DESIGN OF A DIRECT CONVERTER FOR HIGH POWER, RF APPLICATIONS

D. J. Cook, M.Catucci, J. C. Clare, P. W. Wheeler, J Przybyla+

University of Nottingham, NG7 2RD, England, +e2v Technologies, Chelmsford, England. *

Abstract

This paper is concerned with a new type of power supply for high power RF applications for CW operation. The converter is a direct topology operating with a high frequency resonant output stage. Switching losses are minimised by switching at zero current. High operating frequency allows for minimised transformer and filter size. Advantages of this topology over conventional approaches are discussed, along with the potential problems and proposed solutions. Recently, considerable interest has been shown in direct converter (matrix) topologies as an alternative topology in motor drive applications. This approach offers advantages such as reduced energy storage and higher energy density compared to conventional topologies. The work presented in this paper capitalises on these advantages in other fields, namely power conversion for RF supplies. The RF power needs to be stable and predictable such that any variation has a limited impact on the accelerated beam quality. In order to meet the required output voltage specification output filtering is required. Management of the output filter energy in the event of a fault is necessary if damage to the tube is to be avoided.

INTRODUCTION

Accelerators used for experiments in high-energy physics require very high power RF sources to provide the energy needed to accelerate the particles. Existing approaches are based on 50/60Hz designs, and often, the physical size of the converter has not been a deciding factor in the design process. In addition, in order to meet the required output voltage specification such designs require large output filters, with the potential to deliver sufficient energy to damage the klystron in the event of a failure.

OVERVIEW

The converter principally consists of a three phase to single phase matrix converter, where the resulting single phase is used to drive a 20kHz resonant tank, operating with a high frequency transformer/rectifier in parallel with the resonant capacitor. Using a high frequency transformer offers significant size and weight benefits compared to a 50Hz approach for both the transformer and output filter. The transformer secondary feeds a single phase inductively and capacitively smoothed diode rectifier connected to the load (assumed resistive [1]) as shown in 1.

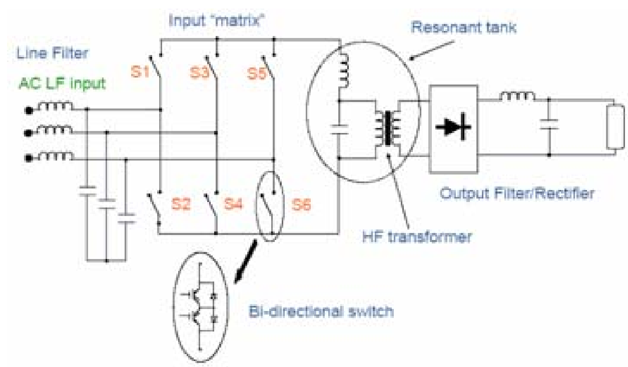

Figure 1: The Circuit Topology

CONTROL

In order to operate with optimum efficiency and be suitable for high power RF applications, there are two fundamental criteria that are imposed on the controller:

- 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, for example [1].

In addition, it is required that the voltage/current stress on the devices and the corresponding energy stored in the resonant tank be as low as possible.

Under ideal conditions, the topology of the resonant tank considered may be regarded as an ideal current source. Thus, to fulfill (1), zero current commutation is required. This will occur naturally if commutation takes place every half cycle; hence a switching frequency of 40kHz is required.

For (2) to be achieved the envelope of the resonant tank voltage should 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 (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

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current switching, and minimises the resonant tank voltage ripple.

The converter can be switched into any one of nine states. There are three zero states, where the tank current simply circulates through the converter, and six states that each apply one of the three line voltages or its inverse. Commutation between states must occur such that the supply is never short circuited and the load is never open circuited. For example in figure 1 gating both switches 1 and 3 would result in supply shoot through, and the resulting current would destroy the converter. Conversely, the inductive load will destroy the converter due to over voltage if it is open circuited. These are inherent requirements of direct (matrix) converters and commutation must be completed by considering the bi-directional switches as two separate devices (one for each direction), as described in [2].

Due to the limitations imposed above, feedback control of the resonant tank on a cycle to cycle basis is not practical. It is therefore necessary to predict the response of the circuit based on the known circuit conditions in order to achieve control.

Predictive algorithms rely on knowledge of particular circuit variables in order to estimate the consequence of an action, such as a switching state. Several control approaches were considered in the development of the controller. Initial work was focused on controlling the tank by regulating the input power drawn by the converter [3], but this had limited success as control is based on the assumption that the magnitude of the resonant tank current will be invariant from cycle to cycle, regardless of any input perturbations. This is true only if the energy stored in the tank is relatively high compared to the energy delivered to the load. (The energy stored in the resonant tank compared to the energy delivered to the load can be defined as the quality ,Q, factor of the resonant tank where $Q = R/Z_0$.) However, it is desirable to operate with a relatively low Q, to reduce component size and component stresses and under such conditions operation of the tank is significantly affected by input perturbations on a cycle to cycle basis. Consequently the magnitude of the current that will drawn by the converter for the next half cycle can no longer be predicted accurately and the control algorithm performance is poor.

PREDICTIVE TANK CONTROLLER

To allow operation with a low Q, a novel type of controller was developed. Rather than keeping the input power constant, the algorithm implemented selects switching states by solely considering the resulting operation of the resonant tank. In this case, the possible voltages that may be applied to the tank are calculated from input voltage measurements. These possible voltages are then used to predict the resonant capacitor voltage at the next half cycle. The converter is then switched to make this voltage as close to a reference demand as possible.

One of the key advantages of this approach in this application is that the converter will always switch to maintain the tank voltage envelope as constant as possible, even in the presence of supply harmonics or unbalance.

However, implementation of this basic algorithm leads to a poor input current waveform, as observed in figure 2 for time 0 to 60ms. This occurs when the application of one line voltage results in a resonant capacitor voltage that is very close to the ideal capacitor voltage. Because the supply frequency is much lower than that of the resonant tank, this will be true for several periods of resonant tank operation.

The result of this is that for one half cycle the converter will apply a particular line voltage, and for the next half cycle it will apply the same line voltage, but inverted. For example, when the resonant current is positive the converter will apply Vab, and when the current is negative the converter will apply Vba. Whilst this leads to the best output voltage waveform, the input current waveform is unacceptable.

STATE BIASING

The proposed solution to improve the input line current is to prevent the controller from applying the same line voltage for more than one cycle at a time. This can be achieved by storing the previous switching state of the converter in the controller, and assigning its opposing state a high error in the cost function.

Whilst this naturally results in sub-optimal operation of the tank, the perturbations are at 40Khz, and thus are easily removed on the DC side by the filter. Consequently, the effects on rectified resonant capacitor voltage are reduced, whilst the input current drawn by converter is greatly improved, as seen in figure 2.

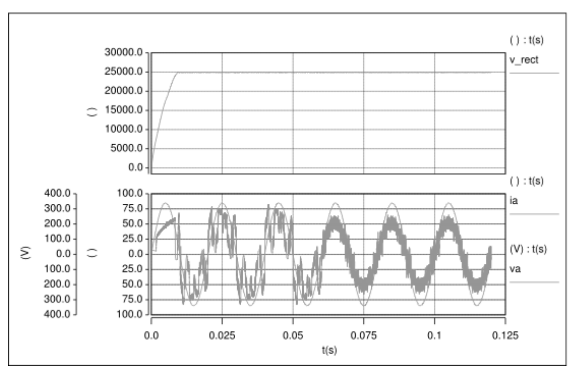

Figure 2: Input Current Waveform With State Biasing Enabled After 60ms)

OPERATING CONDITIONS

Selection of the reference resonant capacitor voltage is determined by considering the input voltage waveform, and selecting a reference so that the average deviation from this reference should be minimised. It is the fundamental of this waveform that must then be considered along with the gain of the tank circuit to determine the optimum operating conditions and, for example, the turns ratio of the transformer.

CONTROLLER RESPONSE

For the controller to be practically implementable, it must be able to tolerate a limited discrepancy between the components that it is intended to operate with and those that are used in practice. In the case of the controller considered, these are primarily discrepancies between the intended resonant inductor and capacitor values and the those that are present in the converter. Consequently, to allow for component tolerances, thermal variations and ageing on these components, the controller has been tested with +/- 10 percent error on both resonant components and found to remain within specification. Variations in gain are accommodated for using an outer voltage controller which trims the demand, whilst deviations in resonant frequency are accommodated using a phase lock loop (PLL) to maintain zero current switching.

Preliminary voltage control is obtained using a proportional controller to set the demand for the tank capacitor voltage envelope based on measurement of the rectified DC voltage. The performance of the controller is shown in figure 3 in which the converter provides a range of voltage demands from 10 to 100 % . The addition of a second load resistor (in this case 1Meg ohm) in parallel with the main load acts to limit the voltage gain of the converter (when combined with the voltage feedback loop) in the event of load open circuit . The second load has almost negligible effect on the circuit, drawing virtually no power from the converter.

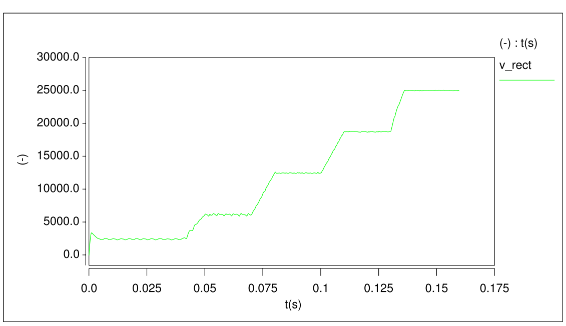

Figure 3: Response to Demand Changes from 10 - 100 %

PRELIMINARY PRACTICAL RESULTS

Preliminary results have been obtained with the converter operating at low power levels (≈2kW) with a rectifier connected directly to the tank (no transformer). Initial waveforms agree closely with simulated results. The input phase voltages and currents, along with the voltage observed on the resonant tank are shown in figure 4

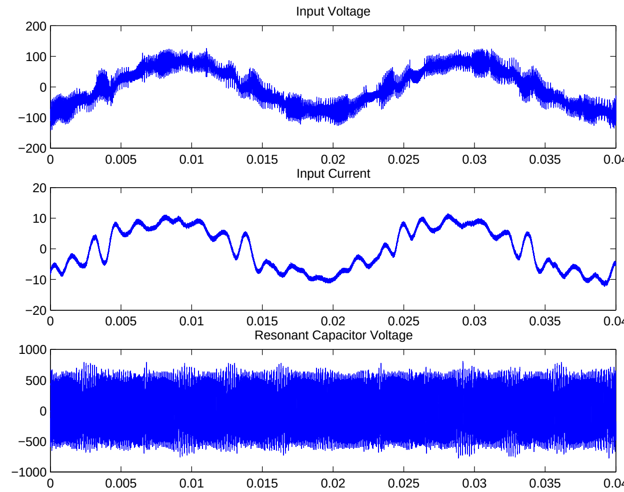

Figure 4: Initial Experimental Results showing an arbitrary phase voltage and current and the resonant capacitor voltage

CONCLUSION

This paper has proposed a direct conversion technique high power RF supplies. The converter proposed offers several potential advantages over existing technologies, namely increased efficiency, reduced energy storage and a more compact, higher energy density converter. Initial practical results show the controller operating as intended, and thus far show the theory presented in this paper is implementable in practice. Experimentation is continuing and higher power, higher voltage results (including an output transformer) are anticipated soon.

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