# DESIGN OF A DIRECT CONVERTER FOR HIGH POWER RF APPLICATIONS

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## *Abstract*

This paper presents practical results from a new type of power supply for high power RF applications for CW operation. The converter is a direct topology, utilising a high frequency resonant link and a high frequency transformer. High operating frequency reduces the transformer and filter size. Soft switching is employed to reduce losses. Two variants of this topology are presented. The first incorporates the high frequency transformer into the resonant circuit. The principle feature of this topology is that parasitic elements associated with all transformers are employed in operation of the converter. However, this requires that the circulating current in the resonant tank flows in the transformer windings. The second topology does not incorporate the transformer into the resonant circuit, therefore requires a smaller transformer. However, the topology will be affected by the parasitic elements of the transformer. Advantages of both these topologies over conventional approaches are discussed. The RF power generated by both topologies is stable and predictable, whilst reduced energy storage in filter components removes the need for crowbar circuits.

## INTRODUCTION

Traditional approaches to CW modulators are based on line frequency rectifier / filter assemblies. This has the disadvantage that extensive filtering is often required to ensure that the DC output meets specification, consequently additional protection circuits such as crowbars are typically required to prevent tube damage in the event of a fault.

To overcome the aforementioned difficulties two variants of a novel type of power converter have been developed. Both converters operate with a high frequency link, allowing for significant reductions in the size of the high voltage transformer [1] and both input and output filters. Furthermore, the converters are soft switched, therefore allowing for high power at high frequency.

## OVERVIEW

The converters principally consists of a three phase to single phase Direct (Matrix) Converter, where the the resulting single phase is used to drive a high frequency resonant tank at its resonant frequency (20kHz for the prototype). The resonant rank is transformer coupled to a rectifier to produce a high voltage isolated DC supply, as shown in Figure 1.

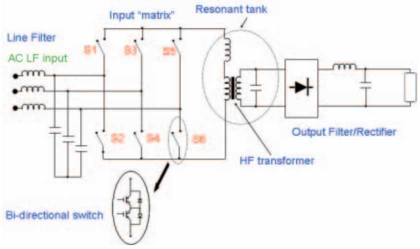

Figure 1: The Circuit Topology for the "Resonant Transformer" Converter

The first proposed converter topology (shown in the Figure) integrates the high voltage high frequency transformer into the resonant circuit. This requires that the resonant inductance be located on the primary of the transformer, and the resonant capacitance be located on the secondary. The second topology proposed operates with both resonant inductance and capacitance located on the primary of the transformer. The relative advantages of these topologies are discussed later. For simplicity, the Klystron is modeled as a constant resistance connected across the output of the rectifier.

To maintain soft switching and meet the requirements of the application, there are 2 principal considerations for the control method to be employed:

1. That commutation between phases should occur at zero current or zero voltage.
2. DC ripple on the rectified output should be as small as possible and within the target specification, [2].

To meet condition (1) implies that either zero voltage (ZVS) or zero current switching (ZCS) be implemented. Under ideal conditions the topology of resonant circuit employed may be considered a current source, therefore ZCS commutation is implemented. This can occur every half cycle of resonant operation when the current drawn by the resonant circuit it zero, therefore a switching frequency of 40kHz is required for the prototype.

For condition (2) to be achieved requires the envelope of the resonant tank be as constant as possible. Theoretically this would result from applying the same voltage to the resonant tank every half cycle (assuming constant load). However, as the input matrix is connected to a standard three phase supply this is clearly not possible. Nor is it possible to use a volt-time control approach, as condition

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(1) fixes the time for which a pulse can be applied in order to reduce switching loss. Consequently a controller design is required that achieves zero current switching, and minimises the resonant tank voltage ripple.

For all resonant circuits it is common to define a quality factor (Q) of resonant operation. A high Q indicates significant energy storage within the resonant tank compared to the energy dissipated into the load. For the Series Resonant Parallel Loaded (SRPL) topology of resonant circuit used, the circulating current in the resonant tank will be Q times the output current, and the RMS voltage across the resonant capacitor will be Q times the fundamental RMS voltage applied to the resonant circuit.

Several control approaches were considered for implementation on the prototype converters. These included Sigma-Delta and Predictive Input Controller [4] algorithms, but these were found to be unable to maintain the operation of the resonant circuit with low Q (required to minimise component stresses and enegy storage within the circuit). Instead a controller was selected that applies a state based on the evolution of the resonant tank, such that the envelope of the resonant tank capacitor voltage operates with minimum possible deviation [5].

## "RESONANT TRANSFORMER" CONVERTER

The first topology considered is shown in Figure 1. Referring to the Figure, the resonant tank comprises an inductor connected in series with the primary winding of the transformer, and a capacitor connected across the secondary windings of the transformer.

The principle feature of this resonant topology is that the leakage inductance of the transformer appears in series with the resonant inductance of the circuit. Furthermore, the interwinding capacitance of the transformer and the balancing capacitance of the rectifier appear in parallel with resonant capacitance. This has the advantage that the unavoidable and often undesirable parasitic elements associated with the transformer are used within this converter. Therefore providing the leakage inductance and parasitic capacitances do not exceed the values required for resonant operation, their inclusion in the circuit is not problematic.

However, integration of the parasitic components requires that the resonant capacitance is connected across the secondary windings of the transformer. This has the undesirable effect that the current circulating in the transformer windings will be a significantly greater than the output current of the transformer (by a factor of Q). Therefore, the transformer needs to have a VA rating significantly higher than the output power of the converter. The requirement for such a VA rated transformer may, in some applications be considered undesirable. Therefore, the concept of moving the entire resonant circuit to the primary of the transformer was investigated, this is discussed in following section.

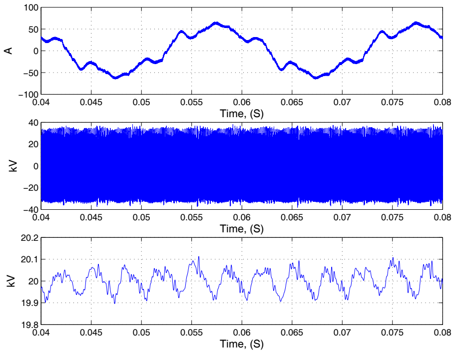

Figure 2: Experimental Results Obtained from the Direct Converter Topology Shown in Figure 1. Top Trace: Phase Current. Middle Trace: Resonant Tank Capacitor Voltage. Bottom Trace: DC Output Voltage.

Experimental results obtained from "Resonant Transformer" prototype converter producing 20kV, 16kW are shown in Figure 2. The DC output produced by this converter has been shown to meet typical application specifications [2].

## PRIMARY RESONANT CONVERTER

An alternative configuration for the resonant tank transformer arrangement is shown in Figure 3. Ideally, the resonant circuit for this converter is located solely on the primary side of the transformer, therefore the high voltage, high frequency transformer does not form part of the resonant circuit. Consequently there is no additional circulating current in the transformer windings and the VA rating of the transformer is approximately the same as the output power of the converter.

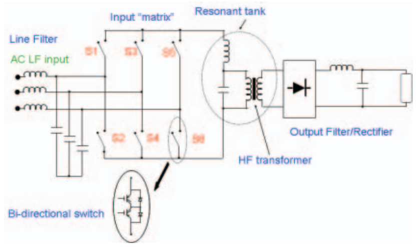

Figure 3: The Circuit Topology for the Primary Resonant Converter

However, the converter will be affected by the parasitic elements of the transformer. If the leakage inductance of the transformer is small and the parasitic capacitance is significant, then the effect of the parasitic elements will be to reduce the resonant frequency and increase the voltage gain of the resonant circuit. More importantly, some of the current circulating in the resonant tank will flow through the transformer windings (the amount of current that does this will be proportional to the relative impedances of the tuning and parasitic capacitances), and the transformer will be required to have a higher VA rating than intended (20% higher in the prototype converter). If the leakage inductance of the transformer becomes significant (quite probable for high voltage designs) the interaction between the parasitic elements and the resonant circuit becomes more significant. The effects of this are shown in Figure 4. Referring to the Figure, the voltage transfer ratio of the ideal case (with no leakage inductance or capacitance) is compared to that of a converter with a set parasitic capacitance and increasing leakage inductance. It is clear from the Figure that an inclusion of the stray capacitance causes a decrease in resonant frequency and (with no leakage inductance) and an increase in the voltage gain of the resonant circuit. It is also apparent that the inclusion of leakage inductance causes a decrease in the voltage transfer function of the resonant circuit (converter). This is significant, because the circulating current in the transformer does not decrease with increasing leakage inductance, therefore there are no advantages to increasing the leakage inductance with this topology.

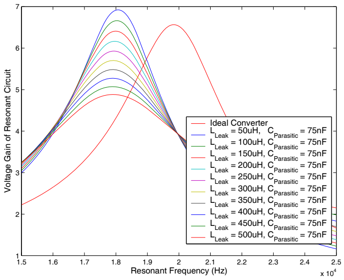

Figure 4: The Effect of Including Leakage Inductance and Stray Capacitance on the Operation of the Converter

Practical results obtained from a converter of this type producing 20kV at 16kW for DC load applications are provided in Figure 5. The DC output produced by this topology is also found to meet typical specifications [2].

## COMPARISON OF TOPOLOGIES

Compared to the "Resonant Transformer" Converter, the Primary Resonant Converter has the potential to be significantly smaller and cheaper, due largely to the reduced ratings of the transformer required. However, the topology is susceptible to the undesirable effects of parasitic capacitance, and in particular leakage inductance. These problems can be alleviated somewhat by careful design of the high voltage transformer (toroidal cores etc), but ultimately the leakage inductance will be dependant upon the output voltage of the converter. These problems are overcome by the "Resonant Transformer" Converter which incorporates the parasitic elements into the operation of the operation of the converter. This is likely to be beneficial for higher voltage designs (100kV+) where the distances between the transformer windings (and hence the leakage inductance) are likely to be significant. Ultimately, selection of topology is likely to be based on the particular requirements of the supply such as space, output voltage and output power.

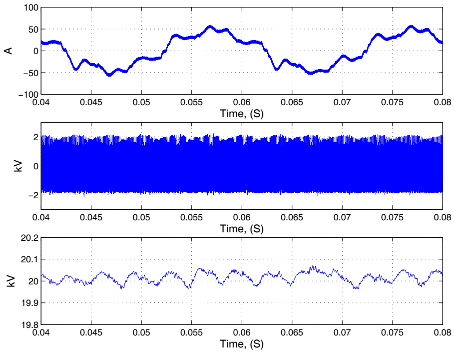

Figure 5: Experimental Results Obtained from the Direct Converter Topology Shown in Figure 3. Top Trace: Phase Current. Middle Trace: Resonant Tank Capacitor Voltage. Bottom Trace: DC Output Voltage.

## CONCLUSION

Two novel Direct Converter topologies suitable for high power RF applications have been presented. The first, a "Resonant Transformer" Converter incorporates many of the parasitic elements associated with transformer and high voltage design and uses them to the advantage of the converter. The second, a "Primary Resonant Converter" is potentially smaller and lighter than the first, but is affected by parasitic and stray elements. Both topologies employ the use of high frequency resonant circuits for reduced size and to allow for soft-switching. Both converter topologies have been validated via the construction of experimental prototypes and shown to operate successfully at 20kW, 16kW and within typical application specifications.

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