Applied Energetics

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A Compact Nested High Voltage Generator for Medium Pulse Duration Applications

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Abstract

The “Nested High Voltage Generator” (NHVG) topology is an effective way of producing and grading high DC voltages. It has been applied to a variety of technical problems including semiconductor ion implantation, X-ray security, and electron beam irradiation. We have built a unit for pulsed power applications including such applications as pulsed X-ray generation, pulsed plastics’ processing, medium power microwaves, and pulsed ion beam annealing. This unit is designed to produce 250 kV and up to 5 amperes for pulses of up to several milliseconds. Previous pulsed versions of the NHVG used “hard tube” power systems, but this unit uses series resonant solid state drive. Repetition rates will vary for this machine from 1 pps to 1 kHz depending on the applied pulse format. We will report on performance and prospects for higher power operation.

I. INTRODUCTION

At energies of 100s of kV and intermediate currents (amperes), pulse compression is often achieved by using a grid controlled ion or electron beam to discharge the capacitance of an accelerator to make a pulsed beam[1]. This has been used in applications such as Free Electron Lasers, accelerator injectors, grid controlled microwave tubes and other applications with considerable success.

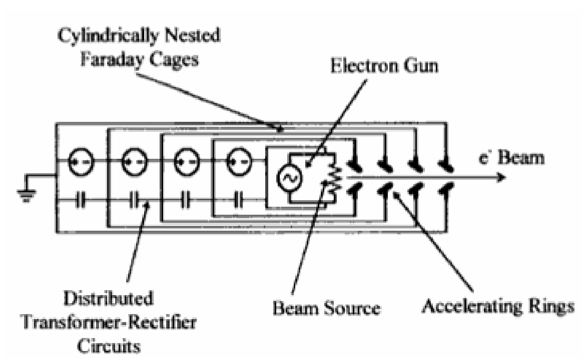

Figure 1. NHVG Operational Diagram

These techniques are often limited by the energy storage capabilities of the accelerator or other system which is used to provide the voltage. If a pure high voltage capacitance is used as the energy storage medium, there can be a significant droop in the pulse when loaded. A pulse forming network can also be used leading to the requirement for higher insulating voltages than operating voltages.

In many applications the pulses are long enough so that the amount of energy storage required at high voltage is unacceptable. Alternately capacitive energy storage is presently much smaller at low voltage than at high voltage. In those applications, the capability of the accelerator as a direct pulsed power supply becomes important. For example if a beam of 10 A at 500 kV is required for a millisecond, it requires 5 MW and 5 kJ. The 5 kJ can be supplied by a modest “supercapacitor” capacitor bank but will be bulky and expensive if created from a set of 100 kV capacitors.

We have studied the use of our “Nested High Voltage Generator” technology[1] for this class of application. In these applications the intrinsic capability of the power supply is the critical question.

II. THEORY

DC and quasi-DC HV power supplies use transformers, voltage multipliers, diode stacks, and other components to produce power at a high voltage. Voltage multipliers have a maximum power output. A typical voltage multiplier running at 50 kHz and 50 kV RF input with 400 pf capacitance has the power output as shown in Figure 2.

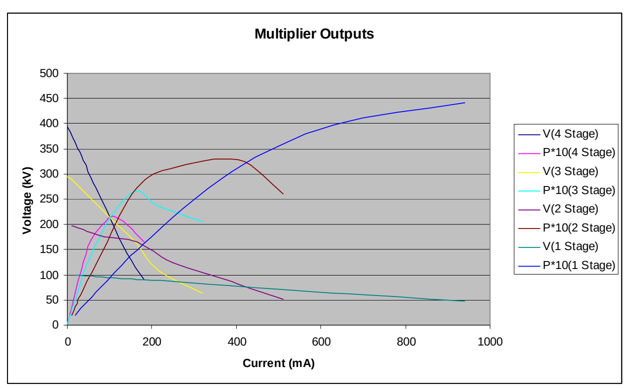

Figure 2. Voltage Multiplier Outputs.

The power output of (say) a 4 stage multiplier is limited to 20 kW for our parameters. Single stage multipliers allow us to reach higher powers but they are clearly not practical above 200 kV due to the large primary voltages required.

Charging the single multiplier is the challenge and the NHVG architecture is well suited to that challenge.

A magnetic core can be used to provide power for HV systems, but conductive cores are awkward to insulate (for example the Insulated Core Transformer or ICT) or they must be non-conductive as in a non-conductive ferrite.

A “dynamitron”[2] configuration can be considered for high powers but the structures tend to become large for such powers independent of the average power. The reason is because they are capacitively coupled, the total voltage is applied across the capacitor.

We have investigated the use of the Nested Generator as a direct drive power supply at high voltage and >1 MW powers[3]. The nested generator consists of concentric nested conductors separated by insulators. Each pair of conductors has a power supply internal to them. So for N+1 conductors, there are N power supplies and these power supplies are in series. In general we have built these units as “air core” units with no magnetic material. We power the unit with parallel or series resonant circuit which creates axial magnetic flux through a solenoidal primary coil. The power supplies are powered by coils which have a voltage proportional to the rate of change of magnetic flux times the area-turns product.

We wished to investigate the general properties of such geometries for power transfer. In general we operate the units with resonant circuits where we can readily remove 2/3 of the energy in the magnetic field. The total energy “recirculated” in the magnetic field is the primary inductive energy $0.5LI^2$ times the frequency times 2 (for each direction of field) = fLI^2. For example if we wish to drive 500 kV and 5 Amperes (2.5 MW) at 100 kHz we require a primary inductive energy of at least 2.5 MW/2/100 kHz = 12.5 Joules. This can be produced (for example) with a 4 uH coil at 2.5 kA with 100 % of the energy extracted. In practice the energy extracted is limited to the energy in the volume of the secondary and so is approximately $kfLI^2$ where k is the coupling coefficient. Note that this is not an absolute limit but rather it is a practical design rule.

The multiplier relationships in Figure 2 tell us that the use of voltage multipliers in these geometries will limit the power, and so we have used two series half wave rectifiers per stage in order to maximize the available power.

Either series or parallel resonance can be used for the primary circuit, but it is quite simple to produce high voltages and currents simultaneously in series resonant circuits. For that reason the experiments described here are those on series resonant circuits.

III. SYSTEM DESIGN

A. *Design Parameters*

Handling over a megawatt of instantaneous power is a significant design task. Table 1 illustrates expected currents in each subsection of the NHVG. As one can see the current reaches large values on the left hand side to allow for a large setup in voltage. As such it is important to not only pay attention to fusing currents but also basic AC impedances. A wire might have a DC impedance of a few milliohms, however due to the skin effect, an instantaneous current pulse may have an impedance orders of magnitude higher. That, in turn, can lead to extremely large amounts of instantaneous power which have to be dissipated.

Location	Simulated Currents	Voltage	Est. Power Loss*
Primary Resonant	6000A	8000V	3600W
Secondary	15A	12500V	20.25W
Output Rectifiers	15A	25000V	54W
*Power Loss in parasitics present in subsection over 1mS pulse at repetition rate of 10 Hz			

Table 1. Estimated Power Loss per section

The system therefore has to handle the high current and loss on the primary side. The secondary side ends up being quite a bit less lossy because the secondary RMS current is relatively low. In order to optimize the efficiency while being conscious of the skin depth constraints, we built the primary with a copper foil. The winding will be composed of foil that is half of the skin depth at the operating frequency. The width of the foil still results in a large cross-sectional area for the primary coil. Our design goal for the primary was to have the overall AC resistance of the coil at operational frequency to be 5 milliohms or less (30 V resistive drop).

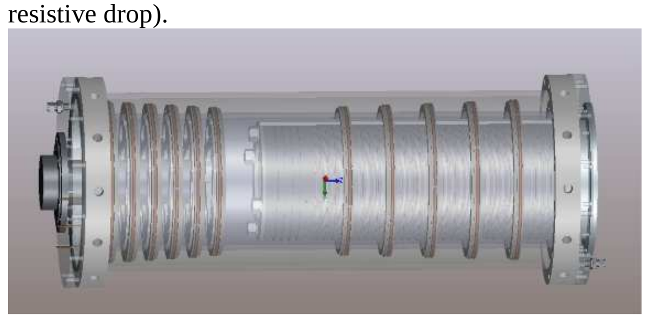

Figure 3. System Assembly 3D

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B. Inverter Design

The inverters used in the system were quad H-bridge inverters utilized on numerous previous projects by AE. These inverters were designed for 50 kHz maximum frequency but for test purposes we elected to operate them as high as 130 kHz. The IGBT losses were large, but given the low duty cycle and active cooling the system performed adequately. These systems have been heavily ruggedized and are capable of driving into full arc conditions with no damage suffered. For future projects that involve high power transfer requirements for pulsed applications a MOSFET based drive would be implemented. This type of drive would be better suited for the high resonant frequency and current sharing aspects of the system.

C. Foil Carrier/Strongback Design

The strongback is the part of the system that has the Kapton and copper foil wrapped upon it. The multiplier assembly and accelerating column nests inside of this structure. It is responsible for grading the axial electric field and also establishing an even magnetic field throughout the internal NHVG structure. The insulating foil used 100 mils of 5mil Kapton. Kapton has a dielectric strength of 3,900 volts/mil as per ASTM-D149-64. We're utilizing 100 mils of Kapton to insulate 50kV, thus our volts/mil is 500V/mil. Historically previous successful operating systems have used this same amount of solid material for insulation.

D. Primary Design

The Primary voltage was designed to 8-10kV. Primary windings were spaced via 5 mil Kapton film. For the 6 turn primary that means we will have a volts per turn of 1666.66V. The insulation of the of the Kapton foil wire will hold off 3,900V. The design margin in the 6T primary is 2.34X more than needed. Initial estimations and simulations denoted approximately 6kA on the primary during the output pulse. The final primary AC resistance measured during testing was 10 milliohms.

E. Secondary Design

The secondary windings were composed of four layered windings. These windings were three layers of 12 turns of 20 AWG magnet wire wound with an insulating layer of Kapton between the layers. Since the secondary voltage is 12.5 kV per winding the volts/turn on the total 36 turns was 347 V. Since we have two layers sitting on top of each other the second layer will at the worst point see the 4.16 kV differential voltage. 30mil of Kapton was utilized between layers along with careful winding techniques to ensure no breakdown occurred in this area.

F. Multiplier Design

The multiplier pucks house the secondary windings, storage capacitance, diode rectifiers, and/or bipolar series multiplier diodes. Each puck contains 9.4 nF of storage capacitance. This allows for 48.95 Joules of energy stored at the peak output voltage. This energy storage allows for the system to respond instantly to power draw while the primary drive resonance cycles up to full voltage. A full wave rectifier scheme was utilized to convert the resonant AC drive to a DC output voltage. The rectifier board was designed such that it could be changed easily to a bipolar series multiplier for future systems.

Multiplier spacing is at 30 kV/in. The multiplier board has twelve devices in series to allow for full voltage hold-off, ripple voltage when utilized as a series voltage multiplier, and also instantaneous voltages caused by subsection arc events. The devices are spaced such that the components have .5 inches distance from their nearest neighbor which is 6 kV different in potential. This gives us a significant design safety factor on the multipliers.

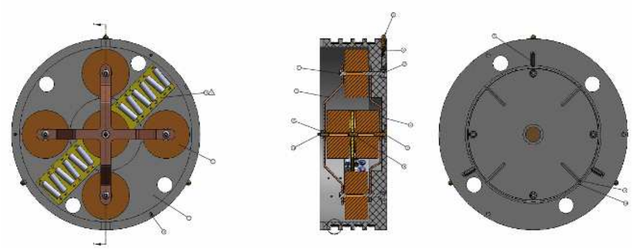

Figure 4. Multiplier Puck Assembly

G. Output Section Design

The output section was designed to accept two forms of power delivery. The primary design was for an integrated, removable electron gun and associated accelerating region that is common to most NHVG units. The second option that was designed was to connect to a 250kV X-ray connector. This secondary option would allow the NHVG to operate solely as a voltage source and or allow the electron gun to be located away from the voltage/filament source. These options are collocated in this single design, the only modification necessary to switch between the options are an adapter flange for the output end.

H. Accelerating Column Design

The accelerating column and cathode design are an integral assembly. This assembly is designed to operate in vacuum and is sealed such that it resides nested within the oil volume of the NHVG. The chosen cathode is an off the shelf part from Kimbal Physics, ES-440. The accelerating column is composed of a Rexolite tube machined to hold a number of grading rings, as shown in figure 3. These grading rings step the voltage down in increments of 50 kV. This allows for a gradual voltage grading that puts the vacuum connection at ground potential and also an accelerating region for the electron beam.

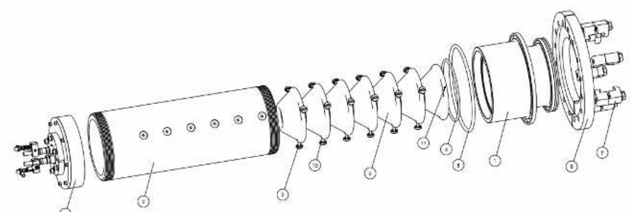

Figure 5. Accelerating Column Assembly.

I. Final Build

Final system assembly went well. Some modifications to the strongback design were needed to ease manufacturing concerns. The most difficult and time consuming aspect of the assembly process was cutting then winding the Kapton/Copper foil layers onto the strongback piece. In the future this process can be greatly simplified by ordering Kapton and copper foils cut to width and length. Figure 6 illustrates the system as built, after the final test run. In this image the multiplier stack has been pulled out for ease of viewing.

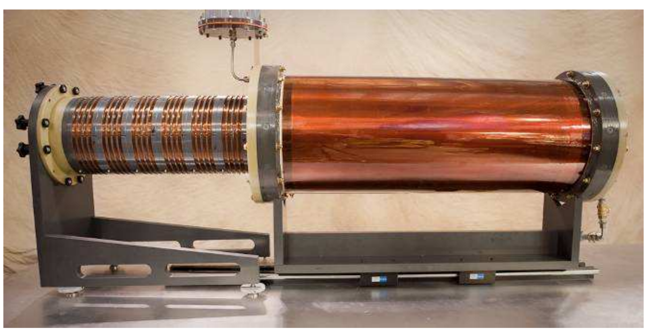

Figure 6. Final System Build

IV. TESTING

System performance demonstrated remarkable efficiencies at high loading, 40k Ohms and 50k Ohms resulted in efficiencies over 80%, while operation in the 80k-150kohm regime performed over 70%. It should be noted that no effort was expended on optimizing the main source of loss (the use of IGBTs rather than MOSFETs). In future designs the inverters will have MOSFET inverters designed for operation above 100 kHz.

Simulations performed allowed for an extremely high confidence in modifying the system. As shown in figure 7 the system responded almost identically in simulation and in testing. This attention to detail in our simulation modeling allowed for changes to be checked before investing time and effort into the modifications.

As shown in figure 7 the NHVG was capable of a 250kV output voltage in to an 83.3 kOhm load resistor. The channel two waveform shows the voltage on the last resistor in a resistor bank composed of 35 equal resistors in series. This represents an instantaneous power of 0.75 MW. Output at 250kV ended up being limited to 3A due to the IGBT limitations. Our budget only allowed for four inverter boxes to be constructed. Each inverter box was limited to 1600 A of resonant current. With the addition of further inverters the system would be expected to operate above 1.5 MW of instantaneous power without difficulty. The waveform shown was generated by pulsing the system up from a zero voltage state. In true operation, the response time would be limited by the grid circuitry associated with the electron gun. One can see that the system responds to full voltage in approximately 200µS into fully loaded circumstances.

Future work will involve integrating the accelerator column with the rest of the accelerator and DC operation at up to 15 kW average.

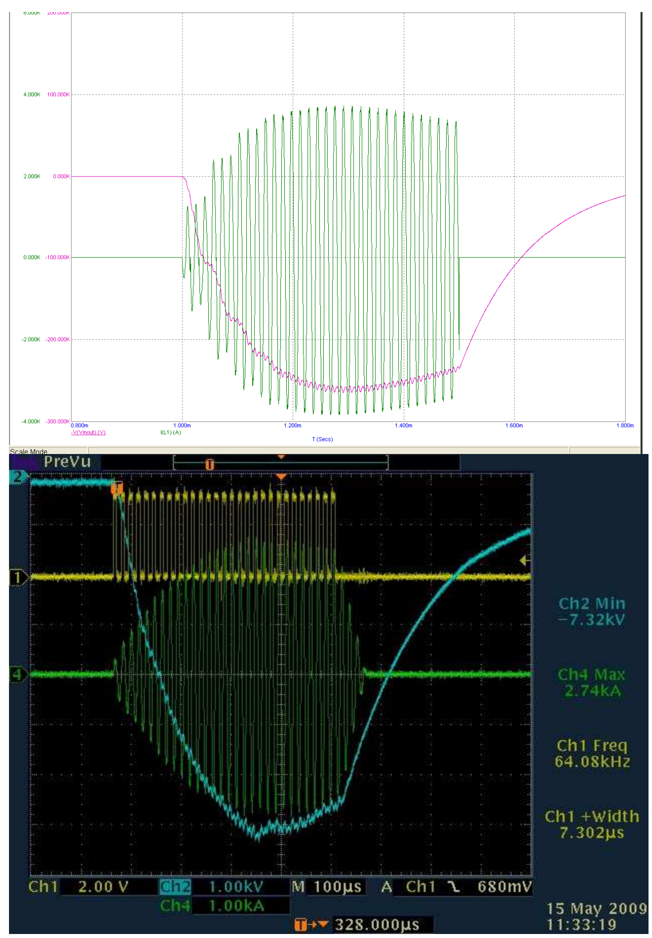

Figure 7. Output Waveform 250kV at 3 Amps (Simulated Versus Experimental)

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V. CONCLUSIONS

We have designed and constructed a dual operation capability Nested High Voltage Generator in a rapid prototype research and development program. This NHVG is designed around a modular approach that allows for future designs in the 100kV to 600kV voltage range and 0.5 to 5 MW peak power regimes. These supplies are capable of integrating in a nested electron gun or simply functioning as a pulsed or DC high voltage power supply.

VI. REFERENCES

[1] R. J. Adler and R. J. Richter-Sand in proceedings of the IEEE Pulsed Power Conference 1991, p. 92. IEEE CH3180-7/92.

[2] M. R. Cleland "Voltage Multiplication Apparatus" US Patent 2,875,394.

[3] R. J. Adler, Patent Pending.