Design of an 80kV, 40A Resonant Switch Mode Power Supply for Pulsed Power Applications

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ABSTRACT

A high power resonant three phase switch mode power supply with low output ripple has been constructed at University of Wisconsin to drive a klystron tube. Output voltage stabilization has been achieved by adjusting switching frequency toward resonance to compensate for capacitor bank droop. The power supply input is connected to a 900V electrolytic capacitor bank and three transformers with loosely coupled resonant secondaries are connected to a doubling three phase rectifier to provide an 80kV, 40A output. A snubber and crowbar sparkgap protects the klystron in the event of an internal arc, while output filters reduce voltage ripple in the output.

Index Terms — **Resonant power supply, loosely coupled transformer, nanocrystalline core, klystron, capacitor bank droop**

1 INTRODUCTION

The use of resonant circuits in high voltage switching power converters allows the voltage boost ratio of the transformer to exceed the turns ratio, resulting in more compact designs, as shown in Figure 1, and reduction of copper usage in the secondary winding.

Figure 1. Three phase resonant power supply.

Further, the strong dependence of the boost ratio on switching frequency allows the power supply to regulate output voltage by shifting switching frequency. By switching at full duty cycle near resonance, the primary voltage and current are in phase, allowing for zero current switching (ZCS), and significant reduction of switching losses. As switching frequency moves away from resonance, the IGBT current at the switching events increases from zero, however with only two switching events per cycle, switching losses remain low. Additional benefits of resonant topologies include the strong dependence of power transfer on a matched output load; in the event of a short circuit, the resonant circuit will be de-Qed and power transfer will automatically reduce without damage to the supply or klystron load.

2 POWER SUPPLY DESIGN

A unique switch mode power converter has been designed to supply a stable 80kV, 40A, 10ms pulse to a klystron tube. The supply is powered from a 900V electrolytic capacitor bank capable of sourcing the required input current over the pulse duration. The supply uses a low inductance IGBT network to switch power from the capacitor bank into the primaries of a three phase resonant transformer system. The resonant transformer assembly utilizes three magnetically separate nanocrystalline iron cores in order to provide suitable volt-seconds and low magnetic loss at switching frequencies of 18.5 to 25kHz [1]. The transformers are driven by independent full H-bridges with a 100% duty cycle square wave of variable frequency and corresponding phase offset. The use of a full duty cycle square wave in conjunction with a resonant transformer allows soft switching during the current zero crossing in the transformer primary. The subsequent reduction in junction heating allows operation of the IGBT network at higher than rated current without damage during the output pulse. Each transformer has a large leakage inductance secondary of 1.36mH with a parallel 50nF capacitor resonator, providing a boost ratio in excess of 120:1 at resonance and rated load while using a turns ratio of 13.5:1. The primary consists of a parallel pair of open air 10 turn helical copper straps around both sides of a square C type core, while the secondaries consists of a parallel pair of oil insulated coils, each with two 135 turn layers connected in parallel. The secondaries of the three transformers are connected in a wye configuration to a doubling rectifier, boosting the output to 80kV as shown in Figure 2.

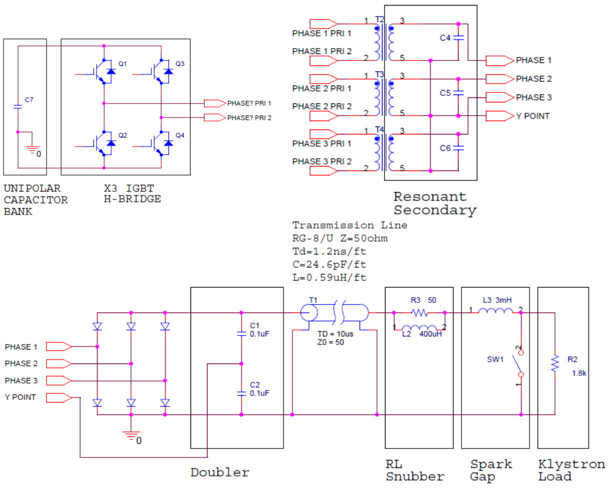

Figure 2. Three phase resonant power supply schematic.

Ramp up times to 80kV of <0.3ms have been measured during operation. Due to the resonant nature of the secondaries, the boost ratio is strongly dependent on load and switching frequency. This provides a measure of safety to the connected klystron since a load change due to an output fault or arc will rapidly drop output power by offsetting resonance and reducing boost ratio [2]. Further, the voltage output of the power supply may be directly controlled by adjusting switching frequency. A microprocessor PID feedback control system provides a stable output by varying the switching frequency toward resonance in order to increase the boost ratio as the capacitor bank discharges.

3 RESONANT TRANSFORMER

A set of three transformers, as shown in Figure 3, with loosely coupled resonant secondaries are used to drive the klystron tube through a doubling rectifier.

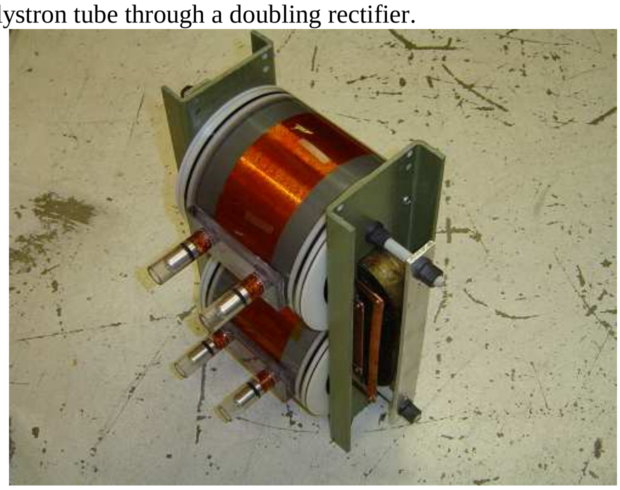

Figure 3. Resonant transformer.

Each transformer is built around a nanocrystalline iron core that allows low loss operation at high switching frequencies while providing a high saturation flux when compared to ferrite materials. The primaries consist of a parallel pair of 10 turn copper strap coils, wound around a polycarbonate form and held in close proximity to the cores. The secondaries consist of a parallel pair of 136 turn coils made out of 24AWG wire. For added current handling capability, each secondary consists of two layers of wire, connected in parallel at the ends of the windings and separated by Mylar insulation. Individual oil jackets enclose each secondary as shown in Figure 4; providing insulation, cooling and preventing corona discharge on the windings. Further suppression of corona discharge is accomplished by grounding the cores to prevent charge buildup and placing a faraday screen consisting of conductive copper tape on the inside surface of the secondary oil tank to prevent displacement current from the windings from capacitively coupling to the core or surrounding air.

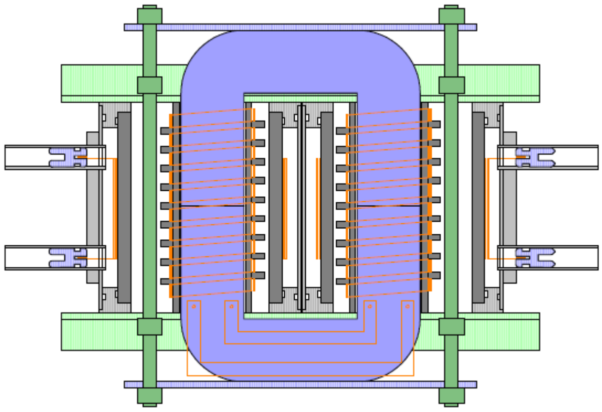

Figure 4. Resonant transformer assembly diagram.

The final transformer design was obtained through trial and error, testing secondary windings with 76 through 156 turns until a final design with suitable inductance for the desired resonant frequency and maximum boost ratio was obtained, as shown in Figure 5.

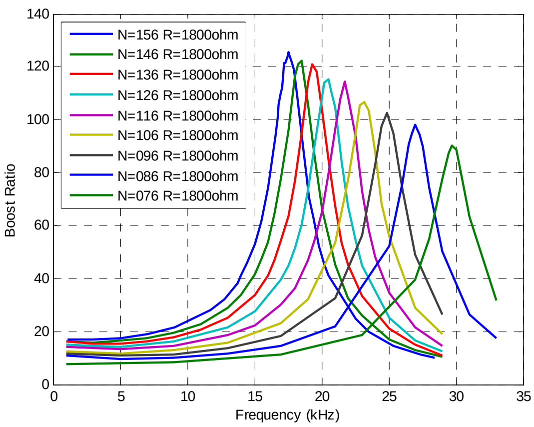

Figure 5. Three phase resonant power supply.

An analytical model for the inductance of a loosely coupled transformer was later obtained by modifying the Wheeler formula for a short solenoid [3] to obtain leakage inductance. Assuming an ideal model of the transformer where magnetic flux is entirely excluded from the core and primary of the transformer when the primary is shorted, the Wheeler formula is modified by subtracting the total core area from the cross sectional area of the secondary winding as in (1) where "r" is coil radius, "h" is coil height, and "A" is coil area.

$$L_{wheeler} = \frac{10\mu_0 N^2 \left(A - A_{core}\right)}{\left(9r_{coil} + 10h_{coil}\right)} \tag{1}$$

The resulting formula, called the "Wheeler compensated area" formula herein, predicts the leakage inductance of the transformer with high accuracy when compared to the Wheeler formula without area compensation and the long solenoid approximation as shown in Figure 6.

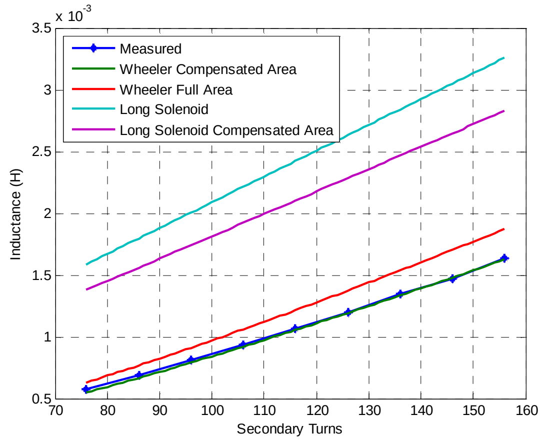

Figure 6. Experimental and mathematical models of the secondary winding.

An analytical model of the transformer's transfer function was developed and compared to experimental data. The transformer model may be simplified to a secondary referred model consisting of a voltage source of N times the primary voltage connected across a resonant circuit including an inductor of finite ESR, and an ideal capacitor with a load resistor connected in parallel across the capacitor as in (2).

$$\frac{V_{sec}}{V_{pri}} = \frac{N}{\left[1 + \left(R_{inductor} + j\omega L\right)\left(\frac{1}{R_{load}} + j\omega C\right)\right]} \tag{2}$$

The resulting transfer function accurately predicts the boost ratio of the transformer over the desired frequency range as shown in Figure 7. Note that (2) uses the DC resistance of the secondary and does not include skin effects which may contribute to the overshoot of the predicted boost ratio at resonance when compared to experimental data.

The use of such analytical models will allow rapid design of loosely coupled transformers without the use of time consuming trial and error methods by providing accurate predictions of leakage inductance, resonant frequency, maximum boost ratio, and transfer function shape.

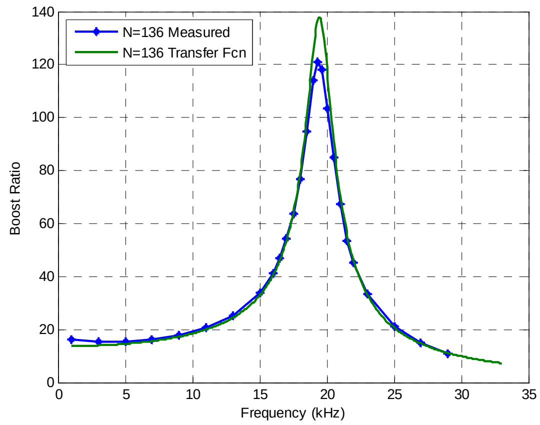

Figure 7. Experimental and mathematical models of boost ratio.

4 TESTING

Open loop testing of the power supply demonstrated the effects of capacitor bank droop; the output voltage will peak after startup and subsequently decrease as the input voltage droops as shown in Figure 8. Transformer primary voltage and current near resonance is shown in Figure 9.

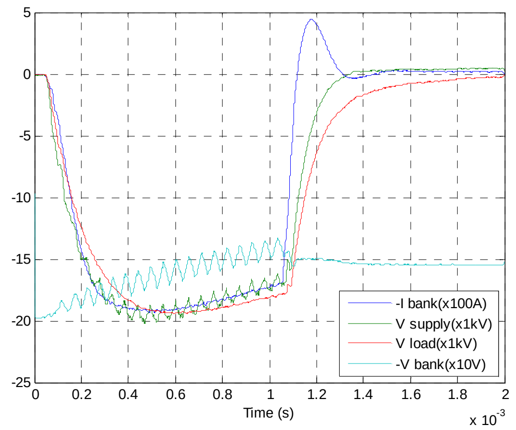

Figure 8. Capacitor bank voltage, current and output voltage during an open loop test at a fixed 18.5kHz switching frequency.

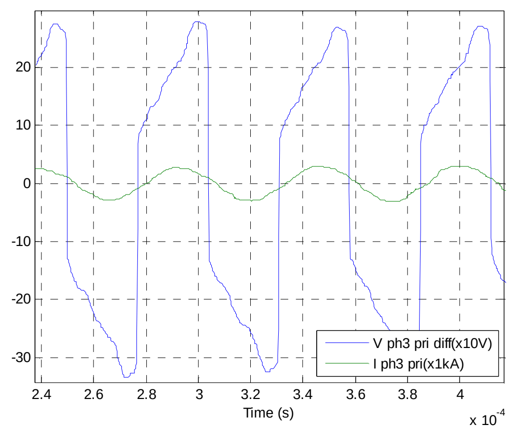

Figure 9. Transformer primary voltage and current during an open loop test at a fixed 18.5kHz switching frequency.

6 DROOP COMPENSATION

High input power requirements on klystron power supplies prohibit direct supply from the 60Hz power grid, requiring use of a capacitor bank for energy storage. During operation the voltage on the capacitor bank droops from its initial value, requiring an increase in boost ratio to maintain a stable voltage output. A linear approximation of boost ratio data gathered from open loop testing as shown in Figure 10, allows a microcontroller to compensate for capacitor bank droop by adjusting switching frequency to vary boost ratio.

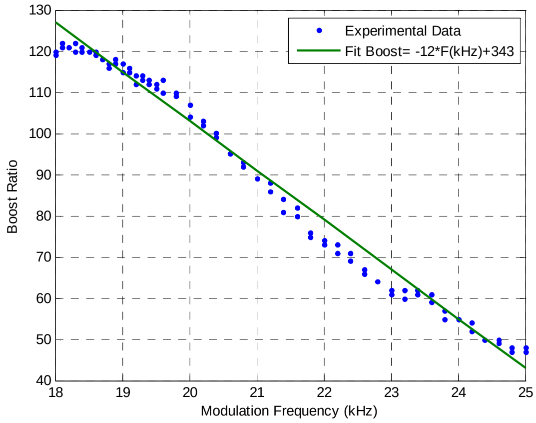

Figure 10. Boost ratio of doubled three phase system as a function of frequency. Boost ratio is calculated as the maximum peak output voltage divided by capacitor bank starting voltage.

The initial switching frequency starts above resonance and tunes towards resonance as capacitor bank voltage decreases thereby increasing boost ratio and stabilizing output voltage as shown in Figure 11.

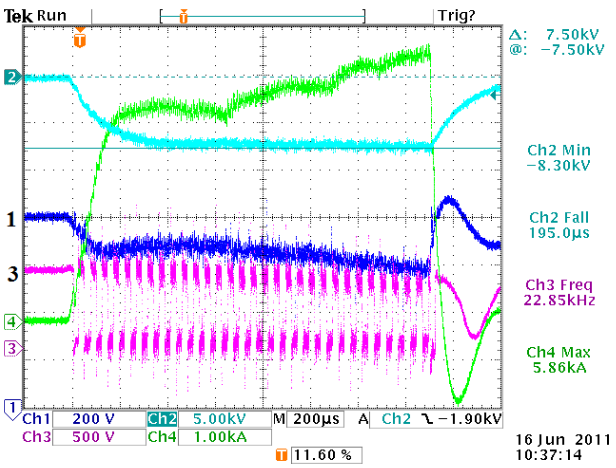

Figure 11. As capacitor bank voltage (CH1) droops during the pulse, IGBT switching frequency (CH3) tunes towards resonance, increasing boost ratio of the resonant transformer and stabilizing output voltage (CH2). As switching frequency tunes towards resonance, current from the capacitor bank (CH4) increases.

7 CONCLUSION

Resonant three phase power supplies show great promise for use as compact, efficient klystron power supplies. The design presents several inherent safety features since the secondary resonator is automatically de-Qed during an arc, interrupting power transfer and protecting both the supply and klystron from damage. Further, the ability for the supply to operate at high frequencies allows the reduction in filter capacitor size, reducing the stored energy capable of damaging a klystron during an internal arc.

The resonant nature of the transformer allows for soft switching of the IGBT H-bridges reducing switching losses and allowing higher primary currents. Use of nanocrystalline core materials further reduces losses and system size by allowing efficient high frequency operation and providing a high magnetic saturation flux. The resonator allows a boost ratio in excess of the turns ratio, reducing the size and copper usage in the secondary. In conjunction with a doubling three phase rectifier, this type of power supply is capable of outputs near 100kV at the 10s of amps required to drive high power klystron tubes.

Use of low cost microcontrollers and linearized models of boost ratio allow for accurate output voltage stabilization by tuning switching frequency towards resonance as capacitor bank voltage droops during a pulse.

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