High Frequency Cascaded Resonant Transformer Rectifier Power Supply For Neutral Beam Injection*

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ABSTRACT

Neutral beam injection for fusion requires DC megavolt power sources at several amperes. The conventional methods of using series or shunt fed multipliers cannot provide the current while the 60 Hz coupled transformer method is difficult to modularize because of size and stores excessive amounts of energy. A technique which borrows from several technologies has been investigated and shows promise for a satisfactory solution. This technique uses resonant multistage high frequency (100 kHz) series coupled ferrite transformer with rectifiers to produce megavolts at several amperes of current. Modularity, high efficiency and low energy storage are desirable features of this power source.

1. INTRODUCTION

Neutral beam injection is an essential part of the international magnetic fusion effort. The four participants in the International Thermonuclear Experimental Reactor. (ITER) have on-going programs to develop neutral beams of several amperes with 1 to MeV of energy. The Lawrence Berkeley Laboratory has been a leader in the development of neutral beams source in the 100 - 200 keV for the past two decades. The US concept for achieving megawatt neutral beams requires development or extrapolation in both the ion sources and the acceleration components (power supply). The power supply requirements for neutral beams is somewhat unique. It is required that the energy storage be as low as possible so that no damage occurs to the high voltage electrodes such as the electrostatic quadrupoles or the negative ion sources under sparkdown conditions. It is also required that it be made modular so that tap points can provide high current bias at any voltage between ground and 1.3 MV. It is also highly desirable that such a power supply be an integral part of the acceleration electrodes so that high voltage will not have to be transported long distances by cables. Above all, the efficiency of the power supply must be above 90% and must also be capable of being switched off quickly to limit the amount of energy deposition into the spark.

Low current megavolt sources are not new to the accelerator community. Megavolt DC sources of several amperes, however, are new. Traditionally, injectors for high energy accelerators have utilized "series-fed" multipliers

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(Cockcroft-Waltons) and "shunt-fed" multipliers (Dynamitrons) to generate megavolts at a few milliamperes of current. Series or shunt-fed high frequency multipliers, although compact, cannot provide the current required for neutral beam injectors. Multipliers or coupled transformers at 60 Hz have been used but for this application are too bulky, have excessive energy storage and are difficult to modularize. The Magnetic Fusion Energy Group at LBL has investigated the application of modular coupled ferrite transformers at high frequency (100 kHz) to generate 2.5 A of D⁻at 1.3 MV A ten stage 100 kV prototype has been built and tested to investigate the feasibility of this technology.

II. CONCEPT FOR A HIGH FREQUENCY CASCADED RESONANT TRANSFORMER RECTIFIER (CRTR) DC POWER SUPPLY

The industrial market for low voltage high current power supplies has been adopting high frequency AC to DC converters for cost effective high efficiency and compactness. This technology has provided power supplies of up to a few tens of kilowatts at a few tens of kilovolts.

The high frequency is chosen for several reasons; first of all, a frequency of 100 kHz allows a considerable size reduction in the coupling transformers; size reduction allows modularity for both the accelerator and other power sources; high frequency allows usage of very efficient high resistivity ferrites made of Nickel-Zinc material making high voltage isolation and tight coupling easier; high frequency also eliminates the need for large filtering capacitors, and hence reduces considerably the energy storage. Semiconductor devices such as MOSFETS and IGBTS have achieved very high efficiencies at tens of kilohertz; the fast response of semiconductors also implies that the power sources can be turned off in less than 10µs under fault conditions eliminating the need for crowbars (a snubber core will still be required to absorb the unavoidable stray stored energy).

The transformers coupled power supplies display reactive losses due to both the leakage inductance $(L \pounds)$ and the magnetizing inductance (L_m) . Under high current conditions, the $L \pounds$ is dominant while under light loads, the L_m is of more concern. To eliminate both of the reactive losses, a series and parallel tuning has been adopted to achieve resonance. Figure 1 is a simplified schematic of the prototype accelerator power supply. The system consists of 10 each 10 kV, 1A modules that are series connected to produce 100 kV. Each module will incorporate filtering (Cf), diode protection and series limiting (RL) circuit to absorb the self stored energy



Fig. 1. Voltage multiplication using single phase cascaded resonant transformer rectifier system. (Note high resistivity ferrite cores biased by center-tap of HF transformer)

during arc-down. Each power supply module will also have the proper series and parallel capacitors (Cs, Cp) to achieve resonance as the power is transmitted in 10 kV increments. Note that even though each power supply is the same, the lower stage transformers will have to carry each individual current plus that of the power supplies above it. Computer studies of the circuit show that the tuning will also difer from stage to stage. The tuning has been chosen that under full load conditions the Q of the system will be slightly above unity. Under light load conditions, the Q will increase to greater than unity, hence the step-up per stage would increase. To maintain a constant voltage level, a feedback system is incorporated which adjusts the input voltage of the high frequency converter (Fig. 2). C_S are the series tuning capacitors and C_p are for parallel or shunt tuning. T1 to T10 are the one-to-one isolation transformers. Since T1 handies the power for all subsequent stages, it will have to wound with the appropriate wire size. T₁₀ handles only the single stage power and will utilize smaller wire. At 100 kHz, close attention will have to be paid to utilizing the optimum core and winding geometries. Even though toroids were used for the 100 kV prototype, it is expected that the high power unit will utilize E-cores to maintain the low leakage at high currents (Fig. 3).

III. PROTOTYPE DESIGN AND TEST RESULTS

The proposed technique of using high frequency coupled transformers to generate megavolts at megawatts of energy looked very appealing for a number of applications. Unfortunately, lack of funds dictated that the experimental program had to be very limited and that it borrow resources from existing programs at LLNL and LBL. A number of ferrite toroids were found available from the beam research program at LLNL and some high power oscillator tubes were found at LBL. It was felt that the crucial aspect of this technique was to see if high frequency, coupled and tuned transformers could deliver high currents with an efficiency of over 90%. Computer studies were performed using a program called MICROcap II. These studies indicated that indeed under heavy load conditions the reactive losses could be tuned out. Fig. 4 shows that the output of a ten stage system would not be usable due to the reactive losses much like a series-fed



Fig. 2. Block diagram of high frequency 1.2 MV. 13A Power supply with regulation feedback system.



Fig. 3. Prototype E-Core for 1.3 MV high frequency cascaded transformer.

Cockcroft-Walton. Fig. 5 shows that under heavy loads the output is actually N times the input where N is the number of stages. A ten stage, 50 kHz prototype was built and tested at LBL. The impedance was chosen to be similar to that of the full voltage device so that leakage and mutual inductances have the same effective losses.

Figure 6 shows the completed prototype with the variable dummy load for testing to high power. Test results from Fig. 5 show good agreement with the computer simulation and that the output is 2Db higher than the number of stages (N = 10) times the input under full load conditions. Figure 7 shows the simplified schematic of the coupled transformers and Fig. 8 shows the output voltage under varying load conditions. It can be seen that the prototype achieved a maximum of 72 kV under light load conditions and 50 kV under full load. The design voltage of 100 kV was not achieved because of a design deficiency in the interstage transformer. Toroidal cores were used because they were readily available but it was recognized early on that this was not the best geometry for high voltage isolation and tight coupling. We incurred several failures from turn to turn arcing and winding to core shorts. Higher voltage under full load was not achieved simply because of the limited output of the 50 kHz oscillator. The frequency was lowered from 100 kHz to 50 kHz because of self resonances in the toroidal transformer. Figure 9 shows the stage voltages for varying loads. This test result shows that considerable variations in voltage occurs from stage to stage when the load is varied from 100 k Ω to



Fig. 4. Frequency Response of ten-stage high frequency transformers with resonant tuning.



Fig. 5. Frequency Response of ten-stage high frequency transformers with resonant tuning.



Fig. 6. Ten-stage 100 kv prototype high Frequency Cascaded Transformer Rectifier (CRTR) System with Dummy Load.



Fig. 7. Simplified Equivalent Circuit of ten-state CRTR.

700 k Ω . The Q of the tuned stages was designed to be small under full load conditions but as the load decreases the Q increases and the stage voltage changes. This is a serious consideration if tap points are required for the acceleration process. For an overall power supply where only the output is used this could offer a viable solution for a high voltage power system. Output voltage regulation can be maintained to 0.1% with a feedback system.

IV. CONCLUSION

The one tenth scale prototype of similar impedance to the final objective was quite successful in providing solid data for directing future research in this technology. It proved a number of significant point: (a) high frequency coupled transformers with tuning in only a few stage produces the desired multiplication of the input voltage, (b) tuning of a few stages cancels the reactive losses of cascaded stages but produces some undesirable voltage division from stage to stage, (c) efficiency exceeds 90%, (d) coupled stages adapt easily to a modular system(e) high frequency clearly means compactness and low energy storage.

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Fig. 9. Stage voltage under various load conditions.