RESONANCE TRANSFORMER POWER CONDITIONERS

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Abstract

Designs for power conditioning systems based upon the resonance transformer [1] have been developed for applications requiring compact, lightweight power supplies ranging from average power levels of 10 kW to over 1 MW. The resonance transformer is a Maxwell patented concept [2] which depends upon a set of resonant LC circuits to produce transformer-like voltage or current gain. Because this approach does not require the magnetic core material associated with a conventional transformer, a significant savings in both size and weight can be realized, particularly at higher power levels. Technical issues associated with the conventional transformer, such as coupling of the primary and secondary windings at both high voltages and high frequencies and thermal management of heat generated in the transformer core, are also avoided. Several designs have been generated and tested, including a 20 kHz, 10 to 15 kW average power system. This power supply will provide a voltage gain of 50 and weighs less than 100 lb. Additional designs for higher average power levels above 1 MW will also be discussed along with information on expected sizes, weights, and general scaling tendencies.

Introduction and Concept Overview

Many applications exist today for compact, lightweight, high voltage power conditioners. Defense technologies such as hypervelocity projectile guns and directed energy weapons (involving high power microwaves, high power lasers, and particle beams) will all require compact power source systems if they are to be effectively used in mobile applications. These high voltage power supplies can be represented by the simple block diagram of a generic power supply shown in Figure 1.

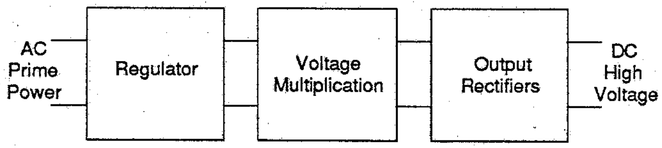

Figure 1. Simple Block Diagram of a Generic High Voltage Power Supply.

As shown in the figure, the input voltage is usually regulated in some manner in order to vary and control the output voltage. The regulated ac voltage waveform is then multiplied and rectified to produce the desired dc output voltage. In most cases, this multiplication is performed by a conventional transformer. Unfortunately, traditional high power, 60 Hz transformers are large and heavy, eliminating their role in mobile platforms. High frequency, switching power supplies (and their associated high frequency transformers) offer significant savings in size and weight since the transformer effective core cross-sectional area is inversely proportional to the operating frequency.

Unfortunately, conventional transformers suffer from several limitations at higher power levels. Thermal management problems associated with heat removal from the transformer core become increasingly difficult at high frequencies with the physically large cores required for high power operation. Issues of transformer winding coupling at both high voltages and high frequencies also exist. In order to operate at high frequencies, one desires a transformer with a low leakage inductance which implies the need for a small area between the primary and secondary windings. However, this distance is ultimately restricted by the minimum spacing required for high voltage insulation.

One solution to this problem of high power transformers is the concept of the resonance transformer, which uses a set of resonant circuits, made up of discrete inductors and capacitors, to achieve a transformer-like voltage gain. Although this concept has been discussed in detail in a previous publication [3], a brief overview of the general approach will be presented in the following discussion. This technique was developed by John Harrison at Maxwell in the late 1970's as an improvement on earlier resonant systems. These improvements included:

- A gain which is relatively insensitive to the load circuit
- A lower ratio of reactive power in the circuit to the delivered power, especially at high gains
- A higher gain limit for a single stage resonance transformer
- The ability to add several stages in series or in a "ladder" connection to achieve a multiplication in the overall gain. Earlier circuits could not be connected in this manner.

The overall concept can be explained by analyzing the single stage resonance transformer circuit provided in the simplified schematic diagram of Figure 2.

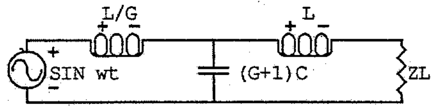

Figure 2. Simplified Schematic Diagram of Single Stage Resonance Transformer.

Given a sinusoidal ac source providing a voltage oscillating at a given frequency, ω, one can design the circuit such that the LC combination is resonant at this operating frequency. A set of loop equations can then be derived and solved to determine the output voltage.

$$\omega = \sqrt{\frac{1}{LC}}$$

$$Z_O = \sqrt{\frac{L}{C}}$$

$$\frac{jZ_O}{G(G+1)}\, i_1 + \frac{jZ_O}{G+1}\, i_2 = \sin \omega t$$

$$\frac{jZ_O}{G+1}\, i_1 + \left[\frac{jGZ_O}{G+1} + Z_L\right] i_2 = 0$$

$$Z_L i_2 = -G \sin \omega t$$

$$V_O = -G \sin \omega t$$

From the equations, it can be seen that the output voltage ($V_O = Z_L i_2$) is merely the input voltage multiplied by the resonance transformer gain (G) and phase shifted by 180° such that the polarity of the output voltage is reversed. These equations also show how the gain is independent of the value of the load.

From the simplified circuit shown in Figure 2, additional reactances are added to the front and back of the circuit to minimize the reactive energy and to provide a unity power factor load on the source when feeding a resistive load. The output load can also be connected in an "auto-transformer" (or "ladder-connected") fashion to increase the gain. In this case, the overall gain is equivalent to G+1 instead of merely G. The resulting auto-transformer version of the voltage transformer circuit is shown in Figure 3.

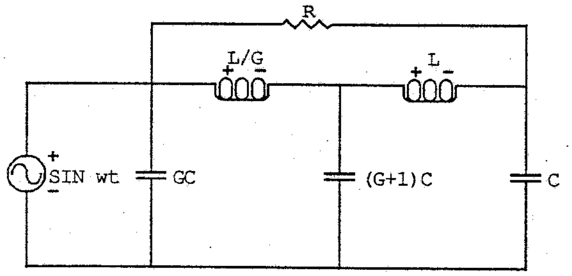

Figure 3. Schematic Diagram of Single Stage Resonance Transformer in "Auto-Transformer", or "Ladder", and Voltage Transformer Configuration.

A variety of different resonance transformer circuits have been identified. Instead of the voltage transformer circuit shown in Figures 2 and 3, a current transformer circuit can be obtained using a pi-type circuit with a single inductor and two capacitors as the core circuit. Both the voltage and current transformer circuits also have inverse circuits in which the capacitors are replaced by inductors of equal impedance and vice versa. The inverse circuit equivalent to that shown in Figure 3 is displayed in Figure 4.

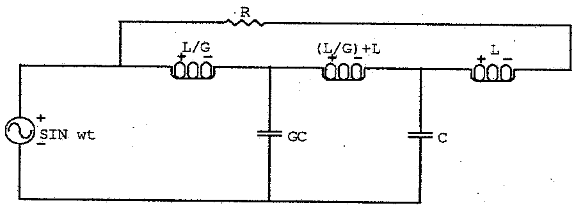

Figure 4. Schematic Diagram of Single Stage Resonance Transformer in "Auto-Transformer", or "Ladder", and Inverse Voltage Circuit Configuration.

Given the concept, a resonance transformer based power conditioner can be developed which functions in a similar manner to that of a conventional switching power supply. An input rectifier converts the input ac power into dc voltage and feeds it to a H-Bridge inverter, which converts the dc to an ac voltage at a high frequency. This voltage is then converted to high voltage ac by means of the resonance transformer. Operation at high frequencies allows the selection of smaller component values in the resonant transformer since the amount of energy transferred to the load per cycle is smaller for the same average power level. The output of the resonance transformer is then rectified to provide a dc output voltage as in the conventional power supply.

One advantage of this approach is that the gain of a multi-stage transformer is multiplicative. Unlike other concepts, such as capacitor voltage multipliers, the overall gain is the product (not the sum) of the individual gains of each stage of the transformer. Hence, if a gain of 100 is required for an application, two stages, each with a gain of 10, may be implemented. A potential disadvantage of this approach is the lack of isolation between the source and the load which is normally provided with a conventional transformer. We will show how this drawback can be avoided when the resonance transformer system is used to provide plus/minus charging for a capacitive energy storage system. In this case, the load does not require voltage isolation since it can be grounded "in the middle".

Several working versions of the resonance transformer concept have been developed over the past few years at Maxwell to demonstrate the technique. The remainder of this paper will describe the design and testing results of these example systems.

Brassboard Resonance Transformer

One of the earlier designs was a two stage transformer designed with the specifications listed in Table 1. This simple experiment was carried out as a first attempt to understanding the basic operation of the transformer and identifying the critical parameters for maximizing its performance. The low average power level (~1 kW) and low switching frequency were selected in order to simplify the design such that the hardware could be assembled and tested in a short amount of time.

Table 1
2 Stage Brassboard Resonance Transformer Device Specifications

Parameter	Specification
Input Voltage:	100 V
Ideal Output Voltage:	10 kV
Ideal Transformer Gain:	100
Operating Frequency:	1 kHz
Design Load Impedance:	64 kΩ

Component Design and Construction

Since the resonance transformer based power conditioner operates similarly to a switching power supply, the same inverter switching technologies can be applied. Solid state switching devices, such as Silicon Controlled Rectifiers (SCRs), Bipolar Power Transistors, Power MOSFETs, Insulated Gate Bipolar Transistors (IGBTs), or MOS-Controlled Thyristors (MCTs) are therefore possible switch candidates. MCTs were rejected since these devices are not yet readily available in large quantities. Bipolar Power Transistors typically require large trigger circuitry because of their drive current requirements and were therefore also eliminated. SCRs were ruled out since they are generally limited to frequencies in the few tens of kHz and at least some of our applications were likely to exceed their capabilities. Previous experience with Power MOSFETs at average power levels of up to 0.5 MW had proven their capability to operate reliably [4,5]. These devices were therefore chosen as the switching technology for the inverter in the resonance transformer based power conditioners.

Given the low power associated with this initial design and testing effort, the H-bridge inverter was constructed with single devices in each of the four legs. For this application, the IRFP450 (rated at 500 V BV_{DSS} and 14 A I_D continuous) was selected.

The two stage resonance transformer was constructed using air-core inductors and ceramic dielectric capacitors. For this initial design, a voltage transformer configuration, as shown previously in Figure 3, was used. Table 2 lists the different specifications for each of the components in the resonance transformer.

Brassboard Resonance Transformer Test Results

Initial testing of the brassboard system revealed that the voltage transformer configuration has certain disadvantages with respect to the inverter operation. Because the inverter directly drives the input capacitor of the resonance transformer, a high peak current is drawn from the inverter to charge up the input capacitor during each half cycle. To reduce the peak current requirements of the inverter, an additional inductance was added between the inverter and the transformer input.

Shown in Figure 5 is an oscilloscope trace showing the ± 80 V inverter (transformer input) voltage and the ± 6 kV output of the two stage transformer operating into its design load impedance of ~60 kΩ. As can be seen from the photo, the gain in this case is

Table 2
2 Stage Brassboard Resonance Transformer Component Specifications

Component	Component Value	Voltage (V)	Current (A)
Stage 1			
C1	7.46 µF	100	4.69
C2	8.29 µF	300	15.6
C3	829 nF	900	4.69
L1	3.40 mH	316	14.8
L2	30.6 mH	949	4.94
Stage 2			
C1	74.6 nF	1000	0.469
C2	82.9 nF	3000	1.56
C3	8.29 nF	9000	0.469
L1	340 mH	3160	1.48
L2	3.06 H	9490	0.494

reduced from the ideal design specification of 100 to a value of 75 due to the losses inherent in the realistic components. It should be pointed out that the inverter voltage measurement is not differential and therefore only displays the positive half-cycle of the waveform. During the testing effort, each of the individual transformer components was characterized by measurement with a Hewlett Packard HP4274A or HP4275A LCR meter. Using the resulting data, a computer simulation model was developed. The results of the computer simulation, displayed in Figure 6, show excellent agreement with the experimental gain. The top trace shows an input voltage to the resonance transformer of ± 100 V while the bottom trace shows the output voltage across the 64 kΩ resistive load of ± 7.5 kV.

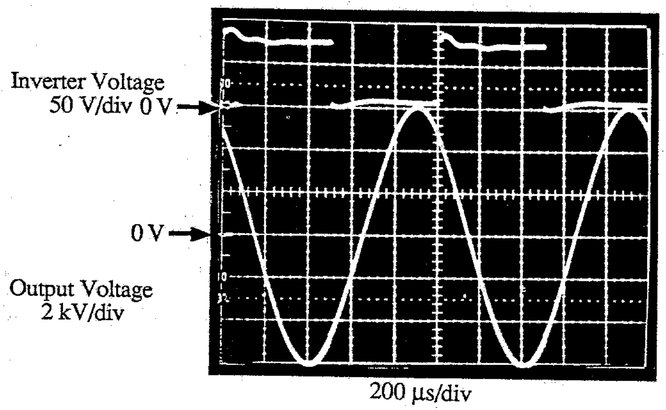

Figure 5. Oscilloscope Photograph Showing Single Ended Measurement of Resonance Transformer Input Voltage (upper trace) and Output Voltage (lower trace).

Based upon the results from the testing of the brassboard, several criteria for maximizing the resonance transformer power conditioner performance were identified including:

- Utilizing the inverse voltage configuration (shown in Figure 4) instead of the voltage configuration since the peak current requirements from the inverter are reduced.
- Design and/or selection of capacitors with high quality factors, or Q's (and corresponding low dissipation factors), and low temperature and voltage coefficients.
- Design of high Q inductors with low stray series capacitances (high self-resonant frequencies).

Testing of the brassboard also revealed that the transformer gain is not significantly affected by mutual coupling of the inductors or by close proximity to metal objects. This was tested by orienting the inductors on axis and physically close to each other and by moving them apart and placing them orthogonal to each other. Only slight differences (less than a few percent) in gain were observed.

Proof of Concept Resonance Transformer

A second design of the resonance transformer concept was then generated, assembled, and tested. The specifications for this example are shown in Table 3. This system was designed to fit inside a cylindrical housing 30" in diameter and 28" in height, weighing less than 100 lbs. Given the experience learned from the previous experiments, this unit was conservatively designed to operate from a 1 kV dc prime power source and provide ± 50 kV dc for charging capacitive loads, such as the compact Marx described in a separate paper presented at this conference [6].

Table 3
2 Stage Proof of Concept Resonance Transformer Specifications

Parameter	Specification
Input Voltage:	1000 V dc
Ideal Output Voltage:	± 70 kV
Ideal Transformer Gain:	70
Operating Frequency:	20 kHz
Design Load Impedance:	163 kΩ

Component Design and Construction

The components in the resonance transformer must have a high quality factor, or Q (Q = energy stored per cycle/ energy dissipated per cycle = $(\omega L)/R = 1/(\omega CR)$), for the circuit to have the proper gain and to minimize the losses. In addition to high Q, the components must also have very small stray impedances associated with them. This is a system design as well as a component design problem. The resonance transformers designed and constructed to date have operating frequencies in the 1 - 100 kHz range. This range is generally limited at the high end due to the switching device speed at these power levels and by transformer component design. Currently available capacitors can have Q's well over 100 (even for devices operating in the tens to hundreds of kHz range) and have series inductances in the tens to hundreds of nanohenries. Polypropylene film capacitors were selected for this application since their dissipation factor (1/Q) is generally on the order of 0.1% or less. Series and/or parallel arrays of commercially available units were made up in order to meet the design requirements of current, voltage, and capacitance.

The difficulty in component design for the current generation of resonance transformers therefore rests primarily with the inductors. The losses in inductors are strongly dependent on the frequency of operation. At high frequencies, the resistance per unit length of a conductor increases due to the skin effect. Using strip (or tubular) conductors is a well known technique for reducing skin effect related losses. An additional loss mechanism called the proximity effect [7] also exists with inductors or any component where current carrying conductors are placed close to one another. This effect is due to the magnetic fields which penetrate the conductors, forcing the current in those conductors into very small cross sectional areas and raising the effective resistance of the conductors. The change in resistance is dependent upon the magnetic field strength as well as the frequency. In order to obtain a high Q, the inductor design must therefore seek to minimize the ac resistance due to both skin effect and proximity effects in addition to the dc resistance.

The stray capacitance in parallel with the inductor is also important, particularly in the transformer output stage where the inductance values are generally highest. The self-resonant frequency of the individual inductor should be significantly larger than the operating frequency of the resonance transformer. In order to reduce the stray capacitance, the inductor design typically utilizes multiple winding sections in order to break up the stray capacitance into a series summation. As a result of all these considerations, a large engineering effort was spent on inductor design.

Table 4 lists the specifications for the components which were used in the proof of concept resonance transformer. In this case, a two stage transformer using the inverse voltage configuration, as shown in Figure 4, was used.

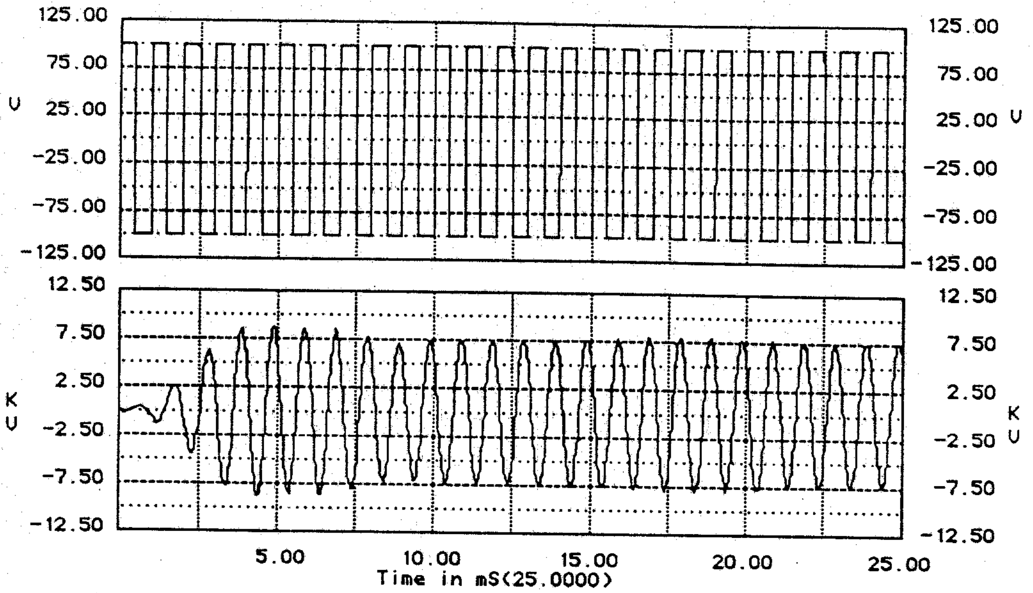

Figure 6. Computer Simulation Results Showing Resonance Transformer Input Voltage (upper trace: 50 V/div, 2.5 ms/div) and Output Voltage (lower trace: 5 kV/div).

Table 4
2 Stage Proof of Concept Resonance Transformer Component Specifications

Component	Component Value	Voltage (kV)	Current (A)
Stage 1			
L1	818 µH	2.71	26.4
L2	6.84 mH	8.37	9.73
L3	6.02 mH	2.71	3.59
C1	77.4 nF	2.89	28.2
C2	10.5 nF	7.85	10.4
Stage 2			
L1	57.2 mH	22.7	3.16
L2	479 mH	70.0	1.16
L3	422 mH	22.7	0.429
C1	1.11 nF	24.2	3.36
C2	150 pF	65.7	1.24

Inverter Design Considerations

The inverter design for high power systems is complicated by the fact that for these power levels and frequencies of operation, no single devices are available to meet the complete requirements. As discussed previously, power MOSFETs have been chosen for most of the applications to date. These semiconductor devices are arranged in a series-parallel array to form the inverter switches. Careful design of the array ensures equal current and voltage sharing in the individual switches. Because power MOSFETs exhibit a positive temperature coefficient, current sharing problems are effectively eliminated. If one device begins to draw more current than the others, its on-state resistance increases, forcing current into the remainder of the array.

In order to meet the voltage and current requirements for this particular application, a conservatively rated array of 3 (series) by 5 (parallel) devices was implemented for each of the four switches in the H-bridge inverter scheme. Once again, the IRFP450 was chosen as the basic building block device because of its low on-state resistance.

Each switching array was designed onto a printed circuit card assembly, which included transient suppression components, trigger circuitry, and three aluminum cold plate heat sinks for mounting of the three groups of power MOSFETs. Each switch printed circuit board then plugged into a motherboard assembly along with the timing and gate trigger printed circuit board. De-ionized water was used to provide cooling of the MOSFET heat sinks.

Proof of Concept Test Results

The proof of concept resonance transformer was assembled and first tested into a resistive water load with an impedance of ~134 kΩ. The input and output voltages were monitored while the inverter frequency was swept from less than 10 kHz to 100 kHz. A plot of the measured voltage gain profile versus frequency is shown in Figure 7.

As with the brassboard, the resonance transformer components were characterized using a Hewlett Packard LCR meter. Based on the data obtained during this work, it became apparent that the inductors procured for the transformer did not meet the design specifications with regards to ESR. In order to verify that this was the primary cause of the reduced gain which was observed, a computer model was developed and used to simulate the transformer frequency response. The results of the simulation showed excellent agreement with the data derived from the experimental hardware. The voltage gain into an open-circuit load was measured to be 50 at the designed operating frequency of 20 kHz.

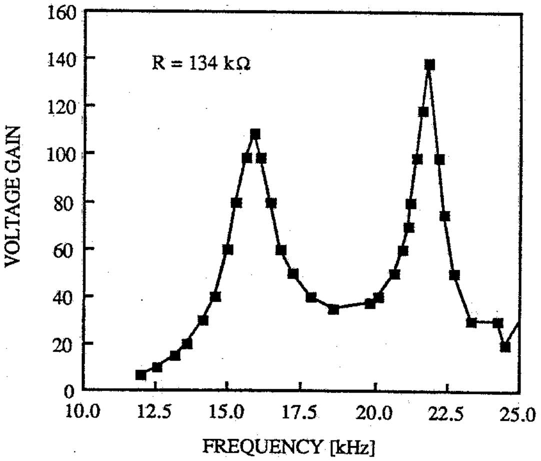

Figure 7. The Voltage Gain Versus Operating Frequency of the Proof of Concept Resonance Transformer Operated into a Resistive Load.

The oscilloscope photograph shown in Figure 8 displays the inverter voltage (lower trace) and the transformer output voltage (upper trace) for a nominal input voltage of 600 V dc. As with Figure 5, the inverter voltage waveform shows only the positive cycle since a differential measurement was not made. From the figure, one can see that the voltage gain is approximately 43. The resonance transformer was operated at this average power level of 2.5 kW for greater than 1 hour. The heating of the water load caused the resistance to begin to decrease and an average power level of 3.6 kW (≈30% decrease in resistance) was reached after some time. The voltage gain during this time remained unchanged.

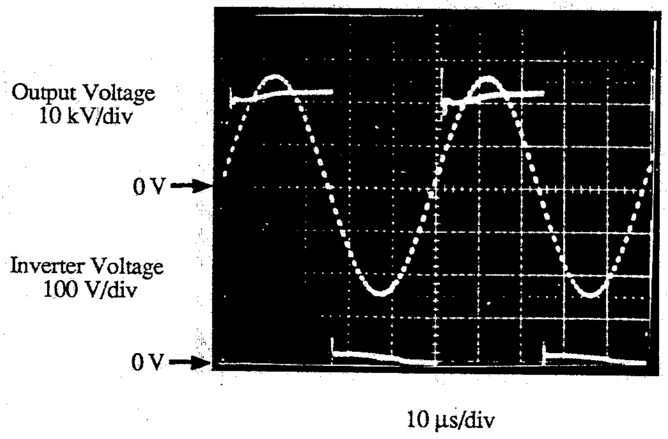

Figure 8. Oscilloscope Photograph of Resonance Transformer Input Voltage (lower trace) and the Output Voltage (upper trace).

To test the resonance transformer in a capacitor charging scenario, the load circuit was configured as shown in Figure 9. The energy storage capacitor used was the 1/4 scale proof of concept version of the multiple capacitor module used in Maxwell's compact Marx generator development effort [8]. The capacitance of each of the two capacitors in the assembly is 40 nF and is rated at a voltage of 100 kV. CR1 and CR2 are 3 (series) by 2 (parallel) arrays of fast recovery rectifiers (VMI SP250F), producing an array rated at 75 kV PIV and 1 A average rectified current. A charging resistance of 150 kΩ was inserted in each leg of the circuit to ensure these rectifier current limitations were not exceeded. A Maxwell standard 100 kV spark-gap switch and two 5 kΩ resistors were used to discharge the capacitors. The gas pressure in the spark-gap was adjusted to self-break at the peak charging voltage at a rep-rate of approximately 1 pps.

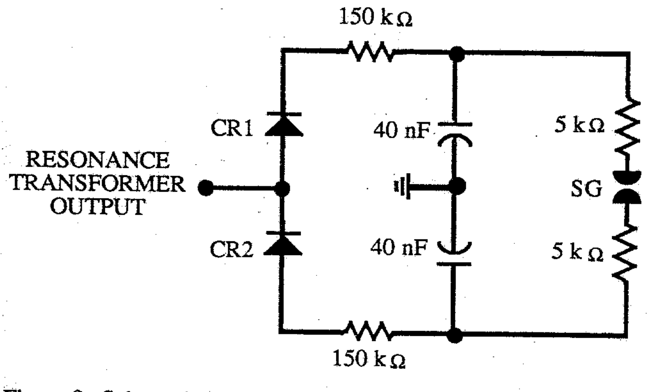

Figure 9. Schematic Diagram Showing the Rectified Resonance Transformer Output Charging Energy Storage Capacitors.

The oscilloscope photograph shown in Figure 10 displays the voltage across the positively charged capacitor. The input voltage to the inverter was 600 V dc. The capacitors were charged to ± 29 kV developing 58 kV across the switch before discharging. The voltage gain is approximately 48 which is similar to the open-circuit gain of 50. This is what should be expected since the capacitors become high impedances as the full charge is approached. The power conditioner was continuously operated under these load conditions for one half hour. The pulse-to-pulse voltage variation was never greater than the resolution of the oscilloscope trace (<2%).

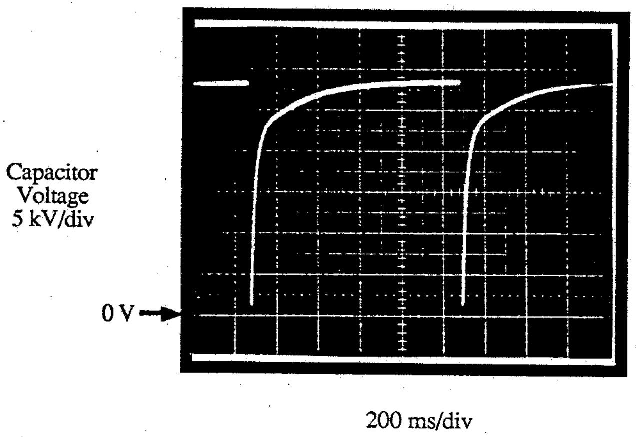

Figure 10. Oscilloscope Photograph of the Capacitor Charging Waveform.

The overall performance of the proof of concept resonance transformer did not meet design expectations with regards to the gain and power capability due primarily to the ESR of the resonance transformer inductors. Although the design specifications requested a Q of at least 150 at the design operating frequency of 20 kHz, the actual values for the first stage inductors ranged from 78 to 108, while those in the second stage ranged from 98 to 160. In addition, several of these inductors have a relatively small surface area which, when considering the low Q, drives the power density to intolerable levels.

MW Class Average Power Design Concepts

There are no fundamental differences between resonance transformers which are designed to operate at tens of kW and those designed to operate at 1 MW and above. The circuits remain the same and the component performance requirements do not change appreciably. The typical operating parameters for the megawatt class power conditioning systems using resonance transformers currently being designed are:

• Input Voltage:	1 - 5 kV dc
• Output Voltage:	50 - 100 kV dc
• Operating Frequency:	10 - 50 kHz
• Power Density:	~10 kW/kg

Due to the large power levels present in these systems, the techniques for meeting the component requirements are more important than those for a lower power system. The thermal and fault protection issues become even more critical at higher power levels and the inverter requires a larger number of devices, which adds to the degree of complexity. There are issues which appear concerning the circuit interaction with its surroundings which must be addressed as well.

Size and weight estimates of a 1 MW resonance transformer, utilizing planned existing system cryogenic cooling for thermal management, have been generated and the results indicate that a 100 kg weight for the power conditioner is not unreasonable.

Transformer Component Selection

As with the resonance transformer design at lower power levels, high Q components are important in maximizing the transformer gain and minimizing losses. Once again, capacitors with large values of Q at the frequencies of interest are relatively common. Techniques to minimize the effects of the proximity effect and maximize the inductor Q focus on inductor geometry.

According to Terman [9], the inductor geometry should be such that the relation $3t + 2b = D$ is satisfied, where t is the radial thickness of the winding, b is the axial length of the coil, and D is the outer diameter of the coil. This assumes that the conductors are wound closely together. This small winding space can be realized with flat strip conductors, which also minimizes the weight of the conductors for a given skin depth. Two design features are incorporated to lower the shunt capacitance of the coils. The first is to introduce a space between layers of a multilayer coil. This is illustrated in Figure 11, which shows a conceptual design for such an inductor. The second is to break the inductor into two or more separate coil sections, so that the stray capacitances are reduced by series circuit addition.

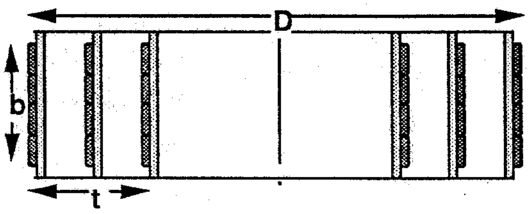

Figure 11. High Power Resonance Transformer Inductor Conceptual Design.

This figure shows the spacing between the layers, and represents one section of the segmented inductors discussed above. An additional important feature of these inductors is that the spacing between the layers allows for cooling each layer individually, which is critical for physically large devices. Given the inductor geometry shown, coolant can be flowed through the inductor in the axial direction across each of the windings to remove the heat dissipated there.

Inverter Design Considerations

As with the inverter design for lower power applications, the design for megawatt class power systems is made up of a series-parallel array of semiconductor switches. The design issues in this case are essentially the same for a system operating at the 10's of kW level, with the exceptions that the array is larger (and therefore more complicated) and the cooling requirements are more stringent.

Resonance Transformer Design

The overall design of a megawatt class system is somewhat more complicated from those at lower power primarily because of the increased importance of cooling requirements, the fault handling requirements, and the coupling with the nearby structures. In general, more attention must be focused on the cooling in high power systems as opposed to low power systems due to the fact that these systems are physically larger. This makes it more difficult to remove heat from the inner regions of the system and components because of the differences in heat transfer. As mentioned earlier, cryogenic cooling systems have been incorporated into several of these MW class power conditioners in order to handle the large heat loads which are generated in these high power density (~10 kW/kg) designs.

The fault handling requirements also gain in importance because there is more fault energy which must be dissipated. At higher power levels, higher currents are present. This further implies that higher magnetic fields also exist, which can cause inductive heating of nearby magnetic materials. These losses also affect the operation of the resonance transformer, since they lower the effective Q of the inductors. This problem is addressed by controlling the materials used in the environment near the resonance transformer and by careful engineering of the transformer layout.

Summary and Conclusions

In summary, several resonance transformer designs have been generated and developed into working models in order to prove the concept and analyze their applicability towards compact, lightweight, high voltage power conditioners. The experiments performed to date have shown the technique to possess significant advantages over conventional transformers which have disadvantages associated with thermal management and transformer coupling at both high voltages and high frequencies. Because the resonance transformer size and weight are relatively weak functions of power, this approach can provide very compact power conditioning systems at the MW power level. Results from the experiments have also provided a better understanding of the transformer operation and those parameters which are important to maximizing the performance. Designs for resonance transformers at power levels of 1 MW and higher have also been produced. These designs are expected to have extremely high power densities (~10 kW/kg).

Acknowledgements

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