Using Parallel High Voltage Multipliers for 100kV Downhole Neutron Generator Power Supplies

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Abstract: Operating 100kV downhole neutron tube power supplies at temperatures above 175 ºC yield low operating efficiency due to excessive diode leakage in the series Cockroft - Walton multipliers typically used. Such circuits are usually limited to less than twelve stages due to N^3 voltage regulation effects resulting in immoderate potentials across the switching rectifiers. This paper discusses the merits of using parallel multipliers with 30 stages or more to achieve higher conversion efficiencies at elevated temperatures in tools with 1.3 inch (32mm) diameters. By minimizing the per-stage voltage, definite improvements are realized due to reductions in reverse current leakage per device. Efficiencies of up to 32% may be achieved at 200 ºC operating temperature by this technique. In addition, ripple voltages present on the output are not a function of the number of multiplying stages in parallel designs.

Electronically controlled pulsed neutron sources have been an established tool in the well logging industry for over fifty years. During this time advances in electronics have allowed reliable operation of this equipment at temperatures on the order of 175 ºC. However, as the demand for logging in deeper and therefore hotter environments increases, there is a desire to reliably operate instrumentation at temperatures of over 200 ºC. This stretches present high voltage technology to its limits. Pulsed neutron generators for wireline operation normally consist of a sealed neutron generation tube incorporating an ion source and a neutron liberating target. Among other components, a high voltage power supply is required for accelerating the ions to accomplish the desired nuclear reaction. Generating 100kV at power levels of up to 10 Watts is somewhat of a chore in a rack mountable power supply, doing this within a diameter of 1.25" (32mm) is a shaky marriage between electrical and materials science. Specifying that a power supply must operate above 200 ºC requires a new approach beyond that currently utilized in existing designs.

The Series Multiplier Problem

Conventional topologies for 100kV well logging power supplies generally utilize the series Cockroft-Walton high voltage multiplier arrangement. This approach affords the use of reasonable value components having practical voltage ratings. A schematic for the CW multiplier is shown in Figure 1. Here a high voltage AC waveform is fed into the multiplier at the Vin terminal and a DC output, stepped up theoretically as many times as there are stages appear at the output. Limitations abound in this scheme however, the most serious resulting in being the droop in output voltage which is a function of output load current and strongly dependent on the number of multiplying stages.

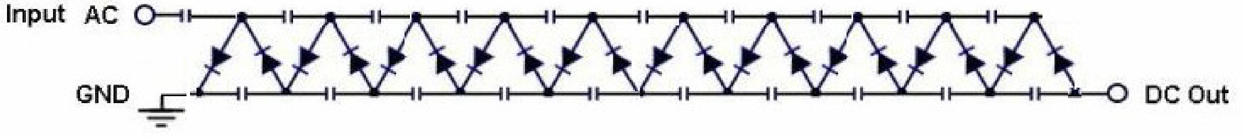

Figure 1: Ten stage Cockroft - Walton series multiplier (negative output)

At first thought, it may seem advantageous to have a multiplier with a great number of stages, effectively lowering the voltage across each component and requiring only a small output from the step up transformer - usually the most common component to fail in any high voltage power supply. Unfortunately nature is not that kind and, as one would expect, the voltage regulation suffers severely as stages are added. It can be shown that the voltage regulation of a series CW multiplier depends upon the capacitance value, the output load current, the frequency of operation and the number of stages according to the following formula.

$$V_{droop} = \frac{I_L\left[\frac{2n^3}{3} + \frac{n^2}{2} - \frac{n}{6}\right]}{fC}$$

Because this equation is dependent on the cube of the number of stages the voltage drop in output when suddenly placed under full load becomes a serious matter if a large number of stages are used. If the accelerating voltage drops below a threshold value during normal pulsed operation the neutron generation rate suffers quite severely and can lead to limited data collection. Voltage regulation of more than 10kV is a serious, but common problem in open loop designs. Because of this drawback the number of stages that can be practically used is usually restricted to a maximum of 12, forcing higher voltages across components in each stage and requiring a high voltage transformer that can produce an output voltage of up to 9kVp-p.

Each parameter in the above equation presents an even greater problem at elevated temperatures and over the years designers have had to find reasonable trade-offs to approach reliable 175 ºC operation. Increasing operating temperatures beyond this point present several obstacles that cannot be overcome currently with the standard series Cockroft-Walton multiplier design and unfortunately, all of the commonly used components.

Transformer Problem

One troublesome area is the high voltage step-up transformer. When considering the 100kV power supply being discussed, with its tight physical specifications, this device, as mentioned earlier, is the most unreliable component in the system for several reasons. First, for efficient multiplier operation a frequency of at least 30kHz must be used. This dictates the employment of a ferrite core due to the efficiency advantage over a metal lamination design. Unfortunately, because the Curie point is much lower in ferrite materials as opposed to a metal tape such as Permalloy, operation at 200 ºC requires operation at relatively low B field. To do this one must place a greater number of turns on the secondary of the step-up transformer which only exacerbates the Ohmic loss because smaller wire diameters must be used to fit them. From experience, a value of 1,000 Gauss is probably maximum for this parameter and is a tradeoff between hysteresis loss or resistive loss. In addition, any step up transformer must closely couple the primary flux to the secondary in order to minimize leakage inductance. This condition is at odds with voltage breakdown considerations and points to the fact that lowering the output voltage of the transformer directly increases system reliability. Because of physical constraints the step-up voltage that can be reasonably obtained at 200 ºC is limited to voltages less than 7kVpp requiring the use of a series multiplier of 15 or more stages.

High Voltage Diode Problem

Another problematic area is that of high voltage diodes whose performance and reliability are both seriously compromised by high temperature operation. As Figure 2 shows, reverse leakage in high voltage rectifiers is a function of applied voltage. If a diode is stressed beyond a certain point by reverse applied voltage, a thermally induced runaway may occur that is catastrophic to the component. Extra high voltage diodes (above 20kV) seem to suffer most from the central junction's inability to conduct heat out through the attachment leads. A glass encapsulated diode shows the highest run-away voltage over plastic case devices as one would expect.

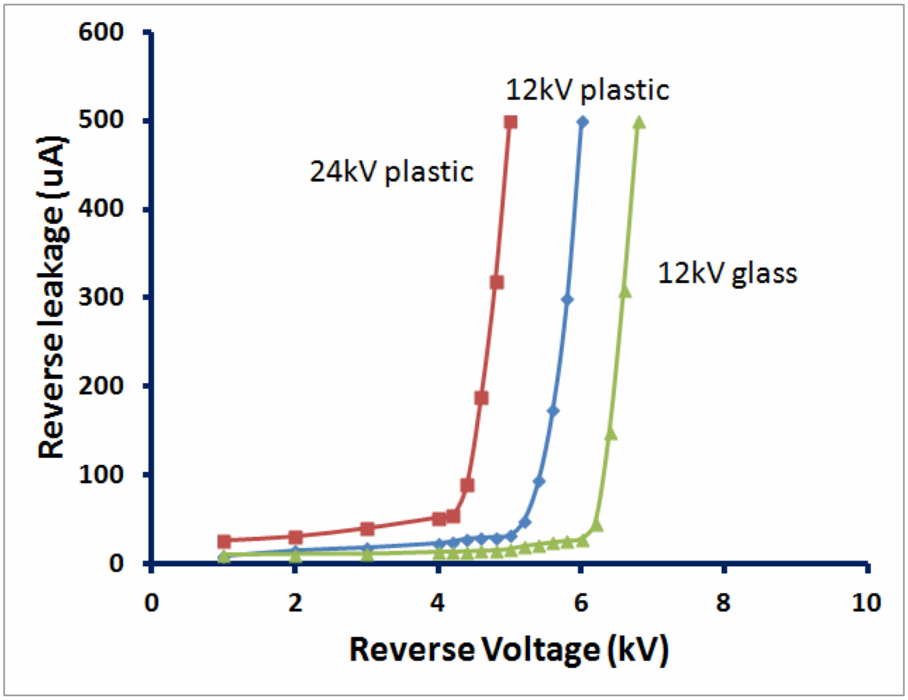

Figure 2: Typical diode leakage as a function of applied reverse voltage in air at a temperature of 200 ºC.

Capacitor Problem

Because of the number involved and their individual size, capacitors are the second most challenging part in the task of packaging a 200ºC power supply. High voltage capacitors need to utilize an NP0 material because the dielectric constant of X7R falls over 65% at a working temperature of 200 ºC. Perhaps the novel dielectric material H will come to the rescue but until then, the much lower dielectric constant of NP0 will need to be utilized but this presents a problem for capacitors that are rated at 10kV and over, with the result that they simply will not fit within the diameter of the device (33 mm) after allowing a 5 mm margin for electric field standoff. Using capacitors that will fit (values less than 500 pF at a rating of 10kV) will produce unacceptable output voltage droop in the series multiplier. For pulsed neutron analysis, where the current peaks may rise an order of magnitude above steady state values, the above factors sadly combine to eliminate the series type Cockroft-Walton multiplier as a solution. Specifying that the power supply must operate above 200 ºC requires a new approach beyond that currently utilized in existing designs to overcome these issues.

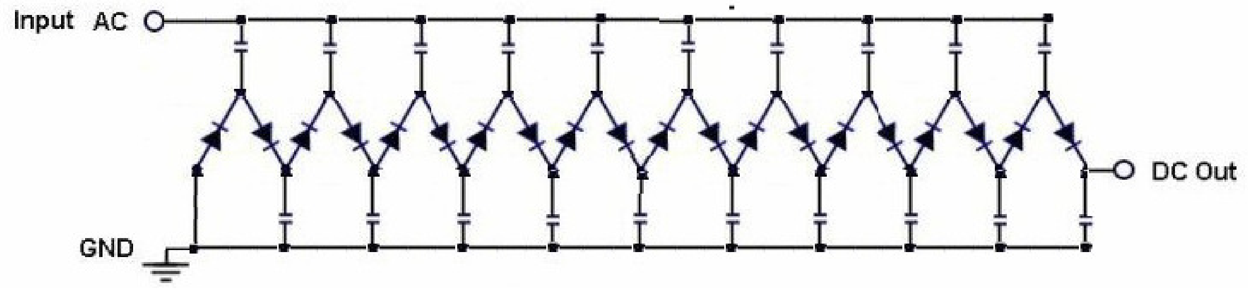

Figure 3: Ten stage parallel multiplier

The Parallel Multiplier Solution

Probably invented by Swiss engineer Heinrich Greinacher before 1920 to provide power to his newly invented ionometer, the parallel multiplier does not suffer the extensive load regulation effects of its sister circuit the series multiplier. In the parallel design all stages are charged directly by the applied AC waveform through gating diodes as shown in Figure 3 above.

Here, the voltage regulation is found to be a linear function of the number of stages:

$$V_{droop} = \frac{I_L \ n}{f C}$$

Since all capacitors are referenced to ground in some manner, the voltage across them increases linearly, as well, with the result that the final DC capacitor must withstand the entire output voltage of the multiplier. This peculiar aspect has usually sidelined the parallel multiplier in favor of the series version because the need to utilize capacitors of increasing voltage ratings as one builds on more stages makes packaging all but impossible, as the last capacitor is required to withstand the entire 100kV output of the power supply.

Using the application at hand we find that theoretically, considering basic formula parameters as above, an adequate parallel high voltage multiplier can be constructed that displays a voltage regulation of less than 10,000 volts, with 30 stages using capacitance values of only 10 pF, while working at 30kHz. In addition, operation at 100kV will only place 1.7 kV across a diode effectively limiting reverse leakage effects at 200 ºC provided that the 100kv capacitor packaging problem can be successfully solved.

Design

Overview: The basic design revolves around the task of creating a 100 plus kV capacitor. The approach implemented is to use a central conductor feeding capacitively through a strong dielectric material to a series of conductive rings in an axial tubular array

Capacitor Solution

To operate successfully at 200 ºC the capacitive components must neither show excessive current leakage nor change their dielectric constant to any degree. This tall order for the AC input capacitors was satisfied by utilizing a film of 1 mil Kapton sheeting, rolled up along a central brass electrode of diameter 15/32" (12mm) that serves as the AC input to the parallel multiplier. Figure 4 shows this construction and the thirty metallic electrodes fashioned around the outer perimeter of the assembly. Due to direct and fringing effects, each electrode of the multiplier furnishes a capacitive value of approximately 13 pF which did not vary appreciably over the entire temperature range. Earlier work on the electrical breakdown strength of Kapton film indicated that at elevated temperatures a value of 2kV/mil could be easily maintained requiring a dielectric having at least 50 layers. Moreover, the polyimide film proved ideal for this application with tests showing no punctures to the concentric electrodes with voltages up to 150 kV, a safety margin judged to be sufficient for a 100kV power supply.

Figure 4: Tube and film arrangement showing elements of the 30 stage parallel multiplier.

Since the power supply is incorporated into a pressure vessel housing, the DC electrodes are connected at the junctions of the gating diodes and like their counterparts, are composed of metal bands that charge to the linearly increasing voltage as one moves up the multiplier string. The DC capacitors were thus integrated into the high temperature polymer housing of the device. It has been found that Torlon 5030 makes a stable structure yet unfortunately has low dielectric constant of 4.3. Ceramics such as Maycor offer almost twice the capacitance but are only available in lengths of 12 inches, requiring one to piece several sections together. In this prototype, using Torlon, DC capacitance values in the vicinity of 9 - 10 pF were observed. This is shown in Figure 5. The outer diameter of the metal ground electrode is 1.25" (31.8 mm) being composed of a brass tube with 0.05 inch wall thickness. During testing it is mandatory that a ground be placed onto the outer surface to complete the return of the high voltage output.

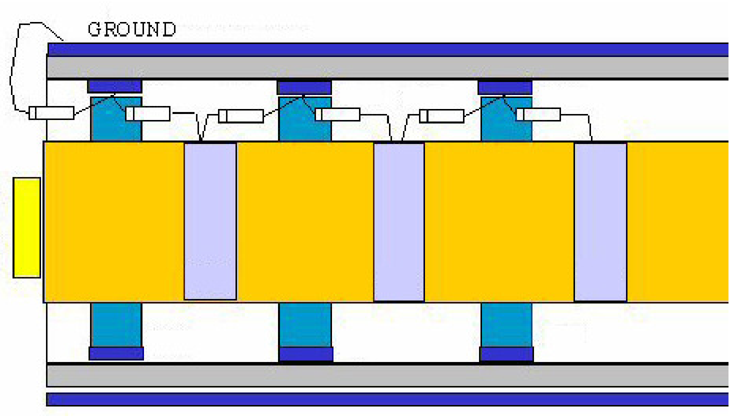

Figure 5 showing diode connections and outer dielectric (grey)

Driving Circuitry and Peripherals

The concentric parallel multiplier was driven from a ferrite high voltage step up transformer, of gain 1:30, located directly at the input end of the high voltage multiplier. The primary of this transformer was energized by a single ended FET switch controlled by a resonant pulse width modulator. Waveforms of the switch are shown in Figure 6. The operating frequency of the transformer was approximately 30kHz, dropping slightly as the temperature of the transformer and multiplier was increased indicating that the effective input capacitance of the multiplier was in the vicinity of 100 pF. Output voltage was monitored by a 1 Gigohm SD-1 divider which also provided the full load to the system. The temperature of the multiplier was monitored by placing two calibrated linear positive temperature resistors (Sensistors) along the metallic housing - one in proximity to the transformer location. The entire assembly along with the divider/load resistor was placed centrally inside of a diameter stainless steel tube that was sealed at both ends by cover plates with high temperature feedthroughs. This tube was subsequently placed inside of a cylindrical oven and pressurized with SF_6.

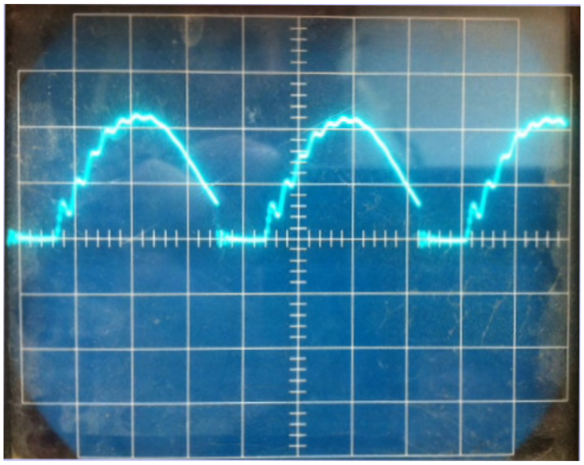

Figure 6: Transistor switch waveform
Vertical: 100 V/cm
Horizontal: 10 uS/cm

Results

Power efficiency

The power transfer efficiency from DC input to DC output, with an output voltage of 100kV into a resistive load of 1 Gigohm was recorded at 63% at room temperature. This dropped to 32% at 200 ºC due, it is conjectured, to a myriad of effects, among them, diode reverse leakage, diode reverse recovery effects, electron and ionic leakage through the dielectrics and along the surfaces between the metallic electrodes, and the series impedance of the high voltage step up transformer secondary winding. The voltage regulation of the multiplier was recorded by keeping the peak to peak voltage of the incoming AC waveform constant and measuring the output with an internal 15 Gigohm divider (incorporated for future regulation purposes) and with the 1 Gigohm load was found to be less than 5% at elevated temperatures.

Voltage Gain

Due to stray capacitance present within the structure of the multiplier, a gain of only sixteen was realized for the thirty stage multiplier. This dropped to fifteen at 200 ºC.

Conclusion

The parallel feed multiplier for downhole 100kV applications is an achievable design made possible by a unique packaging approach that is not dependent upon new state of art devices or materials. It provides a gain of 15 at elevated temperatures thereby allowing operation with a conservative 6.7 kVpp output transformer and only 1.7 kV across each diode. This in turn allows the manufacture of a high voltage power supply that overcomes the temperature and voltage limitations of Cockroft-Walton based design.

References:

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