Technical Note #3

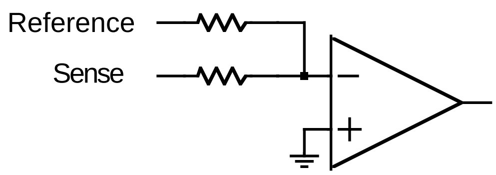
Error Amplifier Design and Applications

Introduction

All regulating power supplies require some sort of closed-loop control to force the output to match the desired value. Both digital and analog means could be used; in this paper, we will explore the analog method of generating the so-called "error" signal, specifically, using operational amplifiers in such applications. This small inexpensive part has the ability to control power supplies up to many megawatts.

Basic Types

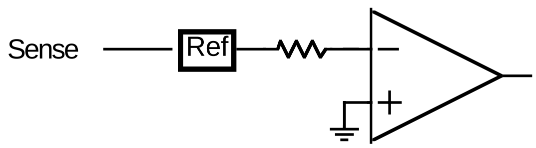
All error amplifiers fall into 3 types as shown below, summing, bucking, and differential.



Summing

Pros
- Scaling is set by the resistor ratios
- No common mode worries

Cons
- Current flows through the resistors
- Resistor Tc directly affects their ratio
- Sensing and reference must be opposite polarity



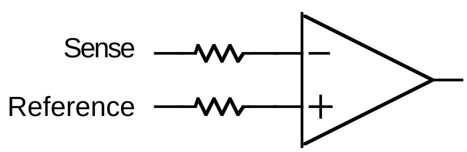
Bucking

Pros

- None

Cons

- Reference must be “floating”
- Leakages because of a imperfect "floating" reference are directly injected into the op amp
- Non-zero impedance of the reference causes problems



Differential

Pros

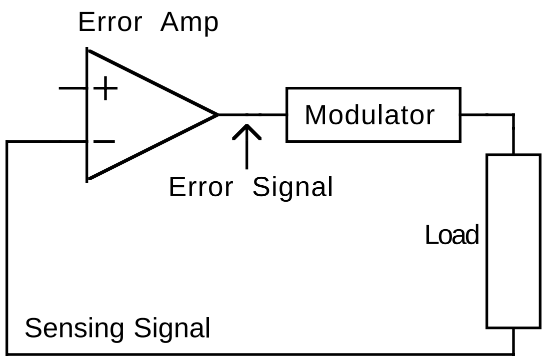
- Reference and sensing are the same polarity and voltage
- Input resistors see no current - tc only affects the ac compensation not the dc drift

Cons

- Inputs must now reject common mode voltage

The Modulator

The error amplifier, if used all by itself, can be used as a power supply. It is capable of outputting about 10 milliamps and 10 volts. All practical power supplies, however, have an additional "power" stage between the error amp and the output. We will call this stage the "modulator"; classic feedback theory would call this the "plant". The modulator accepts the output of the error amp and amplifies it to the desired level. Feedback from either a current sensing resistor or from a voltage sensing divider is applied to the minus input of the error amp in order to "close the loop", as shown below.



We always design our modulator's input so that a zero to 10 volt signal would equate to zero to full scale output voltage. In like manner, we always scale our sensing signals so that when the output is full voltage (or current), we have a 10 volt sensing signal. This 10 volt in - 10 volt out scheme equates to a modulator gain of one. When an error amplifier is added to the circuit, frequency calculations become easier because the gain and phase response of the error amp is identical to the total loop response.

If we only had an op amp to deal with, life would be so easy. Classic op amp theory teaches how to close the loop around the amplifier to achieve different gain, frequency responses, errors, etc. The easiest way to understand the error amplifier is to visualize a perfectly transparent circuit (the modulator), which could be inserted into the feedback path. This would represent a perfect power supply. Notice that as long as its output has a perfect gain-phase relationship to the input it can be inserted and the op amp will not know it's there.

DC Gain Errors

The loop must possess enough open loop gain to reduce any perturbations of the loop down to acceptable levels. Often times this requires the gain to be so high the feedback resistors are too large to be practical. Most error amps are operated open loop in regards to DC, the only feedback being capacitors or series RC's. The high gain of the amplifier cannot continue at all frequencies, forever. Without any intervention on our part, the amplifier response will roll-off as the frequency increases and will have unity gain between 1 to 10 Mhz. The slope of this roll-off is 20 dB per decade and is fixed by internal parts of the amplifier. This roll-off is the cause of 90 degrees of phase shift. We will discuss the problems caused by phase shifts later in this paper.

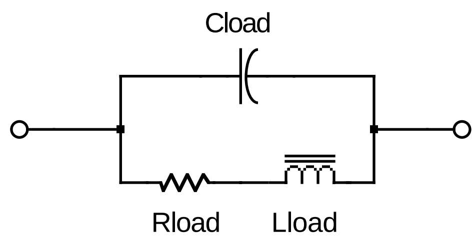
DC Offset Errors

The offsets of the error amp ultimately determine the lowest sensing signal that can still be controlled. Both voltage offsets and current offsets figure into the problem. All modern op amps have current offsets low enough so that they can be ignored, when used with input resistors below about 100 kΩ. The voltage offset adds (or subtracts) from the sensing voltage and "fools" the op amp into thinking that the actual voltage has changed.

The error amp cannot tell if a varying input is caused by the actual sensing has moved or the offset has drifted. Either way, the result is that the error amp will "correct" for it by adjusting the modulator. The offset voltage has both fixed and temperature dependent components. The temperature component of the offset is a major part of the total drift of the power supply. Most often when selecting an error amplifier, the offset parameters are the determining factors in the decision.

Frequency Compensation

Frequency compensation is perhaps the most variable parameter to be tackled. Load characteristics are the predominant influence now. Keep in mind that we are purposely limiting this discussion to inductive loads.



The classic model of an inductive magnet is shown above. R_{load} is the DC resistance of the coil; it is easily measured and/or calculated. L_{load} is the inductance of the coil; it is more difficult to calculate. Measured values are typically determined by one of the following methods, each of which has subtle problems, which may affect the true inductance.

> *Inductance Bridge* - little or no dc current flows, often gives erroneous values on large magnets, especially where an air gap exists in the magnetic circuit.
>
> *Time Constant* - after turning off the power supply, the decay time is measured and inductance is calculated. This is unfair because often the supply has filter capacitors which discharge into the magnet. Alternately, the power supply could be turned on or stepped by some other means. In any case, judgments must be made as to when the 63% level is reached.
>
> *Forcing Voltage* - by applying a small triangle wave to the current control of the power supply the voltage produced by the L*di/dt can be observed. This test could be done at several different DC levels to test for saturation effects, etc.

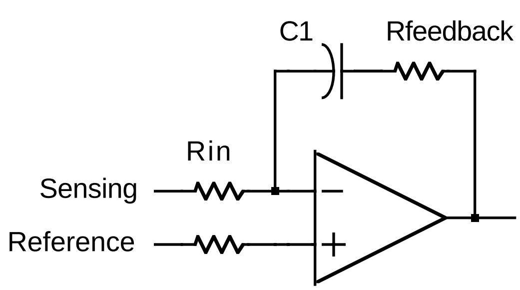
C_{load} is typically turn-to-turn and coil-to-yoke capacitance. This is usually small in comparison to the effects of R_{load} and L_{load} and could usually be ignored for all low frequency models. It should be noted that C_{load} is the culprit in a very common measurement problem. Quite often, the measured "current" ripple is not consistent with the expected current ripple through the magnet. Instances of "high frequency" spikes going into the magnet are almost always caused by current going into the capacity of C_{load} not into the inductance of L_{load}. Of course, current into C_{load} does not generate magnetic fields, except, in as much as it must flow through part of L_{load} because of the distributed nature of C_{load}.

The frequency response of the magnet should be understood before attempts are made to compensate the power supply. Asymptotic (straight line) analysis will show that a corner exists a $R_{load}/(2\pi\ L_{load})$. Below the corner, the response is flat (with the associated no phase shift). Above the corner, the response will fall off at a 20 dB per decade (with its associated 90 degree phase lag). At the corner, the phase shift is 45 degrees and the response is down 3 dB. Keep in mind that the bode plot can have only a limited number of discrete slopes. Each slope has a phase shift associated with it. Any feedback loop with greater than unity gain and 360 degrees of phase shift will perpetuate its own signal and oscillate. The key to taming any loop is to reduce the gain or the phase shift to the point of providing enough margin to prevent oscillation and ringing. The phase shifts of a typical power supply might add up as follows:

A. 180 degrees from regulating action
B. 90 degrees from pole at origin of op amp
C. 90 degrees from magnet above corner frequency

Notice that the total phase shift adds up to 360 degrees. Clearly, some compromises must be made to compensate the system. We could crossover the loop below the magnet's corner, where the shift is less. Alternatively, we could flatten out the response of the op amp and reduce its shift. Either way we must reduce the total phase shift to between 300 and 320 degrees. This will allow between 40 to 60 degrees of phase margin.

Generally, the higher the crossover frequency, the better the step response will be. We will discover that if we crossover the loop at one decade above the magnet's corner, the total phase shift will be 312 degrees. We can develop formulas for calculating the required component values for the following error amplifier circuit.



- The magnets corner F is at $R_{load}/(2\pi L_{load})$

- The desired amplifier corner is at 10F

- The value of $R_{feedback}$ is equal to R_{in}

- $C1 = 1/(2\pi FR_{in})$

- By reducing the equation we find that $C1=L_{load}/(R_{in}*R_{load}*10)$

The equations work well if the magnet's corner is at a point where the modulator's phase shift is negligible. For transistor regulated power supplies, this is below around 1 kHz. For SCR type regulators, the frequency is lower because of the finite switching times of the SCRs. These types of supplies usually also have a passive LC filter to reduce ripple. Anything above around 10 Hz starts to have phase shift, which, of course, adds directly to the current loops phase shifts.

References

1. Venable, H. Dean, "Practical Techniques for Analyzing, Measuring, and Stabilizing Feedback Control Loops in Switching Regulators and Converters", Proceedings of Powercon 7

2. Venable, H. Dean, "The K Factor: A New Mathematical Tool for Stability analysis and Synthesis", Proceedings of Powercon 10

3. "Voltage to Current Conversion", Apex Microtechnology Corp., Application Note 13