot{C}(\tau)}{C(\tau)}C_L q_1 + C_L\left(i_0(\tau) - i_2 - i_{leak}(q_1)\right)\right]; \qquad q_2\big|_{\tau=0} = 0 \qquad (9)$$

$$\frac{di_2}{d\tau} = \tilde{t}^2\frac{q_2}{LC_L} - \tilde{t}Ri_2; \qquad i_2\big|_{\tau=0} = 0;$$

where:

$$i_0(\tau) = \frac{1}{4}\left[1 - \tanh\left(4\tilde{t}t_{rel}^{-1}(p)(\tau-1)\right) - 2\right]\left[1 + \tanh\left(4\tilde{t}t_{rel}^{-1}(p)\tau - 2\right)\right];$$

$$C(\tau) = \begin{cases} \varepsilon_1\varepsilon_0\left[1 + (\varepsilon_1\varepsilon_2^{-1}(p) - 1)/\tau\right]^{-1} & \text{for } \tau \le 1 \\ \varepsilon_0\varepsilon_2(p)Sl^{-1} & \text{for } \tau > 1; \end{cases} \qquad (10)$$

$$\dot{C}(\tau) = \begin{cases} \varepsilon_1\varepsilon_2(p)\varepsilon_0 Sl^{-1}\left(\varepsilon_2(p) - \varepsilon_1\right)\left[\varepsilon_2(p) + \left(\varepsilon_1 - \varepsilon_2(p)\right)\tau\right]^{-2}; \tau \le 1 \\ 0; \tau > 1 \end{cases}$$

$$I_{leak}(q_1) = \left(\varepsilon_2(p)\varepsilon_0\right)^{-1}\lambda_2(p)\tilde{t}q_1.$$

The normalized bulk breakdown condition is:

$$E_{br} > \sigma(p)q_1(\tau)\left[\varepsilon_2(p)\varepsilon_0\right]^{-1}.$$

This set of equations was solved numerically using the Gear and Bulrich-Stoer numerical methods with a relative error for both methods of less than 10^{-5} for all variables.

II. RESULTS

Substituting in the parameters for the EDFEG provided by Texas Tech University, the model was used to calculate the output voltage of their EDFEGs. Since some of the parameters, such as τ_{rel}, σ, ε_2, and λ_2, are not known at shock pressures, they were corrected based on earlier shots and used in calculations for later shots. It should be noted that the actual values of these parameters, after corrections, are reasonable based on the values measured for PZT ceramic materials [3]. A comparison of the calculated to the experimental data for two shots is presented in Fig. 2. Experiments show that shock-compressed ferroceramic modules can generate pulses with amplitudes up to 8 kV in the resistive part of the load and energies per unit volume of module of 0.1 – 0.4 J/cm^3. The duration of the pulse depends on the shock transit time through the module, the “skewness” of the shock front, and the relaxation time of the ferroceramic material. Those factors, which probably limit the output energy and the amplitude of the output pulse, are the electric breakdown strength, which is approximately 3 kV/mm, of the ferroceramic material and the leakage current passing through the compressed portion of the module.

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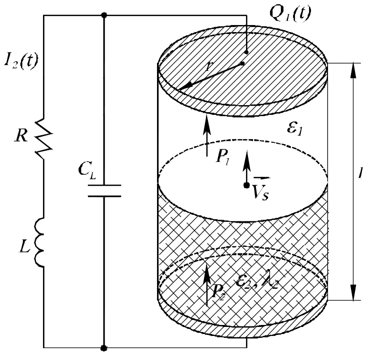

Fig. 1 Diagram illustrating the propagation of a shock wave through a longitudinally driven ferroceramic module and field distributions in the module.

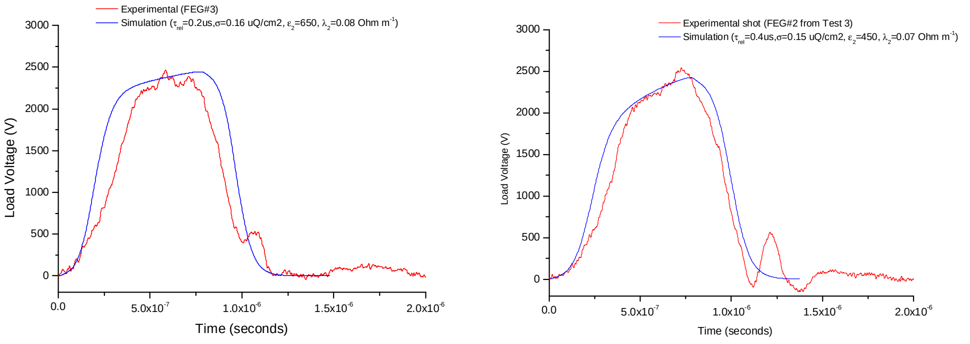

Figure 2. Comparison of Experimental to Simulated Output Voltages of the EDFEG for Two Different generators tested at TTU.