CHARACTERIZATION AND APPLICATIONS OF VECTOR INVERSION GENERATORS *

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Abstract

In 1964, Fitch and Howell [1] developed vector inversion generators (VIGs). To date, they have periodically been studied for a number of applications such as x-ray generators, high-power rf sources, and trigger generators. [2-6] In this current research effort, these devices have been revisited and studied for a variety of applications. In this work, we developed a theoretical description of the vector inversion generator, extracted design guidelines from the theory, established a relevant switch and materials database for various applications, and designed and constructed highly efficient devices using the developed methodology. These spiral-line VIGs that take electrostatically stored energy and convert it to high-power, high-frequency electromagnetic energy in essentially a one-component, one-step process have been built, characterized, and evaluated as a potential power source for several military and NASA applications. We concentrated on minimal size with maximum generated power in both single pulse and repetitive operation. In this paper, we will show that there is a functional relationship between the value of diameter to number of turns ratio (D/n) and the voltage efficiency. This is understandable in the context that for a given diameter, the diameter determines the characteristic "speed" of the "slow" part of the VIG while the length which is directly proportional to the number of turns determines the characteristic "speed" of the fast side. Thus, the D/n ratio is a measure of the ratio of the high/low frequency components of the generator. From a series of devices constructed here, the efficiency of the units doubled as the D/n ratio varied from 1 to approximately 6. Also, in this paper, we will talk about potential applications of this technology and will give point-designs that were used to construct and test devices for these applications.

I. INTRODUCTION

In this work, we built and demonstrated Spiral-Line Vector Inversion Generators that can take electrostatically stored energy and convert it to high power, high frequency electromagnetic energy in essentially a one-component, one-step process. We developed a theoretical description of the Vector Inversion Generator, extracted design guidelines from the theory and established a relevant switch and materials database for applications. We concentrated on minimal size with maximum generated power in both single pulse and repetitive operation. This device will greatly simplify power conditioning for pulse generator systems since it effectively combines the basic energy storage media with the power conditioning in one dynamic element. It allows a well-defined and repeatable high power pulse at high repetition rates. A low cost reliable high power pulser offers a wide array of commercial product potential. Commercial markets exist to varying degrees, from laboratory impulse generators to commercial airport X-ray facilities for security purposes. There is a market for this technology in the propulsion systems for advanced civil, military, and NASA spacecraft. There is a market for civil law enforcement in the field of portable X-ray facilities critical to the examination and evaluation of a potential bomb or other terrorist device. Similarly, impulse radar is a standard military technique to "look several feet below the ground" in order to find subterranean tunnels, land mines, etc. There is an emerging market for impulse radar capable of imaging "through the wall" making it possible to see inside structures with surprising resolution. Impulse radar is being considered for automotive applications to both "look behind and forward" for collision avoidance. The inherent simplicity and low cost of Vector Inversion

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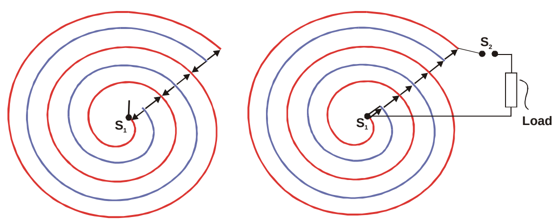
Generators make them ideal for insertion into the technologies that drive these markets.

II. THEORY OF OPERATION

Figure 1 depicts the layout of the vector inversion generators that were constructed. The lines shown are foils used and the space between them is the insulating material. Referring to Fig. 1, during operation, the strip-line is dc charged to voltage of choice, usually between 1KV and 50KV, with electrostatic energy stored in the capacitance C_{vig}. A plotting of the field vectors, turn to-turn, shows that the array will either be electrically neutral or at the charge voltage, depending on the geometry. When a pulse is desired, the input switch, S_1 is triggered.



(a) (b)

Figure 1. Schematic of Spiral Line Vector Inversion Generator (a) DC Charged and (b) Fully Erected

This trigger action starts an electromagnetic wave traveling up one of the strip lines, but to a first approximation, due to the single-turn inductance, not in the second line. This divides the VIG into a "slow" section and a "fast" section. When the wave has propagated up the active line to the open end and reflected back to the switch S_1, the electric field vectors in the active line have been reversed, aligning the potential vectors radially. If this time is short the "slow" section has not had time to discharge appreciably through the single-turn inductance. The net result is a transient high voltage between the lines at S_1 and the outermost turn on the spiral. The voltage-time waveform is a ramp function with rise-time equal to two electrical wave transit-times, determined by the dielectric properties of the material in the lines. Figure 1b illustrates the vector inversion process within the generator as it is ramped to full voltage. Assuming no losses, the peak voltage across the generator is $2nV_c$ where n is the number of turns and V_c is the initial charge voltage. Losses and geometry reduce this to a fraction β of the ideal amplitude. β can be further broken down into β_1 representing switch losses, β_2 representing line losses in terms of dielectric losses and resistivity of metallic shims, and β_3 representing inefficiencies due to the ratio of the "slow to fast" sections of the generator. Note that β_1 and β_2 are ohmic and will show up as thermal energy that limits repetition rates and the time at high average power levels. For some geometries, β can be as high as 0.95.

To a first approximation, we can regard the VIG as two coupled resonant circuits and proceed to analyze the process. Figure 2 is a schematic of the equivalent circuit for a "deconvoluted" VIG.

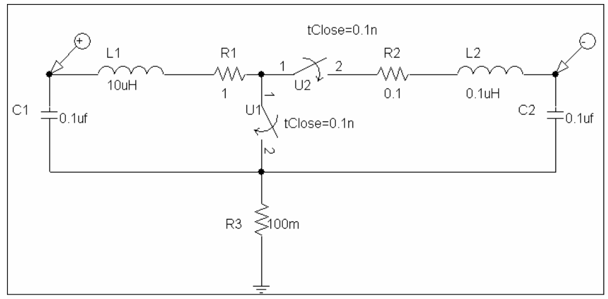


Figure 2. Schematic of Deconvoluted VIG

The left side of the above figure corresponds to the "slow" side of the VIG and the values chosen for the simulation using PSPICE are such that the frequencies associated with the left side is approximately one tenth of that associated with the right side. Obviously, L_1 is greater than L_2 but C_1 is always equal to C_2. R_1 and R_2 represent all losses in each side of the circuit. Comparing the schematic in Fig. 2 with the diagram in Figure 1, L_2 is the switch inductance and C_1 is one half of the total system capacitance. L_1 is the sum of the switch inductance L_2 and a single turn inductance that depends on the diameter of the spiral. C_1 and C_2 are charged and switches U_1 and U_2 are closed to start the equivalent of the erection process for a VIG. If we sum the voltages across C_1 and C_2, we have the equivalent of the erected VIG as shown in Fig. 1b.

The ability of the simple model to predict the shape of the voltage time traces for VIG's leads to an understanding of the experimentally observed dependence of the efficiency of operation as a function of diameter. L_2 in Fig. 2 is essentially the switch inductance and is constant for a given switch geometry and technology. This value however, varies widely depending on the switch technology and configuration. L_1 however is more under the control of the experimenter. The diameter of the device can be chosen to make a single turn inductance much greater than that of the switch. Experimentally, the efficiency is a strong function of the diameter and the length of the transmission lines. This suggests that the voltage efficiency of the device is directly proportional to the diameter of the spiral line and inversely proportional to the length of the spiral transmission lines.

A. Oscillator Mode

It is possible to configure the VIG as an oscillator. In Fig. 1, note that if S_2 is closed, the output capacitance C_o is determined by the formula given in Eq. (1)

$$C_o = C_{vig}/(2n)^2 \qquad (1)$$

The frequency at which it will oscillate is governed by:

$$f = \frac{1}{2\pi\sqrt{LC_O}} \qquad (2)$$

It is convenient to solve the differential equations for the oscillator version of the VIG while including a load that could be an antenna or a thruster. Figure 3 illustrates an erected VIG oscillator connected to a load R_a. Note that it is assumed that there are leads to the output switch S_{13} each having inductance L/2. These are under the control of the experimenter. It is easy to solve the differential equations for this circuit using the method of undetermined multipliers.

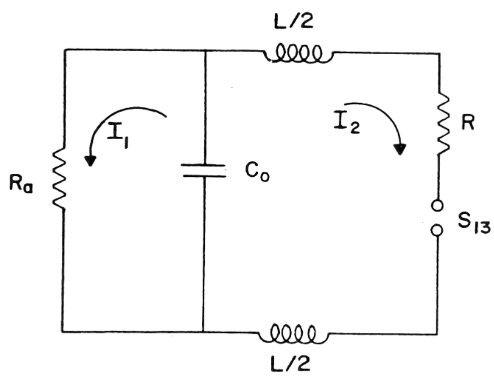


Figure 3. Oscillator Version of the VIG. R_a is the antenna. C_o is the erected capacitance for the VIG pulser as described above.

B. Ferromagnetic materials and effect on efficiency

In Fig. 2, the ratio of L_1/L_2 determines the voltage efficiency of a given VIG. To keep this ratio much greater than one, typically the diameter of the VIG is increased. There is an alternate possibility. If a suitable high frequency ferrite material can be found and a way to insert it into the VIG geometry, then it would be possible to control the L_1/L_2 ratio without increasing the diameter of the VIG. The prime requisite for the ferromagnetic material is that its maximum response be at a frequency near that of the characteristic frequency of the VIG. We have conducted experiments that have shown that ferrite would allow control of the single turn inductance of a VIG. The effect of including ferrites in the “slow” section of the VIG to improve performance and increase efficiency is extremely promising. The inclusion of ferrite isolation in the VIG represents a major advance in the state of the art by allowing the design of highly efficient devices that are small and compact.

III. DESIGN AND METHODOLOGY

The basic design equations for a VIG pulser are:

$V_o = 2n\beta V_c$ For voltage multiplication

$C_{vig} = 2\varepsilon\varepsilon_o A/d$ For Calculation of the VIG capacitance

$C_o = C_{vig}(2n)^{-2}$ For output capacitance calculation

$W = \varepsilon_o \varepsilon_r E^2$ Joules/M^3 For specific energy calculation

$E = C_{vig}V_o^2$ For VIG total energy calculation

$E_{ff}. = \beta^2 E_{the}$ For efficiency calculation

where E is the stored energy, E_{ff} and E_{the} are the measured and theoretical values of the voltage efficiency for the device, and A is the area of the line.

The above equations provide a design methodology by the following step-wise process:

1. Choose average power level needed and repetition rate
2. Assume efficiency needed and possible from experimental data
3. Calculate energy per pulse needed for average power at repetition rate
4. Choose operational voltage, V_{vig}
5. Calculate capacitance needed in VIG, C_{vig}
6. Choose dielectric material
7. Choose diameter and number of turns of VIG consistent with desired output voltage, capacitance, and efficiency
8. Calculate the width of the active elements
9. Choose a switch technology
10. Build the device

The oscillator version is more complicated but consists of adding an oscillator inductance L and appropriate switch technology:

1. Calculate the output capacity C_o
2. Calculate the switch and added inductance L
3. Calculate $I_1(t)$, ω, and α
4. Calculate the load impedance R(t)
5. Calculate the energy absorbed in the load E_L

IV. RESULTS

Using the design methodology developed here, a number of vector inversion generators were constructed and tested. Typical discharge waveforms are shown in Fig. 4 for a Teflon®-insulated VIG consisting of seven turns on a 4.5” diameter mandrel. The baseline case is for the VIG with no ferrites included in the circuitry. The peak output voltage was 12 kV for a 1-kV charge voltage (voltage efficiency ~86%) while the peak output voltage with ferrites was 13 kV (efficiency ~93%). Also, the effects of including the ferrites in the slow section can be seen in the resulting waveform.

Table 1 is a summary of the data obtained from the series of devices built during this research effort, except for the last entry which is from prior work in the 1970s [2]. In the table, n is the number of turns in the device, D is the diameter in cm, Vc is the charge voltage, Vo is the peak output voltage, and the voltage efficiency is ration of

Vo to Vc. Clearly there is a functional relationship between the value of D/n and the voltage efficiency. This is understandable in the context that for a given diameter, the diameter determines the characteristic "speed" of the "slow" part of the VIG while the length which is directly proportional to n determines the characteristic 'speed" of the fast side. The efficiency increases as the value of D/n increases as shown in Fig. 5.

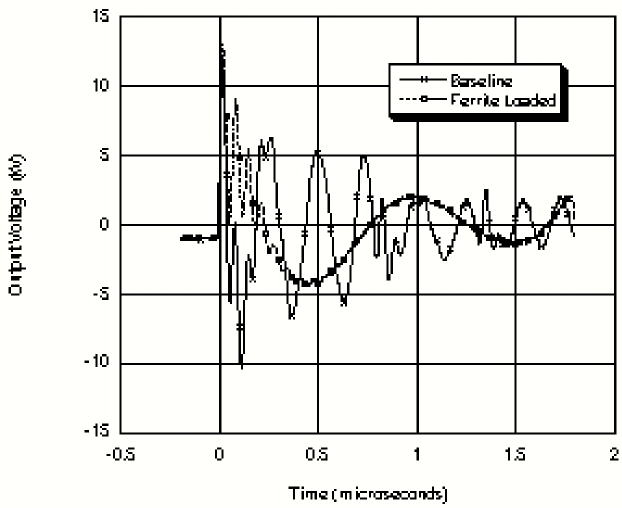


Figure 4. Typical Discharge Waveform for VIG

Table 1. Results from Various VIGs

n	D/n	D (cm)	Vc (kV	Vo (kV)	Voltage Efficiency
3	2.33	7	1	3.6	0.6
3	3.33	10	1	4.8	0.8
3	4.23	12.7	1	5.04	0.84
6	1.17	7	1	6.0	0.5
6	1.67	10	1	6.5	0.54
6	2.12	12.7	0.5	3.9	0.6
12	1.06	12.7	1	13	0.5
5	3.43	17.2	1	7.9	0.79
4	6.35	25.4	1	7	0.89
10	2.41	24.1	3	32	0.54
40	1.14	45.7	30	1000	0.42

V. SUMMARY

In this work, spiral line vector inversion generators have been studied for a variety of applications. We developed a theoretical description of the vector inversion generator that was modeled in PSPICE. Design guidelines were then developed and used to construct a number of experimental devices that were tested and evaluated. The theoretical description of the unit led to a

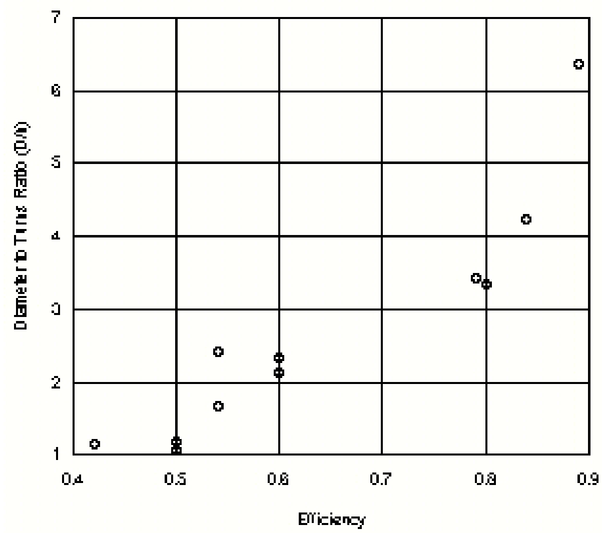


Figure 5. Effect of Diameter to Turns Ratio on Efficiency

breakthrough in the design of these devices with the inclusion of ferrite isolation. The use of the ferrite material will permit the design and construction of highly efficient devices in small, compact geometries that may lead to new potential applications of the technology. Use of the technology and design methodology developed here will enable the construction of relatively inexpensive, highly-efficient compact pulse power sources that have proven to be very reliable with consistent and repeatable high voltage output pulses.

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