MULTIPHASE RESONANT POWER CONVERTER FOR HIGH ENERGY PHYSICS APPLICATIONS

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ABSTRACT

This paper considers the design of a "long-pulse" modulator supply rated at 25kV, 10A (250kW peak power, duty ratio 10%, 25kW average power, pulse length $\approx 1 - 2ms$). The supply is based on direct modulation of a multi-phase resonant power supply, fed by an active rectifier. The objectives of the development are to produce a compact power supply, with low stored energy and with high power quality at the utility supply. The paper provides a brief overview of the technology, followed by a discussion of the design choices. Initial results from the laboratory prototype are included.

INTRODUCTION

Accelerators used for experiments in high-energy physics require very high power radio frequency sources to provide the energy needed to accelerate the particles. The RF power needs to be stable and predictable such that any variation in the supplied RF power has a limited and acceptable impact on the accelerated beam quality.

The output load specifications for high voltage DC power systems are becoming increasingly more demanding. In addition, the impact of such systems on the electricity source is becoming more tightly regulated through power quality directives. These regulations set limits, for example, on the allowable individual harmonic current amplitudes and on "flicker" caused by transient load demands - the latter is particularly important for "long-pulse" ($\approx \ 1ms$) modulators. The requirements above have to be met while still providing higher reliability to a higher specification at lower cost. A situation has now been reached where modulators based on existing approaches cannot meet these specifications and stay within acceptable cost and size limits. This demands that new approaches be taken to provide the power supplies needed for such applications. The research presented here addresses this need.

The majority of current generation power supplies in use in high-energy physics accelerator systems are based upon 50/60Hz, line frequency technology that demands large transformers and capacitors in order to satisfy the stringent specifications. Generally, in the past, this bulk may not have been a serious inconvenience because there has been adequate space available. Current and future applications however, demand a reduction in power supply size.

In addition, with line frequency technology, the large filters necessary to attain the low ripple voltage requirements store potentially damaging energy in the components. In the event of a tube arc, the deposited energy needs to be limited to about 20J, otherwise damage can occur to klystrons or inductive output tubes (IOT's). A rapid discharge circuit (crowbar) is used to divert the stored energy to earth in the event of a fault or internal arc. The crowbar is undesirable due to cost, perceived unreliability and volume. Its elimination in future power supplies is an attractive objective.

TECHNOLOGY OVERVIEW

Figure 1 shows a block diagram of the proposed converter. Traditional approaches to "long-pulse" modulators generally consist of a large capacitor bank which is switched into the load via a high voltage switch [1, 2]. The capacitor back is sized to reduce droop during the pulse to a few percent and various techniques (such as the "bouncer" circuit [1]) can be used to compensate for the remaining droop. A pulse transformer is normally required to match to the load voltage. Some disadvantages of such an approach are the size of the capacitor bank and the need to protect the load against the stored energy under fault conditions (using a crowbar for example).

In the system of Figure 1 direct modulation of a switching power supply is used to produce the pulse. A high-frequency transformer incorporated into the supply is used to step-up from voltages suitable for the semiconductors, to those required by the load. Considerably more droop on the DC link capacitor can be tolerated during the pulse, since the voltage gain of the output stage can compensate for the droop. This reduces the capacitor size significantly. By employing an active rectification stage, the capacitor can be "intelligently" re-charged between pulses to minimise low frequency disturbance (flicker) on the utility supply. Furthermore, such a rectifier can operate with unity displacement power factor and with high quality currents. There is no requirement for a line side (utility frequency) transformer.

To be able to produce a pulse of sufficiently short rise-time, the switching frequency of the switching power supply must be reasonably high. It is also very desirable to raise the switching frequency to minimise the size of the output transformer and the output filter (and its stored energy). However, at the power levels required, these operating frequencies can only be considered if steps are taken to reduce the semi-conductor switching losses. Therefore a resonant power supply topology is proposed - this achieves low losses through "soft-switching" where either the voltage (ZVS) or current (ZCS) is zero across a device at the

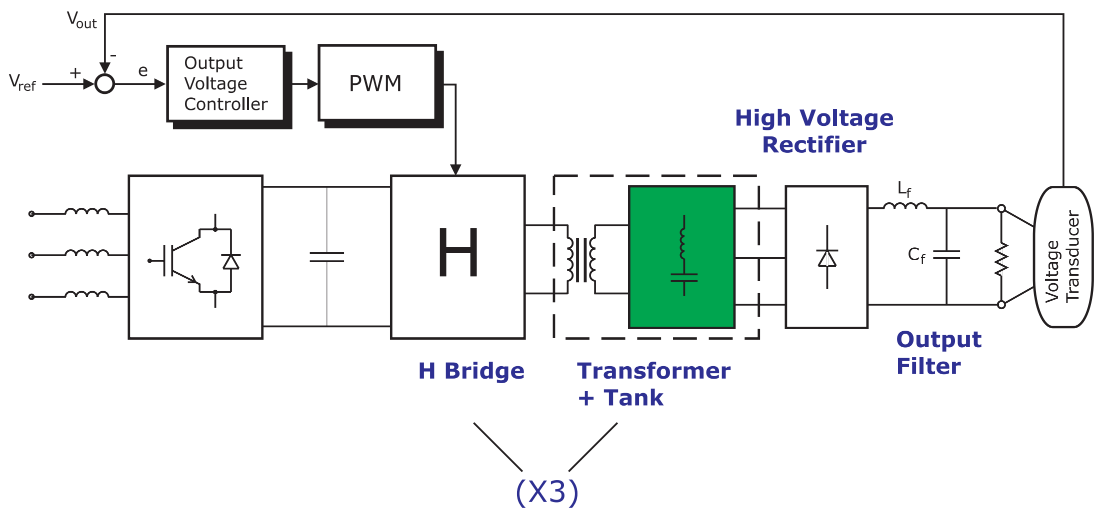


Figure 1: Block diagram of DC link based converter.

instant of switching. To further increase the effective ripple frequency seen by the output filter, a multi-phase (in this case 3 phase) approach is used. This has a frequency multiplication effect of twice the phase number. The multi-phase approach also lends itself to “modularisation” which will be advantageous for high power applications.

Key issues for the design of such a converter are: the resonant topology chosen, the method of achieving voltage control to compensate for DC link droop (whilst maintaining low losses) and the control strategy for producing the pulses with sufficient fidelity. These issues are discussed further in the following sections.

OUTPUT VOLTAGE CONTROL

One of the challenges for resonant converter control is to achieve voltage control (ratio of DC link voltage to output voltage) whilst maintaining low losses. In this application, voltage control is required to maintain the output pulse flat, whilst the DC link voltage droops. The degree of droop can be chosen in the design. Larger values of droop allow a smaller capacitor, but increase the VA rating of the output and input converters, as well as exacerbating the problem of voltage control. Although no optimisation of the value has been undertaken so far, it is anticipated that the DC link droop will be approximately 25%.

Control of the resonant tank output voltage can be achieved by adjusting either the input frequency or the phase shift [3] between the two legs of the H-bridges. In order to minimise the switching losses both the phase and frequency of the H-Bridges is controlled [4].

INTERMEDIATE VOLTAGE (UNITY RATIO) TRANSFORMER

In order to prove the basic concept of the converter and its control, the prototype is being tested initially with unity turns ratio 20kHz transformers. This approach allows more flexible investigation of the circuit control options and makes measurement of circuit quantities more straightforward during the development phase. Working with a reduced output voltage ($\approx 2kV$) has the advantage that much of the initial testing can be carried out without the added complications associated with the high ($25kV$) output voltage. Design and construction of the final HV ($25kV$) transformers is taking place in parallel with the basic circuit and control validation.

POWER CIRCUIT

The power circuit been constructed using a laminated busbar (power plane) approach to minimise commutation inductance. A CAD drawing of the power circuit showing main components and basic layout is shown in Figure 2. In order to meet the ripple current requirements and reduce

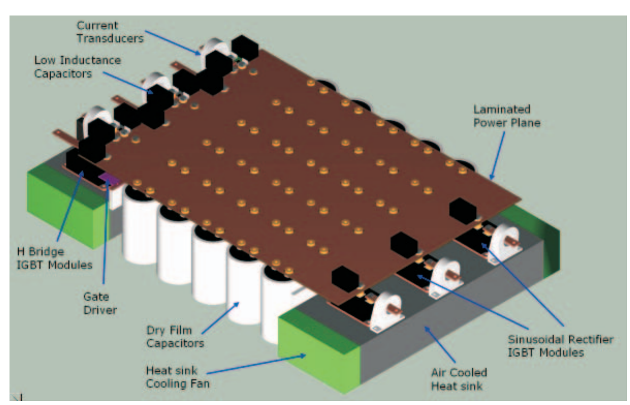


Figure 2: CAD model of power circuit showing Sinusoidal Rectifier, DC link, H-Bridges.

losses dry film capacitors are used for the DC-link. Six standard IGBT/diode modules [5] are used to construct the three H-Bridges.

INITIAL RESULTS

The results presented are produced using feedforward control only. Figure 3 shows waveforms taken during a $\approx 1ms$, $\approx 250kW$ pulse. The load voltage droops by about 5% during the pulse, this is due to losses not taken into account in the converter model used to calculate the switching times. This is further confirmed by noticing that the DC-link voltage falls by about 30% which is 5% more than predicted by the analysis. Figure 4 shows the detail of the soft switching at the start and end of a typical pulse. These waveforms illustrate that a good range of control is possible without incurring excessive switching losses. Closed loop feedback control to compensate for the droop in the load voltage is an area of ongoing research.

Table 1: Conditions for output pulse shown in Figure 3.

Output Power	$250\,kW$
Mean Load Voltage	$1900\,V$
Load Resistance	$14.1\,\Omega$
Rise Time	$50\,\mu s$
V_{DC} at start of pulse	$660\,V$
V_{DC} at end of pulse	$460\,V$
DC-link voltage droop	$30\,\%$

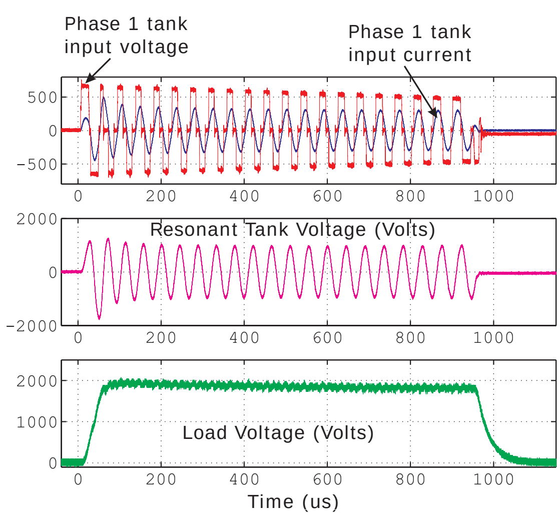
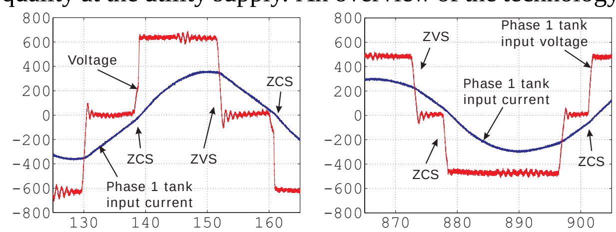


Figure 3: Waveforms measured during a 250kW output pulse.

CONCLUSIONS

This paper has discussed the design of a prototype "long-pulse" modulator based on direct modulation of a multi-phase resonant power supply, fed by an active rectifier. The objectives of the development are to produce a compact power supply, with low stored energy and with high power quality at the utility supply. An overview of the technology has been provided, giving the motivation for various design choices. The prototype is based on a "series resonant, parallel loaded" topology with tri-phase output. Combined frequency and phase control is used to minimise semiconductor losses throughout the pulse duration.



(a) Start of pulse (b) End of pulse

Figure 4: Waveform detail showing that soft switching is achieved for all IGBTs throughout the pulse.

Results showing operation at full power but reduced output voltage were shown. The ability of the converter to compensate for the DC-link voltage droop is confirmed.

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