HIGH EFFICIENCY COMPACT HIGH VOLTAGE VECTOR INVERSION GENERATORS

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Abstract

Vector Inversion Generators, VIG, were invented by Fitch and Howell[1]. The spiral-line VIG takes electrostatically stored energy and converts it into a fast rising high voltage pulse in a dynamic two component, one-step process. We present the results for a variety of units operating over a wide range of parameters. The highest voltage achieved in a single ultra-compact unit has been 500 kV in a device that is 8 inches long and 5 inches in diameter. Two of these units have been operated in tandem to produce a 1 MV pulse generator that failed after about 10 cycles. Finally, we discuss the range of loads that can be driven by this dynamic device in terms of the VIG dynamics and the RC time constant for the load.

Distribution: A

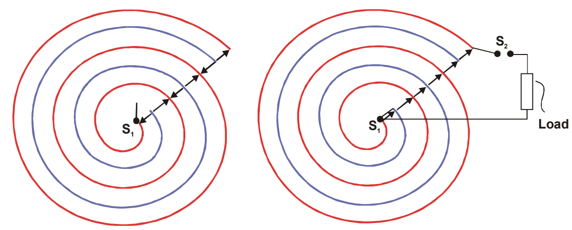
I. INTRODUCTION

In our laboratory, we have built and demonstrated VIG technology, to the megavolt level. Part of our research program has been to find ways to extend the inherent limits by modifying the circuit dynamics. For this purpose, we developed a simple description of the Vector Inversion Generator that allows us to determine the major factors that limit its utility, and extract design guidelines from the theory. We have concentrated on minimal size and maximum peak power. However, if dielectrics are not overstressed, VIGs can be operated with repetitive switching for long life. The inherent simplicity and low cost of Vector Inversion Generators make them ideal for insertion into systems such as impulse radar and portable flash X-ray devices.

II. BASIC THEORY OF OPERATION

A. Simple Circuit Model

Figure 1 depicts schematically the arrangement of the elements of VIGs. The lines shown are metallic foils and the space between them is dielectric film. In this configuration, the VIG is simply two parallel plate transmission lines, wound on a mandrel and sharing a common conductor. During operation, the array is dc charged, with energy stored in the capacitance C_{vig}. A plot of the field vectors, turn to-turn, shows that the array will either be electrically neutral or at the charge voltage, depending on the details of the winding scheme.



(a) **(b)**

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

Closing S_1 starts an electromagnetic wave traveling up one of the strip lines, but to a first approximation, not in the second line. The VIG contains two LC circuits - one "fast" and one "slow." After a two-way transit alternate field vectors plotted in figure 1a are reversed as shown in figure 1b. If this transit time is short, when compared to the rate that the slow section discharges, the voltage across the array is the maximum value, $V_o = 2nV_c$, where V_c is the initial charge voltage and V_o is the output voltage. The net result is a transient high voltage between S_1 and the outermost turn on the VIG. The voltage-time waveform is a ramp function with rise-time equal to the transit time up and back in the active line. Figure 1b illustrates the "ideal" vector inversion process. Losses and geometry reduce "ideal behavior" to a fraction of the ideal amplitude. Figure 2 is a photograph of VIG devices. The largest VIG built to date is one meter in diameter and stores about 200 joules at the design voltage. The voltage efficiency approaches 90%.

Figure 2. Representative Sampling of VIG Devices built in our Laboratory.

Figure 3 is a schematic of the equivalent circuit for a "deconvoluted" VIG.

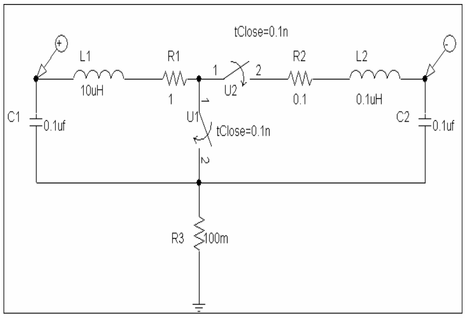


Figure 3. Schematic of Deconvoluted VIG.

The left side of the above figure corresponds to the "slow" side of the VIG. Mathematically, we can write the following expression to represent the voltage across the array at any given time after switch closure:

$$V = V_c\,[\cos(\omega_s t)e^{-\alpha t} - \cos(\omega_f t)e^{-\gamma t}] \qquad 1$$

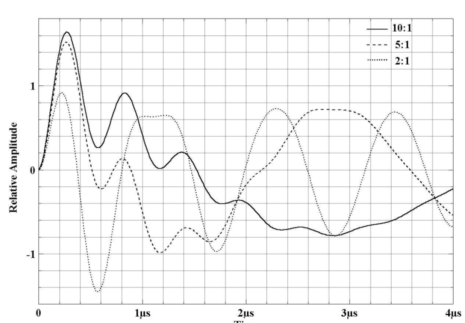
Where ω_s is the ringing frequency associated with the slow circuit of the VIG and ω_f is similarly associated with the fast circuit. The damping constant for the slow and fast circuits is α and γ respectively. Note that:

$$\omega_s = (L_1C_1)^{-1/2} \qquad 2$$

$$\omega_f = (L_2C_2)^{-1/2} \qquad 3$$

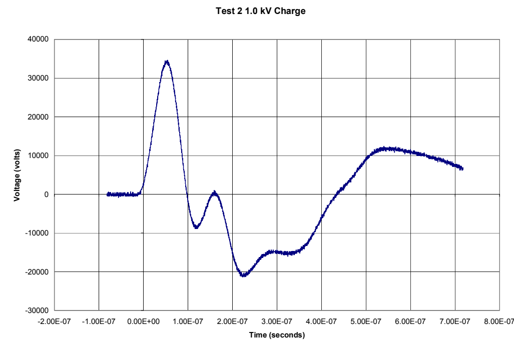
L_1 is the inductance of a single turn of the VIG plus the switch inductance. L_2 is the switch inductance.

Figure 4 is a plot of voltage-time using equation 1 where parameters for L and C are typical of VIG devices. The values of ω_f / ω_s were chose to range from 10:1 to 2:1 to illustrate how this affects the transient properties of a VIG when it is erecting. Figure 4, shows that the efficiency as measured by the ratio of the ideal maximum voltage for $\omega_f / \omega_s >>1$, is drastically reduced as this ratio decreases. The damping constants are typical.

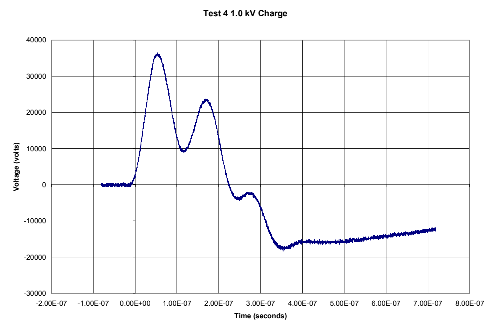


(a)

Figure 4. (a)Voltage-time Plots generated using Equation 3 for various Ratios of ω_f/ω_s.



(a)



(b)

Figure 5. (a) Experimental Trace taken from a VIG with a ω_f/ω_s ratio of approximately 4. (b) Experimental trace with a ω_f/ω_s of approximately 8.

Figures 5a and 5b are experimental data taken from VIGs with ω_f / ω_s approximately 4 and 8 respectively. These results illustrate the validity of our simple model. The ability to predict the shape of the voltage time traces for VIG's leads to an understanding of the experimentally observed dependence of the efficiency as a function of diameter and the number of turns on the VIG. L_2 in fig. 3 is the switch inductance and determines the value of ω_f. The fast line is assumed to function as a quarter wave transmission line oscillator. The diameter of the device, can be chosen to make the single turn inductance much greater than that of the switch. Alternately, the efficiency is directly proportional to the ratio ω_f / ω_s. Equation 1 is a useful tool to explain the fact that the rise time of a VIG is always less than what is predicted theoretically. It is also observed that as ω_f / ω_s increases, the rise time comes to the calculated value. Table 1 is a representative sampling of data calculated from equation 1 to illustrate the effect.

Pri. Freq	Sec. Freq	Freq. Ratio	V(peak)	Risetime(ns)
100	2	50.0	1.63	166.30
100	5	20.0	1.62	165.89
100	10	10.0	1.59	164.51
100	20	5.0	1.47	158.99
100	50	2.0	0.89	133.81

Table 1: Effect of ω_f / ω_s on Peak Voltage and Rise Time for a Constant Value of the Damping Constants.

The values of α and γ chosen produced a result consistent with what is observed experimentally. Note that for a frequency ratio of 50:1, losses in the line during the two-way transit, reduce the peak amplitude, which in this case could be a maximum of 2, to a smaller value due to all loss mechanisms. For our VIGs, we tend to use capacitor grade polypropylene or Teflon due to their low loss tangent at high frequencies. Note also, from table 1, that as the VIG gets less efficient, the rise time of the first maximum decreases from the calculated value. The slow line is discharging with the fast line with the rate determined by the ratio ω_f/ω_s with the result that the peak amplitude shifts to lower values and agrees quite well with what is observed experimentally.

B. Ferromagnetic materials effects

The ratio of L_1/L_2 (figure 3) determines the voltage efficiency of a given VIG. To keep this ratio much greater than one, typically the diameter of the VIG is increased. However, there is an alternate possibility. For a single turn coil, the value of inductance is approximately:

$$L \approx K\mu\mu_o D \qquad 4$$

Where μ is the relative permeability and μ_o is the value of free space and D is the diameter of the single turn coil. K is a constant for a given geometry. Ferrite materials with a wide range of values for μ are available. The ferrite we use has a value of 800. As shown in figure 5, it is possible to procure custom ferrites with known high frequency properties for controlling the single-turn inductance of a VIG.

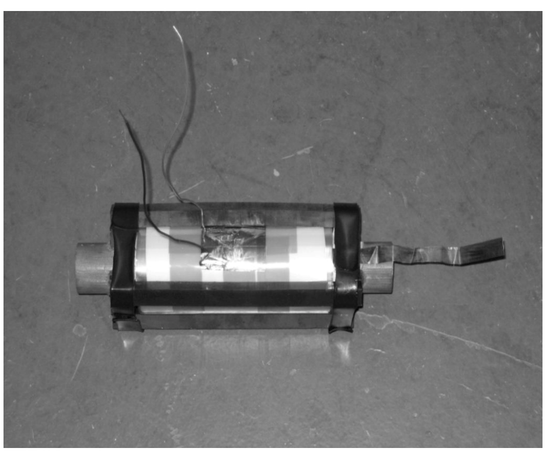


Figure 5. 40 Turn VIG with Custom Ferrite Material in Closed Loop through the Center of the Winding Mandrel.

The addition of a closed-loop ferrite path through the VIG, can improve the voltage efficiency by factors of 2 resulting in factors of 4 more energy available at the output of the generator. As we have seen in figure 4 and table 1, as the ratio of ω_f / ω_s increases, the efficiency of the device also increases. Note that ω_s is proportional to $(L_1)^{-1/2}$ in figure 3 which is the single turn inductance for the VIG. L_1 is proportional to μ so that adding a high μ material drastically increases the value of the ratio ω_f / ω_s.

In table 2, the data given is the voltage efficiency and the addition of a ferrite material results in substantial improvements in the efficiency of a given device.

#Turns n	Diameter D Cm	D/n	Eff. % w/o ferrite	Eff. % w ferrite
50	16.51	0.33	37	55.0
30	6.40	0.21	31	58.0
25	6.40	0.26	56	75.4
25	2.50	0.10	45	71.0
10	16.51	1.65	56	75.0

Table 2. Voltage Efficiency of VIGS with various Dielectric Materials with and without ferrite loading.

Note that the efficiency is also mirrored in the D/n ratio in keeping with previous authors[1,2,3] By controlling the "slow" side of the generator with ferrite materials, cylindrical geometry is no longer a requisite. Figure 6 shows a VIG with a rectangular cross section. It is wound on a ferrite core typical of that used for RFI/EMI applications.

The VIGs in figure 6 are approximately 90% efficient and have rise times of about 9 ns. The effect of the ferrite is large when compared to the single turn inductance and the line length so that small compact VIGs in any geometry are possible.

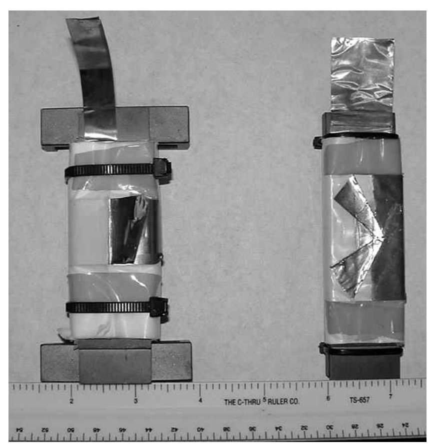
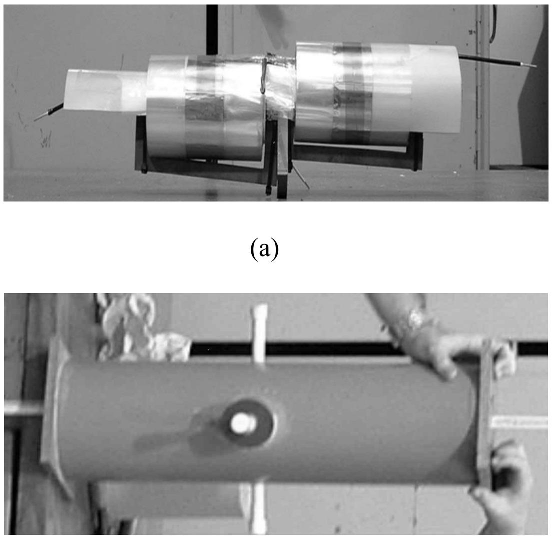


Figure 6. 10 Turn VIG's wound on Ferrite Bar with Rectangular Cross Section.

Merryman Rose and Shotts[2] have given the design methodology for constructing VIGs. The simple models outlined in this paper have been used along with a design methodology to construct hundreds of generators which usually come within 5-10% of the design parameters.

III. DISCUSSION

In this work, spiral line vector inversion generators have been studied for a variety of applications. Figure 7 shows a VIG designed to produce 1 MV pulse in a unit that is about 40 cm in length and about 15 cm in diameter.



(a)

(b)

Figure 7. Two 500 kV VIGS operating $\pm$ to produce a 1 MV Pulse. (a) Units before Potting in Silicone Compound. (b) Unit potted and ready to Test.

The unit was vacuum impregnated using a silicone potting compound. Figure 8 is the voltage-time trace from the VIGs showing a maximum voltage of some 1.1 MV $\pm$ 0.05 MV. The unit failed after approximately 10 charge-discharge cycles and was traced to a small gas bubble in the potting compound that produced a hot plasma on discharge and eventually punctured the dielectric.

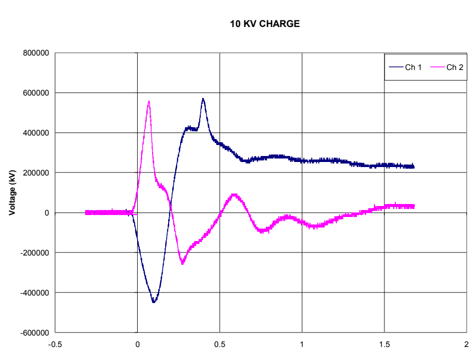


Figure 8. Voltage-time trace for 2 500 kV VIGs operating in a $\pm$ Configuration. The Maximum Voltage across the two VIGs is on the Order of 1.1MV.

The units individually were identical and were ferrite loaded. The fact that they did not erect to the same voltage is due to an asymmetry in the switching scheme that made the current path in one of the devices more inductive than the other. Late time behavior is complex and is not completely understood at this time. We have corrected this asymmetry in further versions.

Utilization of the energy in a VIG is constrained by the fact that the process is a dynamic one that continues as one connects to a load. For efficient energy utilization, the following condition must be satisfied:

$$\tau_r \gg R_l C_{vig} \qquad 5$$

In practice, one usually switches the VIG into the load before the device has fully erected. This tends to produce a somewhat "flatter" discharge that eventually approaches the exponential decay associated with such discharge phenomena.

IV. SUMMARY

We have developed a simple theoretical description of a VIG that matches what is experimentally observed with remarkable agreement. We used the design guidelines discussed in Reference 3 to build approximately 100 devices most of which performed within a few percent of the values expected. The use of ferrite isolation represents a breakthrough in the design of these devices and has led to the development of highly efficient, compact generators that are factors of 2-5 smaller than comparable units without ferrites. VIGs now are "designer' devices that can be accurately built to specifications for a particular user.

V. ACKNOWLEDGEMENTS

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VI. REFERENCES

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