Control Theory: A Practical Approach

Mike Anderson & Tom Bertuccio
Indiana University Cyclotron Facility
Bloomington, Indiana 47405

Abstract

Stability and frequency response enhancements can be made to custom manufactured and off-the-shelf power supplies. Combined power converter and magnet loads that result in poor transient response and marginal loop stability due to inadequate phase margin can be corrected with a systematic approach utilizing lead compensation techniques. Using a Venable Systems 350 Frequency Response Analyzer two actual case studies are documented demonstrating a practical approach to stabilizing and enhancing a power supply's performance. A description of the system and conventions are followed by a description of two power supplies with specific deficiencies. The first case study involves a power supply without a dominant pole output capacitor. The next case study involves a power supply driving a highly damped resonant load. The paper in concluded a by a discussion of measurements pitfalls.

I. INTRODUCTION

This paper will outline two case studies where the frequency response of laboratory grade precision power supplies were enhanced. The techniques used are simple, practical ways to compensate feedback loops. The approach consists of first measuring the frequency response of a system. Second, selecting a desired frequency response (i.e. crossover frequency and phase margin). Third, designing and implementing an error amplifier and/or other compensating amplifiers that fulfill the specifications. And, finally verifying the results by measurement.

Trial and error schemes so often used by power supply vendors proved to be inadequate especially when the favored approach is to employ a large capacitor across the output. The IUCF Cooler Ring having been designed with a highly interactive power supply network required the removal of all output capacitors which necessitated the complete redesign of all control loops. Some 50 channels were involved and simple "seat of the pants' tinkering clearly would not suffice. A device was needed to measure the frequency response (under closed-loop conditions) to allow quick, reliable measurements of loop characteristics over a range of operating conditions, and synthesis methods to properly match the dynamics of all elements of the network.

Past practices at this facility did not have the capability to execute the above approach until the rental and finally purchase of a Venable Model 350 Frequency Response Analysis System (VFRAS). However due to the need for precision ramping of power supplies under adverse condition (i.e. removal of output capacitors), a practical approach was developed to enhance the operation of dozens of power supply channels.

Additionally, efforts have been directed toward successfully modeling measured data. However, to date we have achieved only limited success, although in the near future we expect to complete accurate models.

II. DISCUSSION

A. Test Equipment

The VFRAS consists of a personal computer, software, and a three channel commercial frequency response analyzer.

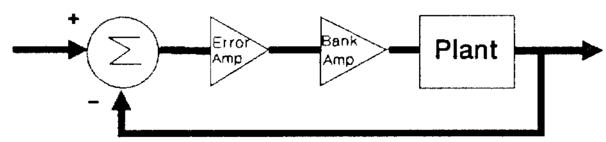

Figure 1 - *System Block Diagram.*

Figure 1 shows a general block diagram of the power supplies that are to be discussed. Measurements are accomplished by inserting a 100 ohm resistor within the loop. An excitation signal creates a perturbance which can be measured around the loop. Transfer functions for different blocks within the loop and the loop itself are represented in Bode diagram format. Furthermore, closed loop plots can be made by exciting the reference input and measuring the output over the input.

Additionally, the VFRAS will design an error amplifier for loops with an undesirable response. There are three error amplifier lead compensation design options which are determined by phase requirements. The first is a simple integrator. The second has a pole at the origin and a zero followed by a pole. The last option is used when phase boost requirements are greater than 90°, and consists of a pole at the origin, two zeros at the same frequency followed by two poles at the same frequency.[1,2]

B. General Block Diagram

As illustrated in Figure 1, there are three main blocks within the control loop, the plant, the bank drive amplifier (BDA), and the error amplifier. The plant is a combination of transistor pass bank, magnet load and feedback transducer. The BDA and the error amplifier can be modified to achieve the desired response. In addition, each block has been modeled using Spice which were later compared to measured data. However, only limited success has been achieved with the plant model.

The pass bank is arranged in a darlington configuration (i.e. 1 transistor driving 9 transistors driving 95 transistors). This system was modeled using Spice and circuit analysis

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techniques. This system consists primarily of a single pole caused by the inductive load. A hybrid pi model was used to model the transistor bank. The driver transistors and the bank transistors can be modeled to a composite transistor representing the entire pass bank[3]. The feedback transducer in the first case is a water cooled shunt and in the second case is transductor.

The BDA feeds the plant and consists of a common emitter amplifier driving a common collector amplifier which in turn drives the plant. A 'thumbnail' derivation proved to be quite accurate and was later verified by Spice. This system is characterized by a constant gain and a zero followed by a pole. This provides phase boost and gain to the feedfoward loop. The results were later used to adjust the frequency response.

The error amplifier is a chopper stabilized inverting operational amplifier whose feedback network is chosen via K factor analysis to the desired loop crossover frequency and phase margin.

C. First Case Study

This power supply furnishes current to coils in several quadrapole magnets and was specified to be ramped. However due to transformer coupling of loads with other supplies the output capacitors had to be removed. This upset the system dramatically and resulted in a 200 amp oscillator. The frequency response without the output capacitor is shown in figures 2 and 3.

To stabilize the supply a large capacitor was inserted across the error amplifier, this enabled the frequency response of the different system blocks to be measured. The ability to view an accurate frequency response of a system greatly enhances an engineers ability to effectively design a compensator. Without measured data the system characteristics can only be modeled by analysis which is cumbersome, time consuming, and does not accurately account for parasitic and variable parameter effects. Data over several decades takes only a matter minutes and is accurate when proper measurement techniques are observed.

To compensate the loop at a suitable crossover frequency the VFRAS was used to design an error amplifier. However, the desired response could not be achieved. This was due to a desired phase boost of the error amplifier to be greater than 90°. When a phase boost greater than 90° is desired, the VFRAS creates an error amplifier with a pole at the origin and two zeros located at the same frequency followed by two poles. The slope of the error amplifier is +1 at crossover (the zeros create a slope of +1 and the phase boost). If the loop has a slope of only -1 at the desired crossover frequency, the loop will not crossover until after the crossover frequency and when the phase boost has diminished. Therefore, the option of using phase boost greater than 90° is limited to modulators with a slope of -2 at the crossover frequency, which in turn will provide the loop with a crossover slope of -1.

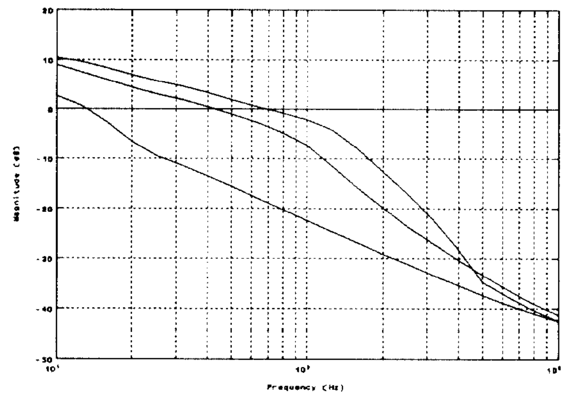

Figure 2 - *Magnitude plot of the plant plus the modified bank drive amplifier at different operating points.*

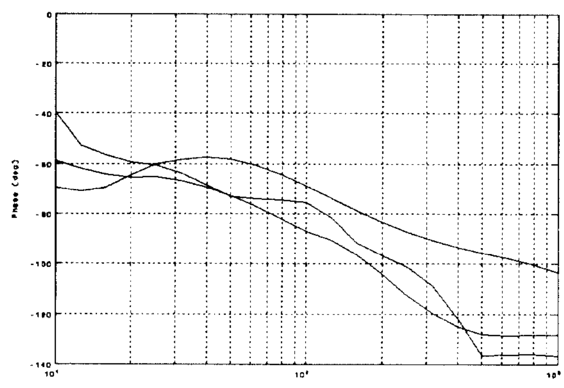

Figure 3 - *Phase plot of the plant plus the modified bank drive amplifier at different operating points.*

To overcome the above setback, the characteristics of the BDA amplifier were capitalized. According to the equation for the BDA the pole and zero can be modified by changing a few feedback components. By using an 'R-C box' and the circuit derivation we were able to predict and monitor the response while modifications were being made. Our objective was to create enough phase boost at a particular band of frequencies to allow the use of an error amplifier which needed a phase boost less than 90^0. This was accomplished and the resulting loop plot is shown in Figures 4 and 5.

The crossover frequency of the loop is a function of the current and V_{ce}. Therefore, a family of plots are taken for the plant at different operating conditions and a median value is chosen for crossover taking care that the phase margin does not become too small at high frequencies.

Given all system parameters such as load inductance, transistor parameters, etc. generally speaking the above, might have been accomplished. However, the power supply in this case drives a fraction of the coils per magnet to which it is connected. Also connected to these same magnets are other power supplies which in turn are connected to other magnets. It was the transformer coupling effect from this arrangement that prompted the removal of the output capacitors from the power supplies.

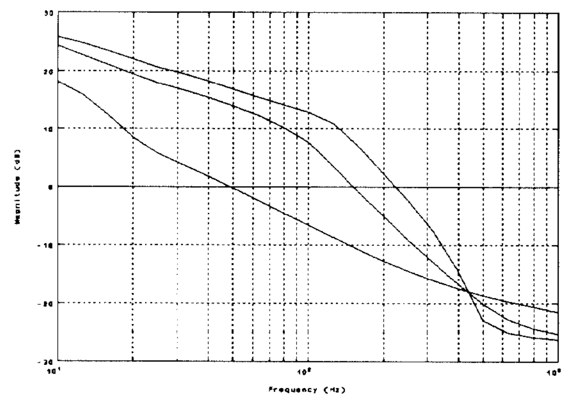

Figure 4 - *Loop magnitude plot at different operating points.*

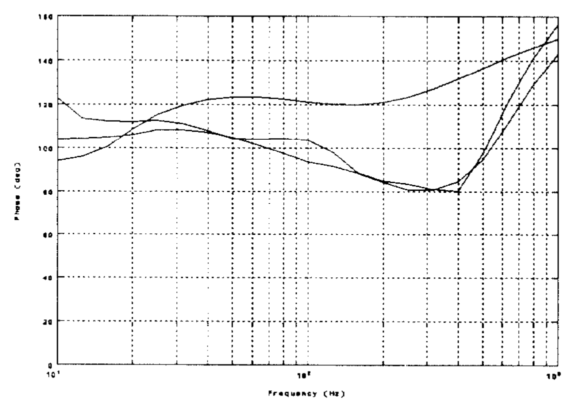

Figure 5 - *Loop phase plot at different operating points.*

Measured data attributes two poles to the plant. However, when the coupling effect of the other magnet coils are ignored, circuit analysis suggests only one pole. Indeed, it would have rather difficult to model the effect of the transformer coupled loads. Without the measured data the above results probably would not have been possible, namely due to the nature of the load.

Furthermore, the variable dynamic response characteristics due to varying operating conditions is involved. The transistor gain, as well as other transistor characteristics vary at different operating points (in this case over five transistor stages). In addition, this supply has no preregulator thus, the V_{ce} changes as a function of operating current, which in turn compounds the variation in transistor gain. All theses characteristics change as the temperature of the system varies.

D. Second Case Study

This study involves a the main Cooler Ring dipole magnet power supply. The load consisted of twelve dipole magnets whose combined inductances 160mH paralleled by a series network of 3 ohms and 20 millifarads. Due to ringing, the output capacitors were modified to a damping network. The added 3 ohm resister to the original 20 millifarad output capacitor (to damp the load) modification resulted in a marginally stable loop.

This supply has a significantly different current capability compared to the first case study. The darlington configuration in this case has one transistor driving 10 transistors driving 66 transistors driving 676 transistors. In addition, the transistors used in the first case were Westinghouse 164-08, and this supply uses Westinghouse D60T transistors.

The approach to achieving a desirable response was similar to case study one. Initially there were several unsuccessful attempts at crossing over the loop at a particular frequency. However, by modifying the BDA and then modifying the error amplifier a desirable frequency response was realized.

E. Pitfalls

Erroneous measurements can occur for several reasons. When using closed-loop measurement techniques circuit impedances should be considered[4,5]. For our application we found, when making measurements at relatively high frequencies (i.e. > +5kHz), the excitation signal should be injected prior to the error amplifier. For measurements of relatively low frequencies the signal should be injected after the operational amplifier. However these are relative to specific operating systems. Ground loops should be avoided by supplying power to the measurement device (VFRAS) via an isolation transformer; and injection transformers should also be used to isolate the excitation signal. In addition loads shorted to ground may result in erroneous measurements.

III. CONCLUSIONS

Specialized laboratory grade power supplies can be modified to meet specific needs of a user. Frequency response measurement device is an invaluable tool for control loop system design. In addition the VFRAS was able to measure the transfer functions of subsystems (i.e. amplifier or plant). The user also has the capability to verify and compare theoretical designs to practical measured data. This approach of measuring a system response gives practical and useful concrete information in a matter of minutes. Furthermore, the package provides in most cases a simple solution to control loop stability problems.

IV. REFERENCES

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