DESIGN AND OPERATION OF A 700 KV ARBITRARY WAVEFORM GENERATOR

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Abstract

The control of voltage in an arbitrary manner has led to fundamental advances in fields which range from music to lasers. Such generators have traditionally been limited to a maximum voltage of 10 V. We have conceived, developed, tested and operated an arbitrary waveform generator with a range of voltages up to 720 kV. These devices have a wide variety of applicability. They are effective, high capability devices for simple square wave generation, and they also allow for a remarkable range of waveforms to be produced. The generators we have built are similar in some ways to solid state Marx generators, but with a novel charging system. The topology – but not the charging system - is also similar to the type of device described by Swanson in US Patent 4,403,197. The topology consists of a set of pulse generators arrayed in series where each pulse generator has a shunt diode. Each of the subunits can be on or off. We array the subunits in series. If M units are on at a voltage V we have voltage MV. We vary M in order to make an arbitrary voltage. The stages are truly independent, so the voltage of an individual stage device never increases due to the action of the other devices. This is in contrast to the action of switching in a series IGBT stack where one slow device will be subjected to N times its rated voltage. The main problem is to charge the stage capacitances $C_1 \ldots C_N$. We have developed a novel means of charging the stages using air core magnetic flux. We place the stages inside rings which have secondary coils on them. We arrange outside the rings - and with adequate spacing - to have a primary coil which provides a time varying axial magnetic field. The individual stages are charged with voltage multipliers connected to secondaries coupled to the magnetic field. In this paper we describe successful construction and operation of one of these devices up to 720 kV.

I. BASIC TECHNOLOGY CONCEPTS

The circuit diagram topology we have used is shown in the left of Figure 1. This shows 3 of M stages (we describe a 220 stage unit in section III) each with separate pulse generation capability. Each Nth subunit consists of a capacitor (CN) a “Turn-on” device QNA, gate drives, and a bypass diode DN. The subunit may also include turn-off devices QNB, and overvoltage protection DZNA or DZNB.
We can choose for each of the sub-units to be either on or off. If the unit is off, current flows through the bypass diodes DN. We array the subunits in series (and in parallel for some high current applications). If I units are on and we charge to a voltage V, we will then have a voltage IV. We vary I in order to make an arbitrary voltage. The charge voltage V is usually fixed. It is important to note that the stages are truly independent, so the voltage of an individual stage device never increases due to the action of the other devices. This is in contrast to the action of switching in a series IGBT stack where one slow device will be subjected to N times its rated voltage.

The power is provided to the unit on the outside as shown in Figure 2. The primary coil is driven by an H-bridge circuit at approximately 50 khz. The oscillating magnetic field is present throughout the oil enclosure. Each secondary coil “picks up” a voltage from the main drive flux which is multiplied and is eventually used to charge the stage. Magnetic flux is simultaneously used to power the main charging capacance and the control systems (which are of course at high voltage) both for gate drive, and for intermediate control circuits. The (oil) insulation between the primary and the secondary coils is designed to withstand the full voltage of the system – as high as 730 kV in oil. The voltage is linearly graded in the vertical direction since each stage has a unit voltage.

**II. DESIGN OF THE STAGES**

We designed each stage for 3.5 – 3.8 kV operation. 20 stages were placed on each platter. The height of each platter was 12.5 cm. The switch selected was the Powerex QIS4506001 4.5 kV IGBT. This device was tested to 120 A for our applications with satisfactory results. The complete single stage schematic of version 1 (with series resistors) is shown in Figure 3. One IGBT caused the voltage to go “up” and the other shorted it back to ground.

Zener diodes were used for protection of the IGBTs (and most other components) against incidental transients. Each stage used four (two are drawn) “Unlytic” capacitors from Electronic Concepts to store approximately 12 J. The Unlytic capacitors were charged from the secondary coil through an 8-stage multiplier circuit.

**Figure 2.** General setup of the charging system.

The most difficult part of building and operating such a circuit is the operation of the charging circuit. Charging circuit components are not shown in Figure 1. A variety of methods have been used involving diodes, and involving the observation that Q1B can be used for charging purposes. Isolation with resistors or inductors is problematic because of losses, and because the charge times for multiple sections become very long. Resistive charging, inductive charging, or charging via QNB makes DC operation impossible.

We have developed a method of charging through the use of magnetic flux coupling in which we place a primary coil on the outside and a set of secondary coils on the inside. This power system is similar to the arrangement in our “NHVG” DC accelerators1. This flux coupling technique is remarkably versatile and convenient. In the unit described in this paper, we place groups of 20 stages inside “rings” which have secondary coils on them.

**Figure 3.** Schematic of one stage of the 220 stages.
The control components receive their power from two step-down transformers which are connected to the primary.

Setting the turns ratio of these transformers properly was important because the ratio choice was a compromise between a higher voltage, more power loss, and a larger range of control and a lower voltage which had a reduced range of control.

In addition to 11, 75 – 80 kV nominal platters, we had a central platter which had “Fan-outs” to the pulser platters. We had 16 input fibers and each input fiber controlled and fanned out to approximately 30 (15 up/15 down) IGBTs.

III. RESULTS

The initial platter tests involved running the system at 1 – 2 Hz (our normal rep rate was 1 – 10 Hz) and verifying that each platter could withstand an arc to ground. In “Version 1” of the system, we had a 20 ohm resistor in series with each stage for overcurrent and transient protection purposes. Maximum currents were anticipated to be 10 A or less in regular operation. The net system capacitance was approximately 150 - 200 pF and this “internal load” was 20 A at 700 kV. The range of operation (given the control system power) was approximately 250 kV – 730 kV.

The system was initially operated with open circuit loading when fully assembled. The primary difficulty to be overcome was the loading observed due to “cross-over”. Cross-over is the situation where the two series IGBTs in a single stage turn on at the same time. This reduces the effective drive voltage and perpetuates the fault by lowering the control voltage. This occurs when the two circuits are each driven by 7 V instead of the required 15. This always occurred during turn-on before the problem was solved. We eliminated this fault by reducing the duration of the “shutdown” phase of the switching by providing a series capacitance between the gate and the shutdown IGBT.

The primary load for the AWG was the LIPC (Laser Induced Plasma Channel) and associated basic physics experiments. During these experiments the LIPC channel would arc to ground from time to time and the system withstood the arcs well.

For experimental reasons associated with creating the maximum possible rate of rise the series resistors were removed, and the system was operated. Arcs in the load would still occur, and without the resistors we found that significant numbers of IGBT driver chip (4420 and 4420 failures occurred (up to 20 from a single shot). These sometimes caused IGBT failures. While it is always in principle possible to protect any component we instead chose to replace the drivers with somewhat slower circuits which use medium voltage (200 V) discrete FETs. The failures during arcs stopped at that point and we were able to perform significant experiments.

Figure 4. AWG assembled with electrode, primary, oil tank, secondary oil confinement tank, and air pads.

We show 4420 and 4429 drivers as the IGBT drive component. As discussed in the results section, we eventually removed these devices and replaced them with a very rugged discrete FET circuit.
IV. SAMPLE WAVEFORMS

We spent about 30 minutes making a diverse set of waveforms as shown in Figure 5. Note that we did not separately program all 220 stages but rather split them into approximately 22 groups so a small ripple is visible. The load consisted of ≈150 pF internal capacitance + 100 pF electrode capacitance. The output voltage for the waveforms is nominally 650 kV at 3.5 kV/stage and 220 stages. The difference between 220 * 3.5 kV is partly an incomplete charge on the top and bottom platters, and the significant capacitance relative to the load capacitance. The total series drive capacitance was 1 uF/220 = 4500 pF. The 250 pF load is a measureable loading for the complete system.

V. CONCLUSIONS AND ADDITIONAL WORK

To the best of our knowledge this is the highest voltage “Marx stacked” style pulse generator that has been built and demonstrated. The project took about a year to complete, and at this point the limiting factor is breakdown on the air side of the air/oil interface. We have demonstrated a technique for coupling multiple primaries without electrical connections. This technique will allow us to increase the air insulation distance from ground to high voltage, and will allow us to make future units smaller.

VI. REFERENCES