5.5 Operational Amplifier Implemented PID Controllers

Figure 5-26 is a repeat of general negative feedback control and its implementation for servo control in Multisim.

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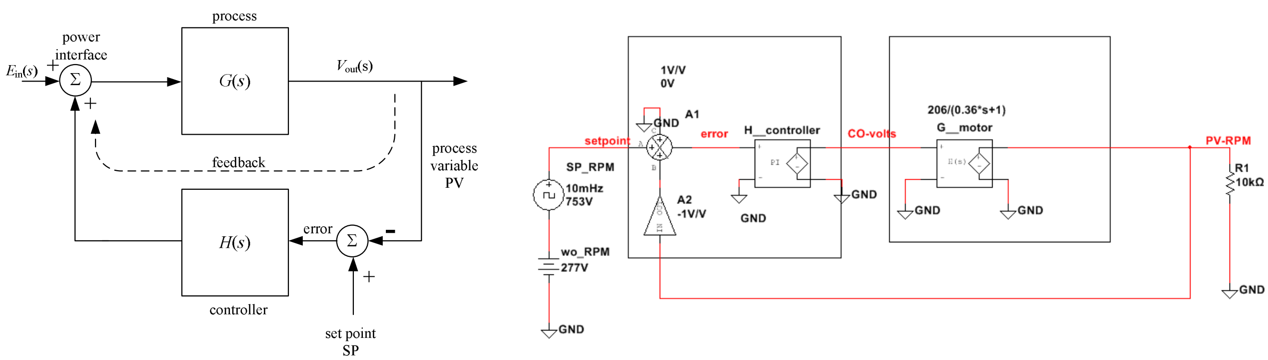

(a) General block diagram
Repeat of Figure 5-6

(b) Multisim servo control schematic
Repeat of Figure 5-13

Figure 5-26 Closed loop system implementation

Error Amplifier

The Error Amplifier calculations

$$v_{\text{error}} = v_{\text{set point}} - v_{\text{process variable}}$$

This is just the difference amplifier, from Chapter 1, and shown in Figure 1-9. For that circuit to work well,

$$R_{i1} = R_{i2} = R_i$$
$$R_{f1} = R_{f2} = R_f$$

The output is

$$v_{\text{out}} = \frac{R_f}{R_i}(e_{\text{in1}} - e_{\text{in2}})$$

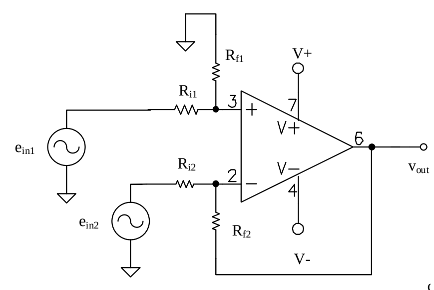

Figure 1-9 Difference amp

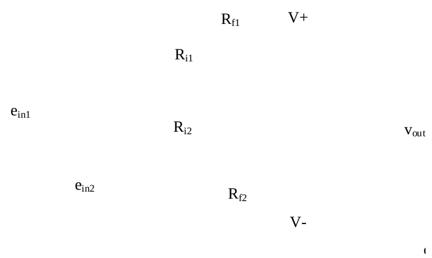

Figure 1-9 Difference amp

To use the circuit in Figure 1-9 as an error amplifier, match *all* four resistors as closely as possible, making them relatively large (e.g. 100 kΩ). This reduces the tendency the error amp may have to load down whatever is producing $v_{\text{set point}}$ and $v_{\text{process variable}}$.

$$\frac{R_f}{R_i} = \frac{100\ \text{k}\Omega}{100\ \text{k}\Omega} = 1$$

Then

$v_{\text{set point}} = e_{\text{in1}}$ (the positive input)
$v_{\text{process variable}} = e_{\text{in2}}$ (the negative input => negative feedback)

The op amp will be damaged if either of its input pins is driven above its supply voltages. If $v_{\text{set point}}$ and $v_{\text{process variable}}$ come from electronic circuits located close to the error amp and powered from the same supplies as the error amp this should never happen. But, often one or both of these signals are produced remotely, perhaps by the process being controlled, or are sent quite a distance in cables that are subject to interference or damage. In that case, it is prudent to provide input protection, as shown in Figure 2-27.

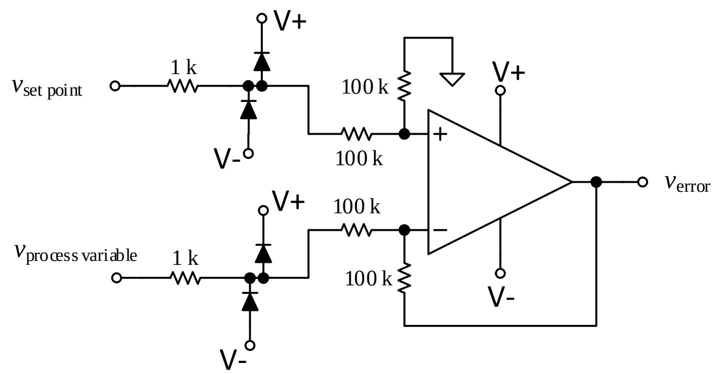

Figure 2-27 Error amplifier with input protection

Should either input voltage exceed the supply, the associated input diode turns on, clamping the voltage at V±. The 1 kΩ resistors are large enough to limit the fault current without degrading the amplifier's gain of 1.

Before moving on to the controller, it is wise to test the circuit before you use it to drive the controller stage. The inputs are in volts, not RPM, with a maximum of $\pm$ 10 V. The motor speed examples have all used a set point with a base of 277 RPM and steps up an additional 754 RPM. (Look back at Figure 5-26(b) or Figure 5-13.) This is used to drive a motor with a gain of 206 RPM/V. So the input *voltages* should be:

$$V_{\text{in min}} = 277\text{ RPM } \times \frac{V}{206\text{ RPM}} = 1.34\text{ V}$$

$$V_{\text{in pp}} = 754\text{ RPM } \times \frac{V}{206\text{ RPM}} = 3.66\text{ V}$$

Figure 2-28 is a simulation of the error amplifier. The input protection has been omitted. The *set point* steps from 1.35 V up 3.66 V to 5.00 V. The *process variable* has been half-way between the set point max and min, 3.17 V. So the output should be a square wave that goes from

$$V_{\text{out min}} = 1.34\text{ V} - 3.17\text{ V} = -1.83\text{ V}$$

$$V_{\text{out max}} = 5.00\text{ V} - 3.17\text{ V} = +1.83\text{ V}$$

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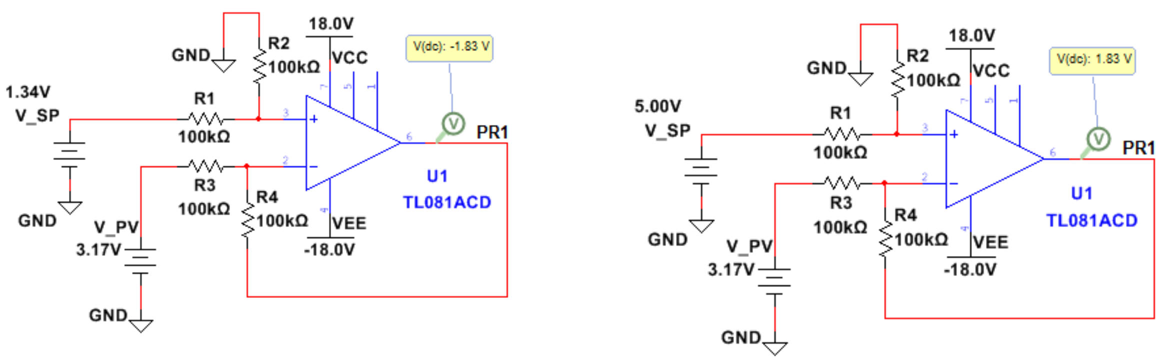

Figure 5-27 Error amplifier simulation

Proportional Controller

The transfer function of a Proportional Controller is

$$\frac{\boldsymbol{Controller\ out}}{\boldsymbol{Error}} = \boldsymbol{k_\mathrm{p}}$$

It is just a simple *noninverting* amplifier. But, its gain may be far smaller than one and then be adjusted to be far above one. The traditional noninverting amplifier has a gain of

$$k_{\mathrm{noninverting\ amp}} = 1 + \frac{R_\mathrm{f}}{R_\mathrm{i}}$$

There is no way to adjust R_f or R_i to drop the gain below one. So, a traditional noninverting amplifier is a poor choice for the Proportional Controller. Instead, use an inverting amplifier with a gain of $-k_p$ followed by an inverting amplifier with a gain of -1.

Finally, the output of the Proportional Controller may be summed with the outputs from the Integral Controller and the Derivative Controller. So, make that second inverting amplifier an inverting *summer*. Look at Figure 5-28.

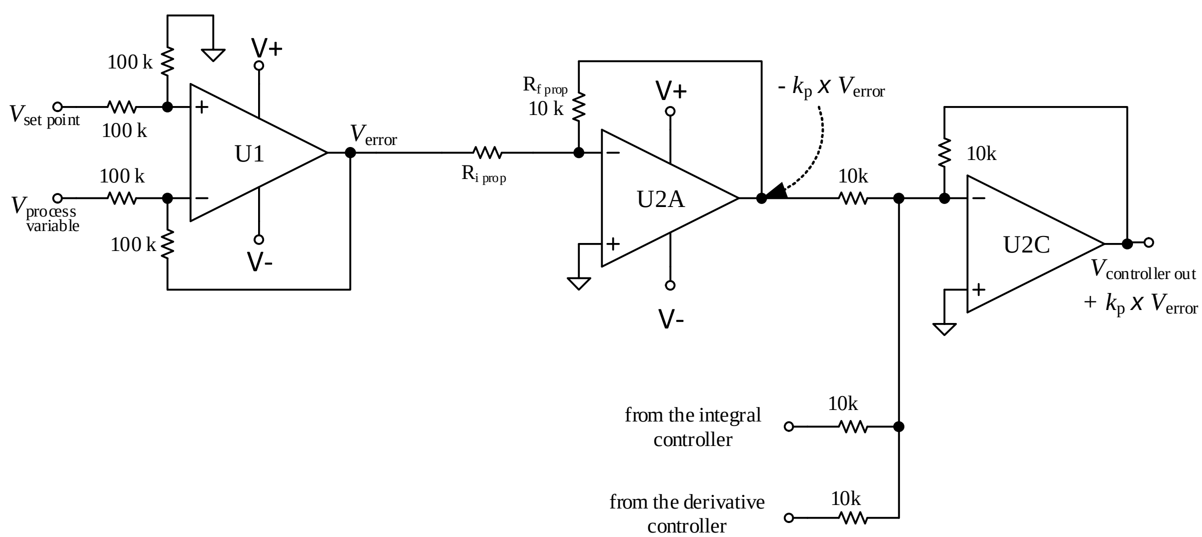

Figure 5-28 Schematic of error amplifier driving a proportional controller with summer.

Figure 5-29 shows the simulation results for the error amplifier and proportional controller. The controller's constant, k_p has been set to

$$\boldsymbol{k_\mathrm{p}} = \frac{\boldsymbol{R_{\mathrm{f\ prop}}}}{\boldsymbol{R_{\mathrm{i\ prop}}}} = \frac{10\ \mathrm{k\Omega}}{5\ \mathrm{k\Omega}} = 2$$

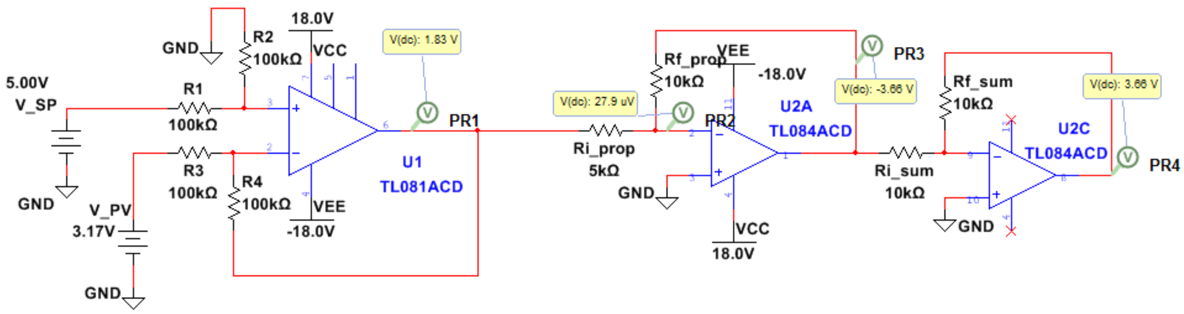

Figure 5-29 Proportional controller simulation

Look at the voltage at the inverting input of U2A. It is virtually 0 V, ground. Remember, with negative feedback, the op amp's output goes to whatever voltage is necessary to force its inverting input pin to track its noninverting input pin. Since U2A's noninverting input pin is connected to ground, its inverting input pin is driven virtually to ground. All of the other voltages match theory. This circuit is working.

Tachometer

In the previous examples, the output of interest was the motor's speed, in RPM. The motor has a nearly linear response with a gain of

$$m_{\mathrm{motor}} = 206\ \frac{\mathrm{RPM}}{\mathrm{V}}$$

When the controller outputs 10 V, the motor spins up to about 2000 RPM. That's the *process variable, PV*. To input that variable into the error amplifier, a tachometer is needed. It senses that spinning shaft and outputs a proportional voltage. This may be done optically, counting the frequency of spots on the shaft as they pass, then converting that frequency into voltage. Or, it may be done with a generator, the compliment of the motor. Spin the shaft of a generator and it outputs a voltage proportional to the speed of its shaft. Optimally, the tachometer would match the motor. In the examples, the motor spins at 2000 RPM when a voltage of 10 V is applied. A properly sized generator then would output 10 V when its shaft spins at 2000 RPM.

$$m_{\text{motor}} = \frac{RPM_{\text{out}}}{V_{\text{in}}} = \frac{2060 \text{ RPM}}{10 \text{ V}} = 206$$

$$A_{\text{tach}} = \frac{V_{\text{out}}}{RPM_{\text{in}}} = \frac{10\ V}{2000 \text{ RPM}} = 0.005$$

Also, remember that the *set point*, *SP*, into the error amplifier must be provided in *volts* not RPM.

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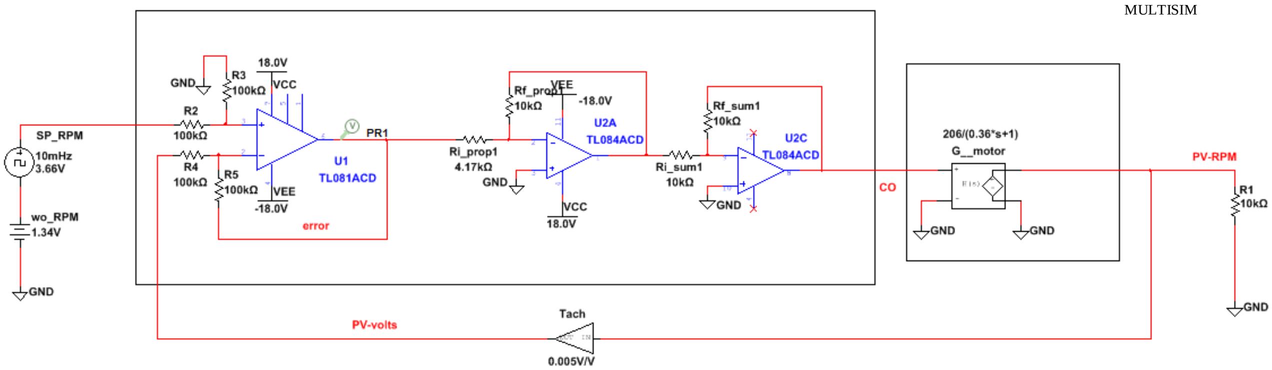

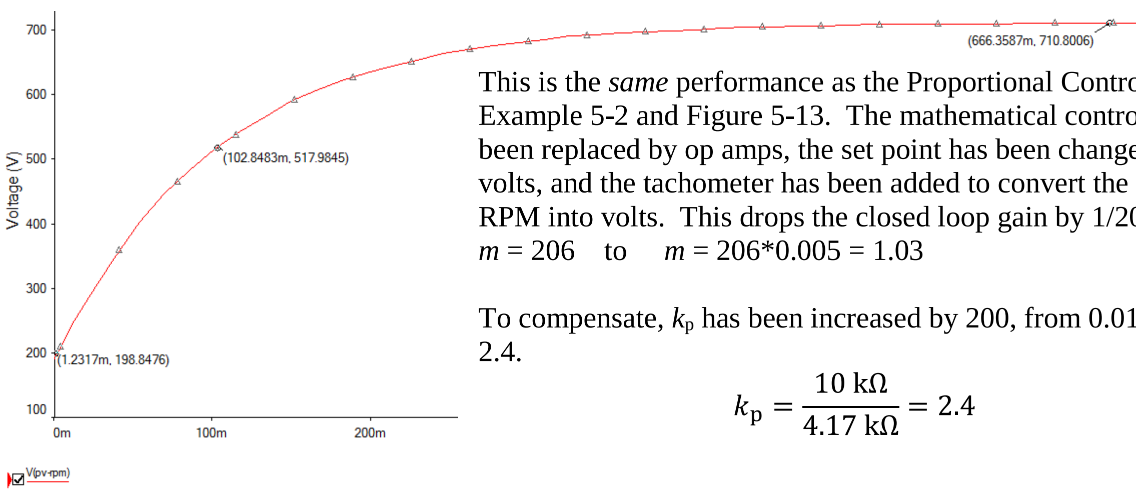

This is the *same* performance as the Proportional Controller in Example 5-2 and Figure 5-13. The mathematical controller has been replaced by op amps, the set point has been changed to volts, and the tachometer has been added to convert the motor's RPM into volts. This drops the closed loop gain by 1/200, from $m = 206$ to $m = 206*0.005 = 1.03$

To compensate, k_p has been increased by 200, from 0.012 to 2.4.

$$k_p = \frac{10 \text{ k}\Omega}{4.17 \text{ k}\Omega} = 2.4$$

Figure 5-30 Op amp proportional controller