HIGH STABILITY SWITCHING MODE POWER CONVERTERS FOR MAGNET LOADS

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ABSTRACT

The availability of general purpose switching mode power supplies in the KW range has prompted the possibility of using them for powering optical elements in linear accelerators. They are, however, not designed specifically to be operated as high stability current sources into inductive loads.

We have modified and conditioned commercial, off the shelf switching mode power supplies for use in powering multipole magnets. Temperature stability in the constant current mode has been upgraded to 15 ppm/C. Other stability parameters have been similarly improved. We modeled power supply operation using the program Spice, and verified its results experimentally. An analog controller was designed to compensate for instabilities in the feedback loop. This circuit was incorporated into a Bitbus power supply controller which is used as interface to the control system. Analysis of shielding techniques and tests results for a 2.5 KW power supply are provided.

Introduction

The South Hall Ring (SHR) under construction at the MIT Bates Linear Accelerator center will provide high duty factor (CW) electron beams and an internal target capability for nuclear research. This project is the culmination of Bates developments over the last decade aimed at providing coincidence capability throughout the important energy range up to 1 GeV. Proper operation of the proposed pulse strecher ring places stringent criteria on the operation of all magnetic elements such as dipoles, quadrupoles, sextupoles, etc. A large number of power supplies, with power capabilities ranging up to 10 kW and stabilities better than 15 ppm full scale, are needed to power up all the multipole magnets.

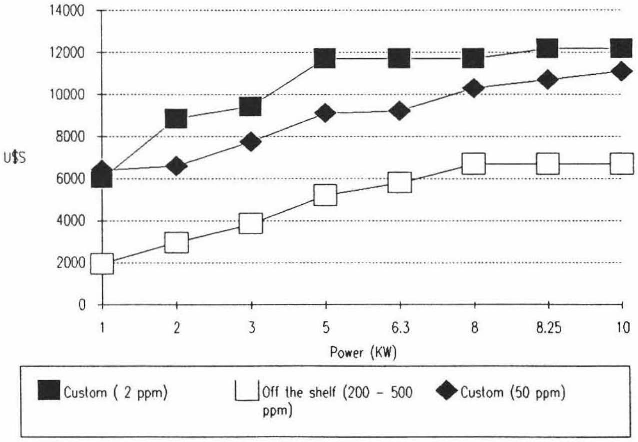

Figure 1. Power supply costs (with controller)

These requirements are normally satisfied with custom designed power supplies. However, in the Pulse Strecher, large number of these supplies are needed and cost factors rule out this approach (figure 1).

The well known advantages of switched mode power supplies, such as high efficiency, low weight and cost, make them very attractive for medium and high power levels. This popularity resulted in availability of off the shelf products at very reasonable prices. However, they are not optimized to work as current controlled power supplies. They are usually built to operate in voltage controlled mode and powering resistive loads.

The solution adopted here was to analyze the performance of various commercial power supplies and modify them to suit our needs. The internal controller was upgraded to enhance performance and stability with inductive loads. The current shunt was replaced by an external one with low temperature drift characteristics. In addition, a digital interface was provided for remote operation from a personal computer.

Operation

After a preliminary selection of different vendors we opted for the EMS 40-60-2 power supply. This particular unit delivers 2.5 kW but its circuitry is very similar for all the models ranging from one to five kilowatts. The supply operates in current and voltage modes and is suited for resistive loads. It exhibits a long term stability of 500 ppm with a temperature coefficient of 300 ppm in current mode. It regulates within a 0.1 % with load or input voltage changes and has a ripple of 30 mV at 40 V/60 Amps. A block diagram of the switched mode power converter is shown in figure 2.

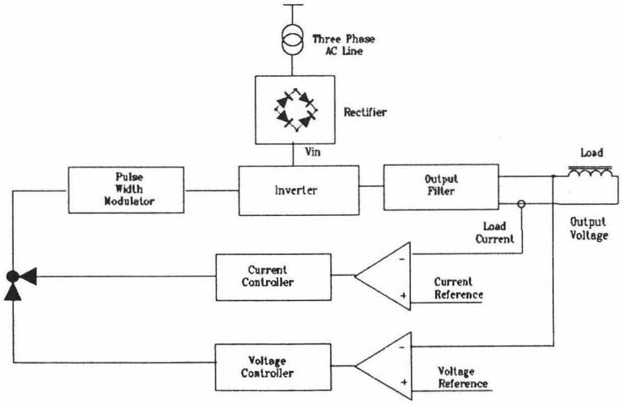

Figure 2. SMPS block diagram

The three phase input AC is rectified and filtered to provide an unregulated voltage (265V - 350V) DC bus, which is converted into a high frequency square wave through a high frequency power transformer. This AC is then rectified and filtered to provide a low level DC output. Control of the output voltage or current levels is achieved by modifying the duty cycle of the high frequency AC voltage.

In the current controlled mode, the output current must be sampled and compared with a reference. The error signal is sent to integrated PWM controllers (UC3524), operating in the master slave mode. They control the duty cycle of the drivers, which are magnetically coupled to the output stage.

In order to operate the Power Supply with the desired long and short term stability of fifteen parts per million, some critical components must be improved. It can be easily proven that in a feedback loop, if enough gain is provided in the direct loop, the elements that determine the accuracy and stability of the system are the transductor, the reference and the error amplifier.

The internal shunt, made of Manganin, with a temperature coefficient of 150 ppm was unsatisfactory. A zero flux transductor would be appropiate to monitor the high output current but its cost becomes prohibitive when large number of them are required. Instead, a more inexpensive unit, a resistive shunt made of Zeranin, was utilized. These shunts exhibit a temperature coefficient better than five parts per million per degree Celsius over the range of 0° C to +60° C. The shunt is water cooled and the temperature of the water is kept within one degree Celsius. The unit tested dissipated up to 100 Watts, delivering one volt at 100 Amps. This signal is amplified by a low noise instrumentation amplifier.

The internal reference was also replaced by an external one, with very low drift (0.6 ppm)/ and excellent line regulation (2ppm/V). The reference feeds a sixteen bit Digital to Analog converter that can be set remotely from a computer. The output of the DAC is used to provide the current reference to the power supply.

The error amplifier was upgraded to a low drift instrumentation amplifier providing very high gain (140db) at low frequencies, thereby reducing the errors in the stationary state. The original current and voltage regulators were coupled with diodes to the Pulse Width Modulator, and by using the same method to incorporate our upgraded controller to the loop we avoided the need to modify the power supply motherboard.

Modelling and compensation

The supply used in our tests operates in a full bridge configuration as a Buck converter. A simplified diagram of this type of converter is shown in figure 3. The inductor is energized when the transistors are conducting, with a slope given by Vi-VO/L, and discharges across the capacitor and load when the transistors are off, with a slope given by -VO/L.

Using two state averaged differential equations , a simplified model for the PWM can be easily derived [ref 3 and 4]. This model replaces the PWM with a Voltage source that depends on the duty cycle "d" and a filter as shown in figure 4.

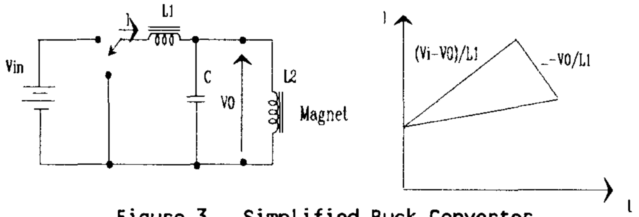

Figure 3. Simplified Buck Converter

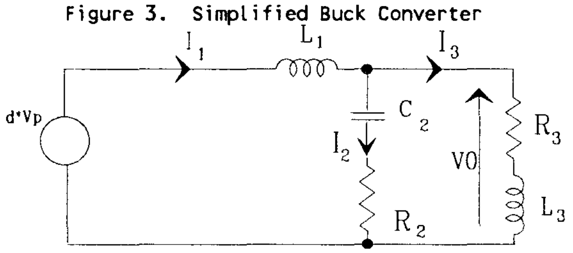

Figure 4. Simplified model for the PWM

The internal shunt was originally placed before the output filter capacitor and, even though the average current across the capacitor should be zero, a temperature dependent leakage current was measured which affected the regulation. Placing the shunt resistor in series with the load solves this problem but increases the order of the transfer function and the internal compensators were no longer appropriate.

Solving the current and voltage expressions for the circuit in figure 4, the transfer function between the output current and the control signal is:

$$G(s) = \frac{(1 + s\,C2\,R2)}{(s^2\,L1\,C2 + s\,R2\,C2 + 1)(s\,L3/R3 + 1)}$$

By inspecting the previous equation, it can be seen that the PWM presents a zero introduced by the capacitor with its ESR, it has a complex poles produced by the filter LC and extra pole introduced by the load. Replacing the components by its numeric values the roots are as follows:

poles:

$p1,2 = -362.7 \pm 664.52i$ (fn = 121 Hz)
$p3 = -10.114$ (f3 = 1.6 Hz)

zero:
$Z1 = -800$ (f1 = 127 Hz)

An external compensator was designed with three lead and one lag circuit. The first lead has a zero to cancel the pole introduced by the load. The second lead has it zero cancelling one of the complex poles. The third lead was placed at high frequencies to improve the phase margin, and the lag circuit introduces a pole at the origin to integrate any possible dc error. The gain was chosen to obtained a closed loop response with a frequency bandwidth of two kilohertz.

The design was verified with a model developed in Spice (Figure 5). Figure 6 is a Bode Plot that compares the models (Spice and Mathematica) with the values measured experimentally with 4 mH Magnet load.

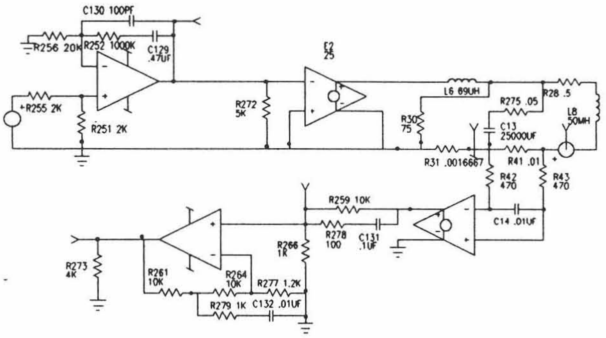

Figure 5. Spice model of the upgraded power supply

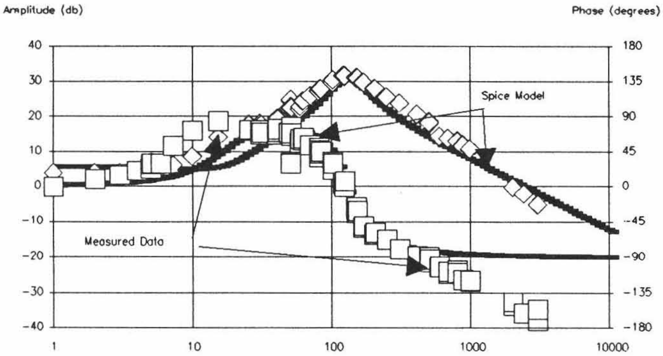

Figure 6. Open Loop Frequency Response of the PWM

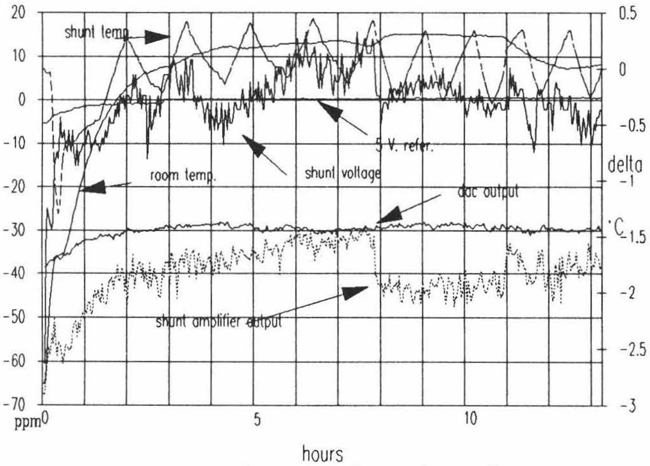

Figure 7. Experimental results

Shielding

The shielding techniques for the controller are critical to the succesful operation of the power supply. This is obvious for any high gain, low signal amplifier. Three basic rules for shielding techniques were followed [see ref.6]. First, all shields and enclosures must be tied to a zero reference to be effective. The enclosures for the power supply, analog controller and power shields are all tied to earth ground. The shields for the signals and the analog ground plane are all tied to the controller zero reference in the power supply. Since the output of the supply must be floating, the analog shield and the earth shields are capacitively coupled. The analog shields must drain current away amplifier inputs, i.e. toward the source. They should also be configured to avoid ground loops from shield to shield so no daisey chaining of the shields is allowed. Each shield is connected at the same point in the controller, which is also connected to the signal common in the power supply. Separate shields for each independant signal into or out of the controller box and an additional shield for the power entrance was provided.

Several configurations of the ground and shield connections were tried. The setup in figure 8 has had the best results. A Ferrite core was needed in the shunt cable to reduce the high frequency common mode noise entering the controller from that point.

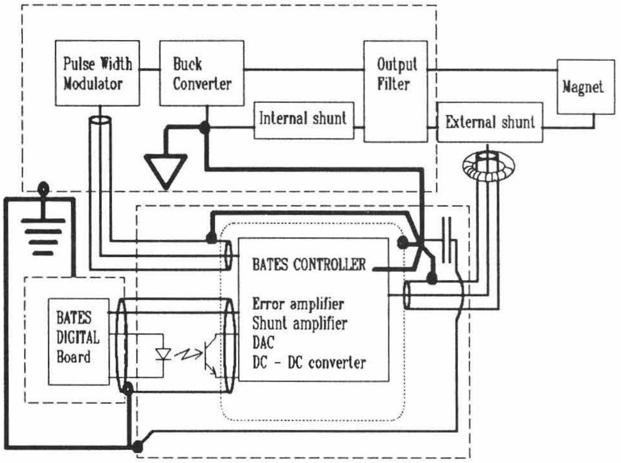

Figure 8. Shielding techniques

Conclusions

Power units from different manufacturers where tried out and the circuit developed was modified only slightly to regulate properly. Power levels ranged from 1 to 2.5 kWatts. Some noise is still measured in the prototype version and the shielding needs to be improved. Some of the problems observed in the prototype will be solved when a pc board is developed with proper ground planes for digital and analog signals. Analysis is been developed to build a state variable feedback type of controller. By using feedback from the internal shunt and also from the output voltage, we believe that the compensator can be reduced to simple coefficients, improving the dynamic response and simplifying the design.

References

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