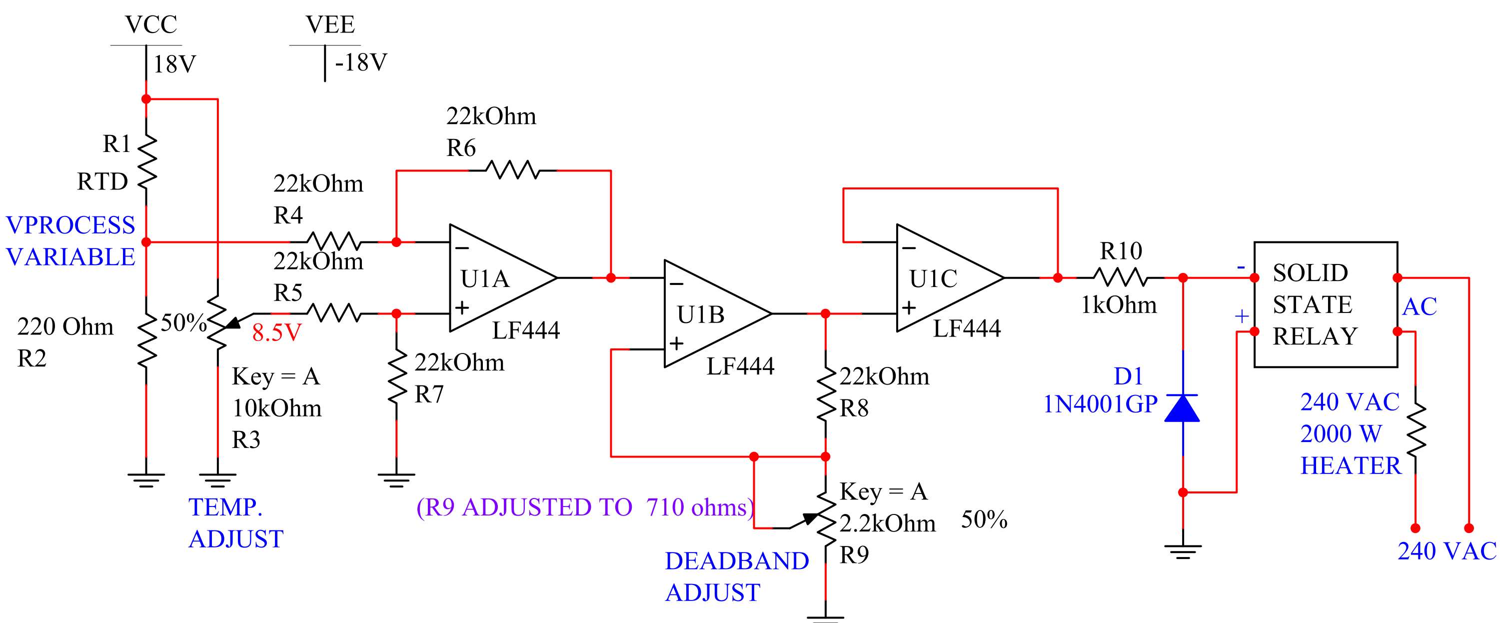
Control Systems Handouts



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SAN JOSE STATE UNIVERSITY
Department of Aviation & Technology

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Introduction to Process Control

1.1 Explain how the basic strategy of control is employed in a room air-conditioning system. What is the controlled variable? What is the manipulated variable? Is the system self-regulating?

Solution:

The basic strategy of the room air-conditioning system can be described as follows:

1. Measure the temperature in a room by using a "thermostat", which is nothing more than a sensor of temperature. Thus *temperature* is the *controlled variable*.
2. The measured temperature is compared to a set point in the thermostat. Often this is simply a bimetal strip which closes a contact when the temperature exceeds some limit.
3. If the temperature is too low then the compressor and distribution fan of the air-conditioner are turned on. This causes room air to be circulated through the unit and thereby cooled and exhausted back into the room. Therefore you can see that the *manipulated variable* is the *temperature* of the recirculated air.

The *system is self-regulating* because even without operation of the air-conditioner, the room will adopt some temperature in equilibrium with the outside air, open windows/doors, cooking, etc.

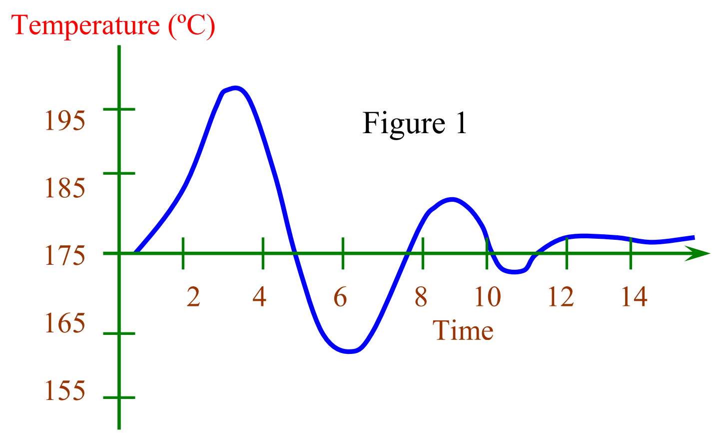
1.2 Can you think of any other situation in which a control is employed? What is the controlled variable? What is the manipulated variable? Is the system self-regulating?

1.3 Is driving an automobile best described as a servomechanism or a process-control system? Why?

Solution:

Driving a car is a servomechanism because the purpose is to control the motion of the vehicle rather than to regulate a specific value. Therefore the objective is to cause the vehicle to follow a prescribed path. Of course keeping the speed constant during a trip could be considered process control since the speed is being regulated.

1.4 A process-control loop has a setpoint of 175°C and an allowable deviation of ± 15°C. A transient causes the response shown in Figure 1.
(a) Specify the maximum error and
(b) settling time.



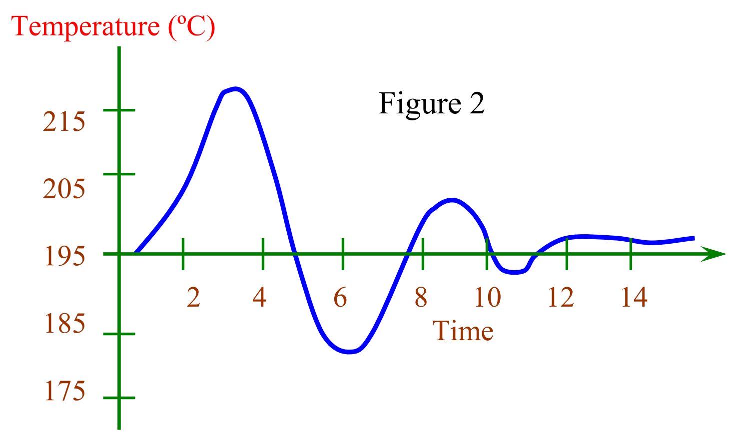
Solution:

(a) Maximum error = peak error - setpoint = 197 °C - 175 °C = 22 °C

(b) Settling time = time of first excursion beyond 175 ± 5 °C to the time that range is reacquired.

= 9.8s-1.4s = 8.4s

1.5 A process-control loop has a setpoint of 195°C and an allowable deviation of ± 20°C. A transient causes the response shown in Figure 2.
(a) Specify the maximum error and
(b) settling time.



1.6 The second cyclic transient error peak of a response test measures 6.4%. For the quarter-amplitude criteria, what error should be the third peak value?

Solution:

Since each peak must be a quarter of the previous one, the next peak must be:

$$a_3 = (1/4)\ a_2$$

$$a_3 = (1/4)\ (6.4\%) = 1.6\%$$

1.7 The second cyclic transient error peak of a response test measures 5.6%. For the quarter-amplitude criteria, what error should be the third peak value?

1.8 Does the response of Figure 1 satisfy the quarter-amplitude criterion?

Solution:

A close observation of Figure 1 shows:

The 1st peak error = 197.5 – 175 = 22.5

One quarter of this is (1/4) (22.5) = 5.6 but the actual peak is 7.

The third peak should be about (1/4) (7) = 1.75 but is 2. Thus, we conclude that the tuning does not match the quarter-amplitude exactly since each peak is higher than the predicted by the criteria.

1.9 An analog sensor converts flow linearly so that flow from 0 to 400 m^3/h becomes a current from 0 to 80 mA. Calculate the current for a flow of 250 m^3/h.

Solution:

Since it is linear we can calculate the current for each m^3/hr of fl of flow rate.

(80 mA)/(400 m^3/h) = 0.2 mA/m^3/h. Now, we can calculate current:

I = (250 m^3/h)(0.2 mA/m^3/h) = 50 mA

1.10 An analog sensor converts flow linearly so that flow from 0 to 600 m^3/h becomes a current from 0 to 100 mA. Calculate the current for a flow of 450 m^3/h.

1.11 Suppose each bit change in a 4-bit ADC represents a level of 0.15 m.
(a). What would the 4 bits be for a level of 1.7 m?
(b). Suppose the 4 bits were 1000_2. What is the range of possible levels?

Solution:

We can make a table of changes for the 16 states of the 4-bit ADC

Binary	Level	Binary	Level	Binary	Level
0000	0	0110	0.90	1100	1.80
0001	0.15	0111	1.05	1101	1.95
0010	0.30	1000	1.20	1110	2.10
0011	0.45	1001	1.35	1111	2.25
0100	0.60	1010	1.50		
0101	0.75	1011	1.65		

a. We can see that a level of 1.7 m would result in an output of 1011_2, since the level is greater than 1.65 but not yet 1.8 for the next bit change.
b. If the bits were 1000_2 then the MOST that can be said is that the level is between 1.20 m and 1.35 m. Thus there is an uncertainty of 0.15 m.

1.12 Suppose each bit change in a 4-bit ADC represents a level of 0.25 m. (a). What would the 4 bits be for a level of 2.9 m? (b). Suppose the 4 bits were 1010_2. What is the range of possible levels?

1.13 Atmospheric pressure is about 15.6 lb/in^2 (psi). What is this pressure in pascals?

Solution:

P_{at} = (15.6 psi)/(1.45 x 10^{-4} psi/Pa) = 107,600

1.14 Atmospheric pressure is about 26.8 lb/in^2 (psi). What is this pressure in Pascals?

1.15 An accelerometer is used to measure the constant acceleration of a race car that covers a quarter mile in 8.4 s

a. Using $x = at^2/2$ to relate distance, *x*, acceleration, *a*, and time, *t*, find the acceleration in ft/s'.

b. Express this acceleration in m/s^2.

c. Find the car speed, v, in m/s at the end of the quarter mile using the relation $v^2 = 2ax$.

d. Find the cm energy in joules at the end of the quarter mile if it weighs 2500 lb, where the energy $W = mv^2/2$.

Solution:

1 mile = 5280 ft and 1 ft = 0.3048 m

(a) for the acceleration we find,

$a = 2x/t^2$ = (2)(0.25 mile)(5280 ft/mile)/(8.4^2) = 37.42 ft/s^2

(b) In m/s^2 we have a = (37.42 ft/s^2)(0.3048 m/ft) = 11.4 m/s^2

(c) We have velocity, $v^2 = 2ax$, so

v^2 = (2)(11.4 m/s^2)(0.25 mile)(5280 ft/mile)(0.3048 m/ft)

$v^2 = 9.173 \times 10^3\ m^2/s^2$

v = 95.8 m/s

(d) The weight must be converted to mass in kg

$m = (2500 \text{ lb})(0.454 \text{ kg/lb}) = 1135 \text{ kg}$

$W = (1135 \text{ kg})(95.8 \text{ m/s})^2/2$

$W = 5.21 \times 10^6 \text{ kg-m}^2/\text{s}^2 = 5.21 \times 10^6 \text{ J}$

1.16 An accelerometer is used to measure the constant acceleration of a race car that covers a half mile in 12.6 s

a. Using $x = at^2/2$ to relate distance, *x*, acceleration, *a*, and time, *t*, find the acceleration in ft/s'.

b. Express this acceleration in m/s^2.

c. Find the car speed, v, in m/s at the end of the quarter mile using the relation $v^2 = 2ax$.

d. Find the cm energy in joules at the end of the quarter mile if it weighs 2500 lb, where the energy $W = mv^2/2$.

1.17 A controller output is a 4-mA to 20-mA signal that drives a valve to control flow. The relation between current and flow is $Q = 45[I - 2\ \text{mA}]^{1/2}$ gal/min. What is the flow for 15 mA? What current produces a flow of 185 gal/min?

Solution:

For a current of 12 mA we have a flow given by:

$$Q = 45[I - 2\ \text{mA}]^{1/2}\ \text{gal/min} = 45[15\ \text{mA} - 2\ \text{mA}]^{1/2}\ \text{gal/min} = 162.3\ \text{gal/min}$$

To find current we can derive an equation,

$$Q = 45[I - 2\ \text{mA}]^{1/2}$$

$$Q/45 = [I - 2\ \text{mA}]^{1/2}$$

$$(Q/45)^2 = I - 2\ \text{mA}$$

where $I = (Q/45)^2 + 2\ \text{mA}$

then $I = (185/45)^2 + 2\ \text{mA} = 18.90\ \text{mA}$

1.18 A controller output is a 5-mA to 22-mA signal that drives a valve to control flow. The relation between current and flow is $Q = 50[I - 2\ \text{mA}]^{1/2}$ gal/min. What is the flow for 13 mA? What current produces a flow of 150 gal/min?

1.19 An instrument has an accuracy of ± 0.4% FS and measures resistance from 0 m 1200 Ω. What is the uncertainty in an indicated measurement of 485 Ω?

Solution:

± 0.4% FS for 0 to 1200 Ω means (± 0.004)(1200) = ± 4.8 Ω.

Thus a measurement of 485 Ω actually means 485 ± 4.8 or from 480.2 to 489.8 Ω

1.20 An instrument has an accuracy of ± 0.3% FS and measures resistance from 0 m 1000 Ω. What is the uncertainty in an indicated measurement of 345 Ω?

1.21 A sensor has a transfer function of 0.6 mV/°C and an accuracy of ± 1%. If the temperature is known to be 50 ºC, what can be said with absolute certainty about the output voltage?

Solution:

A 0.6 mV/°C with a ± 1% accuracy means the transfer function could be 0.6 ± 0.006 mV/°C or 0.594 to 0.606 mV/°C.

If the temperature were 50 °C the output would be in the range,

(0.594 mV/°C)(50°C) = 29.7 mV to (0.606 mV/°C)(50°C) = 30.3 mV

or 30 ± 0.3 mV. This is, of course, ± 1%.

1.22 A sensor has a transfer function of 0.45 mV/°C and an accuracy of ± 1.5%. If the temperature is known to be 70°C, what can be said with absolute certainty about the output voltage?

1.23 A temperature sensor transfer function is 52.5 mV/°C. The output voltage is measured at 9.28 V on a 3-digit voltmeter. What can you say about the value of the temperature?

Solution:

This is a linear transducer so it is represented by the equation of a straight line with a zero intercept,

V = KT with K = 52.5 mV/°C, or V= 0.0525T

If V= 9.28 volts then, T= V/K = 9.28/0.0525 = 176.762 °C

but we have only three significant figures, so the temperature is reported as,

$$T = 177°\text{C}$$

1.24 A temperature sensor transfer function is 45.5 mV/°C. The output voltage is measured at 8.36 V on a 3-digit voltmeter. What can you say about the value of the temperature?

1.25 A temperature sensor has a static transfer function of 0.15mV/°C and a time constant of 2.8 s. If a step change of 26°C to 60°C is applied at t = 0, find the output voltages at 0.5 s, 2.0 s, 3.3 s, and 9 s. What is the indicated temperature at these times?

Solution:

We do not have to use the transfer function at all since the relation between voltage and temperature is linear. Using the equation for first-order time response,

$T = T_i + (T_f - T_i)(1\text{-}e^{-t/\tau})$

$T = 26\ °C + (60\ °C - 26\ °C)(1\text{-}e^{-t/2.8s})$

$T = 26\ °C + 34(1\text{-}e^{-t/2.8s})\ °C$

$T = 0.5\ s \rightarrow T = 26\ °C + 34(1\text{-}e^{-0.5/2.8s})\ °C = 31.6°C$

$T = 2.0\ s \rightarrow T = 26\ °C + 34(1\text{-}e^{-2/2.8s})\ °C = 44.5°C$

$T = 2.8\ s \rightarrow T = 26\ °C + 34(1\text{-}e^{-2.8/2.8s})\ °C = 47.5°C$

$T = 9.0\ s \rightarrow T = 26\ °C + 34(1\text{-}e^{-9/2.8s})\ °C = 58.6°C$

1.26 A temperature sensor has a static transfer function of 0.22mV/°C and a time constant of 3.5 s. If a step change of 20°C to 50°C is applied at t = 0, find the output voltages at 0.5 s, 1.5 s, 4.8 s, and 8.5 s. What is the indicated temperature at these times?

1.27 A pressure sensor measures 38 psi just before a sudden change to 80 psi. The sensor measures 46 psi at a time 3.5 s after the change. What is the sensor time constant?

Solution:

Using the equation for first-order time response,

$P = P_i + (P_f - P_i)(1\text{-}e^{-t/\tau})$ and substituting values

$46 = 38 + (80 - 38)(1\text{-}e^{-3.5/\tau})$

$46 - 38 = (42)(1\text{-} e^{-3.5/\tau})$

$8 = (42)(1\text{-} e^{-3.5/\tau})$

$8/42 = 1 - e^{-3.5/\tau}$ or $e^{-3.5/\tau} = 1 - 8/42 = 0.81$

Taking natural logarithms of both sides,

$-3.5/\tau = \ln(0.81) = - 0.211$

Thus, $\tau = - 3.5/(- 0.211) = 16.6$ s

1.28 A pressure sensor measures 45 psi just before a sudden change to 78 psi. The sensor measures 39 psi at a time 4.25 s after the change. What is the sensor time constant?

1.29 Plow rate was monitored for a week, and the following values were recorded as gal/nun: 10.6, 11.2, 10.7, 8.4, 13.4, 11.5, 11.2, 12.5, 8.9, 13.5, 12.3, 10.3, 8.7, 10.9, 11.0, and 12.3. Find the mean and the standard deviation for these data.

Solution:

There are 16 values, if xi represents the values of flow rate then the mean is found from:

$$\overline{X} = \frac{\sum xi}{N} = \frac{10.6 + 11.2 + 10.7 + 8.4 + 13.4 + 11.5 + 11.2 + 12.5 + 8.9 + 13.5 + 12.3 + 10.3 + 8.7 + 10.9 + 11.0 + 12.3}{16}$$

$$\overline{X} = 11.1 \text{ gal/min}$$

The standard deviation is found from: $\sigma = \dfrac{\sum(xi - |x|)^2}{N-1} = 1.53 \text{ gal / min}$

1.30 Plow rate was monitored for a week, and the following values were recorded as gal/nun: 11.4, 12.5, 11.9, 9.9, 13.8, 12.8, 11.9, 13.9, 10.5, 14.9, 12.9, 13.2, 9.9, 12.5, 12.0, and 13.2. Find the mean and the standard deviation for these data.

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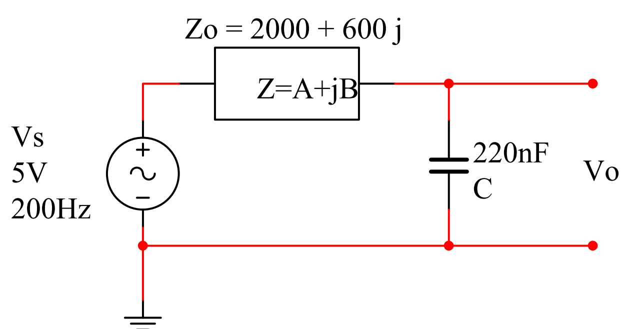
Analog Signal Conditioning

2.1 The unloaded output of a sensor is a sinusoid at 200 Hz and 5-V amplitude. Its output impedance is 2000 + 600j. If a 0.22-uF (220 nF) capacitor is placed across the output as a load, what is the sensor output voltage amplitude?

Solution:

The circuit is as shown below:



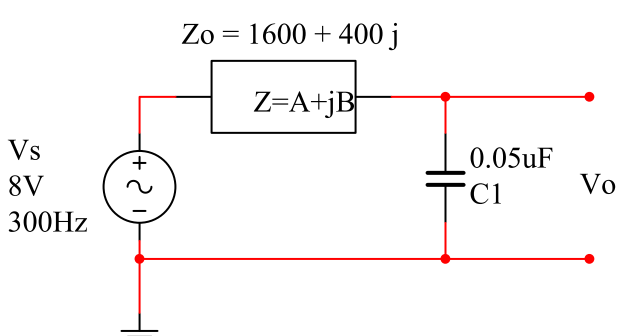
The output is a voltage divider voltage: $Vo = \dfrac{Vs\,Xc}{Zo + Xc}$

Where $Xc = \dfrac{1}{2\pi fC} = \dfrac{1}{2\pi(200)(0.22 \text{ x } 10^{-6})} = 3617\,\Omega$

And $Zo = \sqrt{(2000)^2 + (600)^2} = 2088\,\Omega$

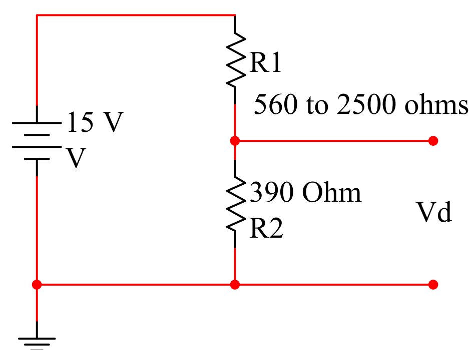
Then the output voltage is $Vo = \dfrac{5(3617)}{2088 + 3617} = 3.17\text{ V}$

2.2 In the circuit shown below (a) Calculate the sensor output voltage amplitude. (b) If C1 opens determine Vo. (c) If C1 shorts find Vo.



Solution:

2.3 A sensor resistance varies from 560 to 2500 Ω. This is used for R_1 in the divider of the Figure shown below, along with R_2 = 390 Ω and V = 15.0 V. Find (a) the range of the divider voltage, Vd, and (b) the range of power dissipated by the sensor.



The divider output voltage is found from:

$$\mathrm{Vd} = \frac{VR_2}{R_1 + R_2} = \frac{(15)(390)}{R_1 + 390}$$

(a) For R_1 = 560 Ω, then $\mathrm{Vd} = \dfrac{(15)(390)}{560 + 390}$ = 6.16 V

For R_1 = 2500 Ω, then $\mathrm{Vd} = \dfrac{(15)(390)}{2500 + 390}$ = 2.02 V

The range of Vd is from 2.02 V to 6.16 V.

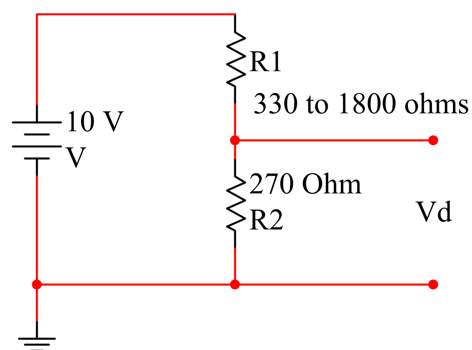
(b) Sensor dissipation is given by $P_{R1} = \dfrac{(V_{R_1})^2}{R_1}$ where $V_{R1} = V - Vd$

For $R_1 = 560\ \Omega$, $V_{R1} = 15 - 6.16\ V = 8.84\ V$ and $P_{R1} = \dfrac{(8.84)^2}{560} = 140\ mW$

For $R_1 = 2500\ \Omega$, $V_{R1} = 15 - 2.02\ V = 12.98\ V$ and $P_{R1} = \dfrac{(12.98)^2}{2500} = 77\ mW$

The power dissipated by the sensor is from 77 mW to 140 mW.

2.4 A sensor resistance varies from 330 to 1800 Ω. This is used for R_1 in the divider of the Figure shown below, along with $R_2 = 270\ \Omega$ and $V = 10.0$ V. Find (a) the range of the divider voltage, Vd, (b) the range of power dissipated by the sensor, (c) If R2 opens calculate Vd, (d) If R1 shorts calculate Vd, (e) If R1 opens calculate Vd, and (f) If R2 shorts calculate Vd.

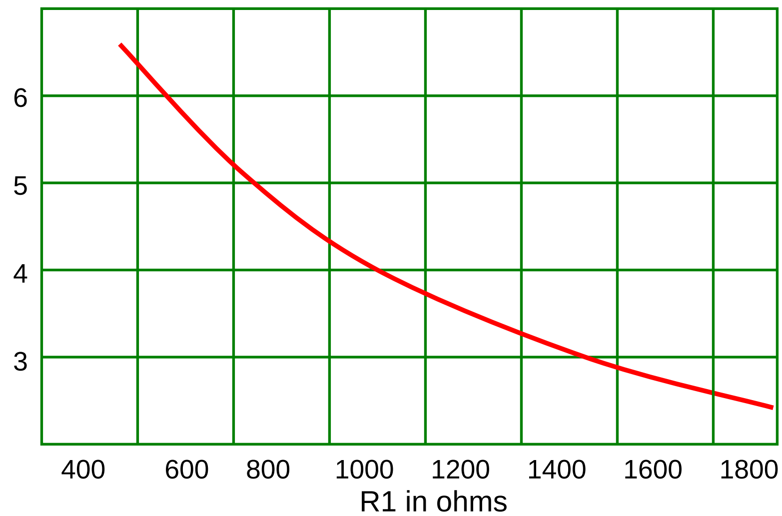


2.5 Prepare graphs of the divider voltage versus transducer resistance for Problem 2..3. (a) Does the voltage (Vd) vary linearly with resistance? (b) Does the voltage (Vd) increase or decrease with resistance?

Solution:

We can use the following equation: $\text{Vd} = \dfrac{VR_2}{R_1 + R_2} = \dfrac{15(390)}{R_1 + 390}$

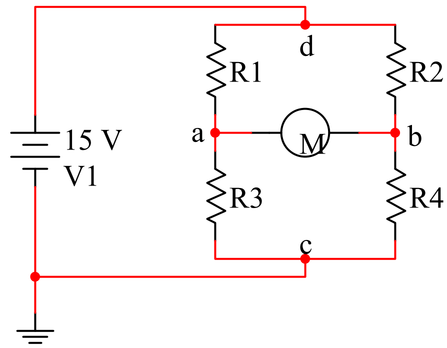
A plot of this function for R1 varying between 560 Ω and 2500 Ω is shown below:



This is nonlinear and the output voltage (Vd) decreases with increasing resistance.

2.7 Prepare graphs of the divider voltage versus transducer resistance for Problem 2.4. (a) Does the voltage (Vd) vary linearly with resistance? (b) Does the voltage (Vd) increase or decrease with resistance? (c) At approximately what R1 value Vd is about 3.5 V?

2.8 A Wheatstone bridge, as shown below, nulls with $R_1 = 319\ \Omega$, $R_2 = 524\ \Omega$, and $R_3 = 1265\ \Omega$. Find R_4.



Solution

The null condition is obtained when the multiplication of the value of two non-adjacent branches are equal to the multiplication of the value of two other non-adjacent branches.

In this case: $R_1 R_4 = R_2 R_3$, therefore, $R_4 = R_2 R_3/R_1 = (524)(1265)/(319) = 2078\ \Omega$

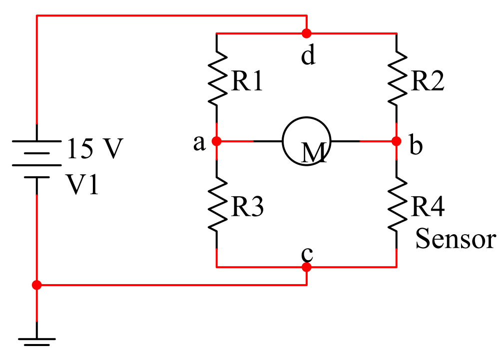
2.9 A Wheatstone bridge, as shown above, nulls with $R_1 = 456\ \Omega$, $R_2 = 856\ \Omega$, and $R_3 = 1543\ \Omega$. Find R_4.

Solution

2.10 A sensor with a nominal resistance of 60 Ω is used in a bridge with $R_1 = R_2 = 120\ \Omega$, $V = 12.0$ V, and $R_3 = 150$-Ω potentiometer. It is necessary to resolve 0.1-Ω changes of the sensor resistance.

a At what value of R_3 will the bridge null?

b. What voltage resolution must the null detector possess?



Solution

(a) For a null condition: $R_1 R_4 = R_2 R_3$, therefore,

$$R_3 = R_1 R_4/R_2 = (120)(60)/(120) = 60\ \Omega$$

(b) The detector resolution needed to resolve a resistance change of 0.1 Ω is found from the following equation when R_4 has changed to 60.1 Ω (or 59.9 Ω).

$$\Delta V = \frac{VR_3}{R_1 + R_3} - \frac{VR_4}{R_2 + R_4}$$

For $R_4 = 60.1\ \Omega$ $$\Delta V = \frac{(12V)(60)}{60+120} - \frac{(12V)(60.1)}{60.1+120} = \text{-4.44 mV}$$

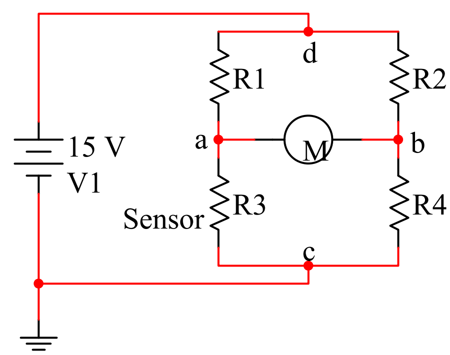
Or,

For $R_4 = 59.9\ \Omega$ $$\Delta V = \frac{(12V)(60)}{60+120} - \frac{(12V)(59.9)}{59.9+120} = \text{-4.44 mV}$$

2.11 A sensor with a nominal resistance of 48 Ω is used in a bridge with $R_1 = R_2 = 150\ \Omega$, $V = 15.0$ V, and R_4 = 200-Ω potentiometer. It is necessary to resolve 0.15-Ω changes of the sensor resistance.

a At what value of R_4 will the bridge null?

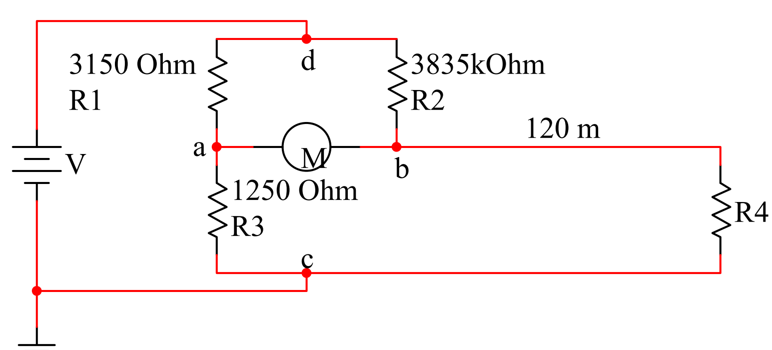
b. What voltage resolution must the null detector possess?



2.12 A bridge circuit is used with a sensor located 120 m away. The bridge is not lead compensated, and the cable to the sensor has a resistance of 0.36 Ω/ft. The bridge nulls with $R_1 = 3150\ \Omega$, $R_2 = 3835\ \Omega$, and $R_3 = 1250\ \Omega$. What is the sensor resistance?

Solution

The diagram will help understand this problem.



If we use the null equation to find R4, it will give the resistance from *b* to *c* in the schematic, which includes the two 120 m lead resistance. Thus, these must be subtracted to find the actual sensor resistance.

$R_4 = R_{bc} - R_{lead}$

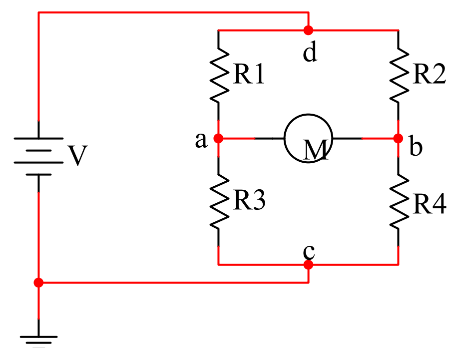
$R_{bc} = R_2 R_3 / R_1 = (1250)(3835)/(3150) = 1522\ \Omega$

$R_{lead} = 2(120\text{ m})(0.3048\text{ m/ft})(0.36\ \Omega\text{/ft}) = 26.34\ \Omega$

The actual sensor resistance is then: $R_4 = R_{bc} - R_{lead} = 1522\ \Omega - 26.34\ \Omega = 1495.8\Omega$

2.13 A bridge circuit is used with a sensor located 150 m away. The bridge is not lead compensated, and the cable to the sensor has a resistance of 0.45 Ω/ft. The bridge nulls with $R_1 = 2250\ \Omega$, $R_2 = 3255\ \Omega$, and $R_3 = 1510\ \Omega$. What is the sensor resistance?

2.14 A potential measurement bridge, such as the one shown below, has: $V = 15.0$ V, $R_1 = R_2 = R_3 = 11$ kΩ. Find the unknown potential if the bridge nulls with $R_4 = 10.93$ kΩ.



Solution

$$Vab = Va - Vb$$

$$Va = \frac{V R_3}{R_1 + R_3} = \frac{12(11\,k\Omega)}{11\,k\Omega + 11\,k\Omega} = 6\text{ V}$$

$$Vb = \frac{V R_4}{R_2 + R_4} = \frac{12(10.93\,k\Omega)}{11\,k\Omega + 10.93\,k\Omega} = 5.981\text{ V}$$

$$Vab = 6 - 5.981 = 19\text{ mV}$$

2.15 A potential measurement bridge, such as the one shown above, has: $V = 12.0$ V, $R_1 = R_2 = R_3 = 12.8$ kΩ. Find the unknown potential if the bridge nulls with $R_4 = 15.53$ kΩ.

2.16 A low-pass RC filter has R = 110 Ω and C = 0.5 μF. (a) Determine fc, (b) Find the attenuation of a 900-Hz signal and (c) Determine the attenuation of a 5000-Hz signal.

Solution

(a) To determine the cutoff frequency or fc, we use the equation:

$$\text{fc} = \frac{1}{2\pi RC} = \frac{1}{2\pi(110)(0.5\mu F)} = 2894 \text{ Hz}$$

(b) The attenuation is found from the following equation:

$$\left|\frac{\text{Vout}}{\text{Vin}}\right| = \frac{1}{[1+(f/fc)^2]^{1/2}} = \frac{1}{[1+(900/2894)^2]^{1/2}} = 0.955$$

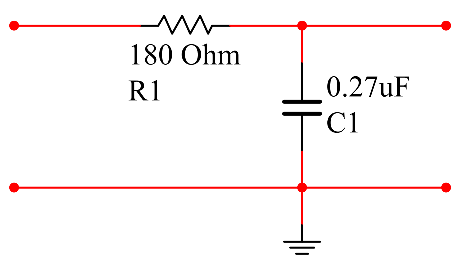
Thus the attenuation is 1 – 0.955 = 0.045 or 4.5%.

(c) The attenuation of a 5000-Hz signal is:

$$\left|\frac{Vout}{Vin}\right| = \frac{1}{[1+(f/fc)^2]^{1/2}} = \frac{1}{[1+(5000/2894)^2]^{1/2}} = 0.501$$

Thus the attenuation is 1 – 0.501 = 0.499 or 49.9%.

2.17 In the low-pass RC filter shown below, (a) calculate the attenuation of an 1100-Hz signal and (b) Determine the attenuation of a 10000-Hz signal..



2.18 A high-pass RC filter must drive 60 Hz noise down to 0.8%. (a) Specify the filter critical frequency, (b) values of *R* and C and (c) the attenuation of a 20-kHz signal.

Solution

(a) We find the critical frequency for which a 60 Hz signal has an output to input voltage ratio of 0.008 (0.8% as stated in the problem statement);

$$\left|\frac{\text{Vout}}{\text{Vin}}\right| = \frac{(\text{f/fc})}{[1+(\text{f/fc})^2]^{1/2}}$$

From this equation we derive *fc*.: $\text{fc}^{\,2} = \dfrac{(\text{f}^2 - \text{f}^2(\left|\frac{\text{Vout}}{\text{Vin}}\right|)}{\left|\frac{\text{Vout}}{\text{Vin}}\right|} = \dfrac{(60^2 \text{ - } 60^2(|0.008|)}{|0.008|} = 44.6\ \text{kHz}$

Then $fc = \sqrt{44600} = 668$ Hz

(b) If we select C = 0.002 μF then $\text{R} = \dfrac{1}{2\pi(fc)C} = \dfrac{1}{2\pi(668\,\text{Hz})(0.002uF)} = 1191\,\Omega$

The standard value is R = 1.2 kΩ.

(c) The attenuation of a 20 kHz signal is calculated from this equation:

$$\left|\frac{Vout}{Vin}\right| = \frac{(f/fc)}{\left[1+(f/fc)^2\right]^{1/2}} = \frac{(20000/668)}{\left[1+20000/668)^2\right]^{1/2}} = 0.999$$

So the attenuation is 1.00 - 0.999 = 0.001 or 0.1%.

2.19 A high-pass filter is found to attenuate a 2-kHz signal by 30 dB. What is the critical frequency?

2.20 A high-pass filter is found to attenuate a 1-kHz signal by 25 dB. Find the critical frequency.

Solution

In this case we solve for *fc*. Down 30 dB means that:

$-30\text{ dB} = 20\log_{10}(\text{Vout/Vin})$

$-30/20 = \log_{10}(\text{Vout/Vin})$

$-1.5 = \log_{10}(\text{Vout/Vin})$

$\text{Vout/Vin} = 10^{-1.5} = 0.032$

$$\left|\frac{\text{Vout}}{\text{Vin}}\right| = \frac{(\text{f/fc})}{[1+(\text{f/fc})^2]^{1/2}}$$

From this equation we derive *fc*.:

$$\text{fc}^2 = \frac{(\text{f}^2 - \text{f}^2(\left|\frac{\text{Vout}}{\text{Vin}}\right|)}{\left|\frac{\text{Vout}}{\text{Vin}}\right|} = \frac{(2\text{kHz} - (2\text{ kHz})^2(|0.032|)}{|0.032|} = 121\text{ MHz}$$

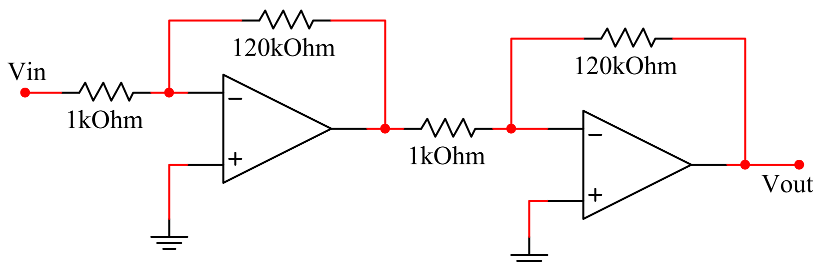
And $fc = \sqrt{121\text{ MHz}} = 11\text{ kHz}$

2.21 A high-pass filter is found to attenuate a 1-kHz signal by 25 dB. Find the critical frequency.

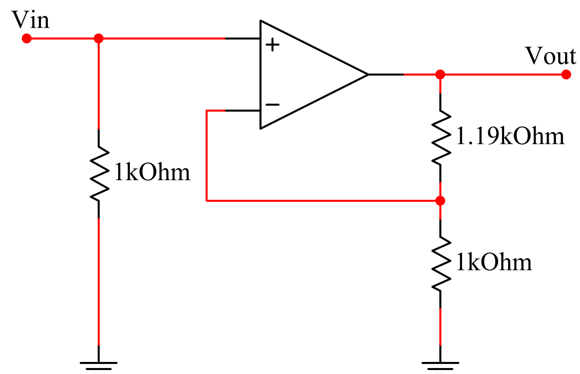
2.22 Show how op amps can be used to provide an amplifier with a gain of +120 and an input impedance of 1 kΩ. Show how this can be done using both (a) inverting and (b) non-inverting configurations.

Solution

(a) In the case of the inverting amplifier we need two so that the overall gain will be +120. Thus, the following circuit will satisfy this need. The first has a gain of -120 and an input impedance of 1 kΩ and the second a gain of - 1.



(b) A non-inverting amplifier can be constructed with only one op amp as:



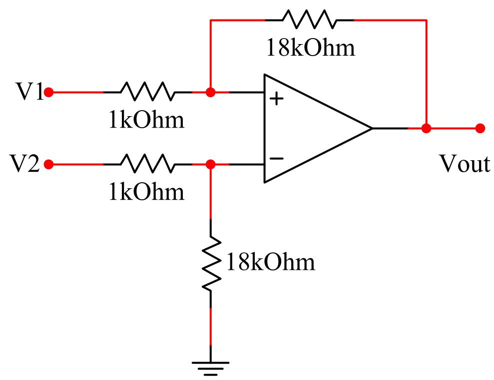
Since a non-inverting amplifier has a very high input impedance, the 1 kΩ resistor placed in parallel with the input terminal ensures that the input impedance be 1 kΩ.

2.23 What change(s) would you do to provide an amplifier with a gain of +180 and an input impedance of 5.6 kΩ in both the (a) inverting and (b) non-inverting configurations.

2.24 Specify the components of a differential amplifier with a gain of 18.

Solution

A differential amplifier with a gain of 18 can be built as follows:



2.25 What change(s) would you do to provide a differential amplifier with a gain of 22.

2.26 Using an integrator with RC = 5 s and any other required amplifiers, develop a voltage ramp generator with 0.6 V/s.

Solution

Since the output is constant the output equation is:

$$Vo = \frac{-(Vin)t}{RC} = \frac{1}{RC}(Vin)\,t$$

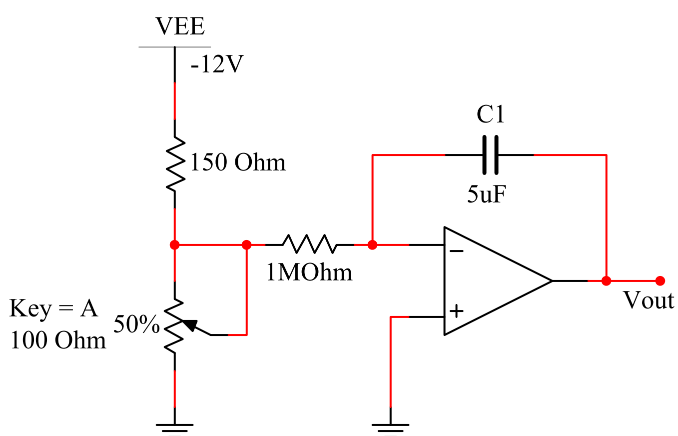
However, since RC = 5 s, then $Vo = \frac{-1}{5}(Vin)t = -0.2(vin)t$

Since the output should be 0.6 V/s

$$0.6\ V/s = -0.2\ (Vin)\ t \rightarrow Vin = \frac{0.6}{0.2} = -3\ V$$

The following circuit will provide the required output. We need to adjust the potentiometer until the voltage at point A is – 3 V.

To get RC = 5 s, we select R = 1 MΩ and C = 5 μF. RC = 1 MΩ (5 μF) = 5 s.



2.27 What change(s) would you do to provide to the integrator shown above if we need RC = 8 s to develop a voltage ramp generator with 0.5 V/s.

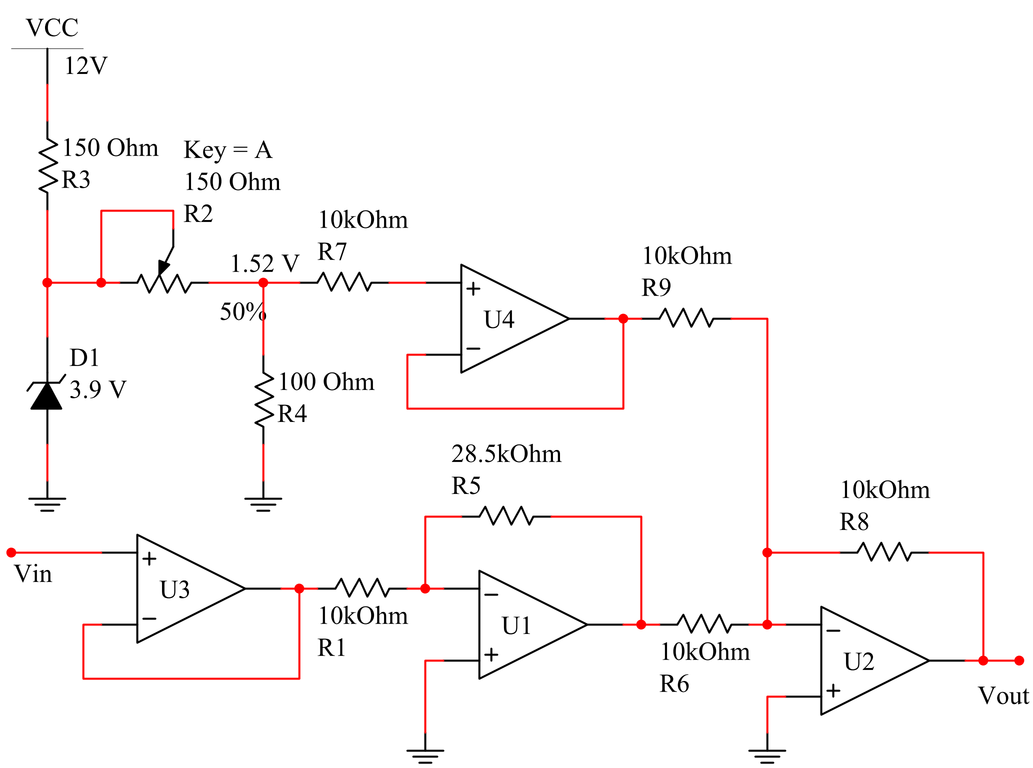
2.28 The analysis of a signal-conditioning circuit has produced the following equation:

$$V_{out} = 2.85\ Vin - 1.52$$

Design circuits to implement this equation using (a) a summing amplifier and (b) a differential amplifier.

Solution

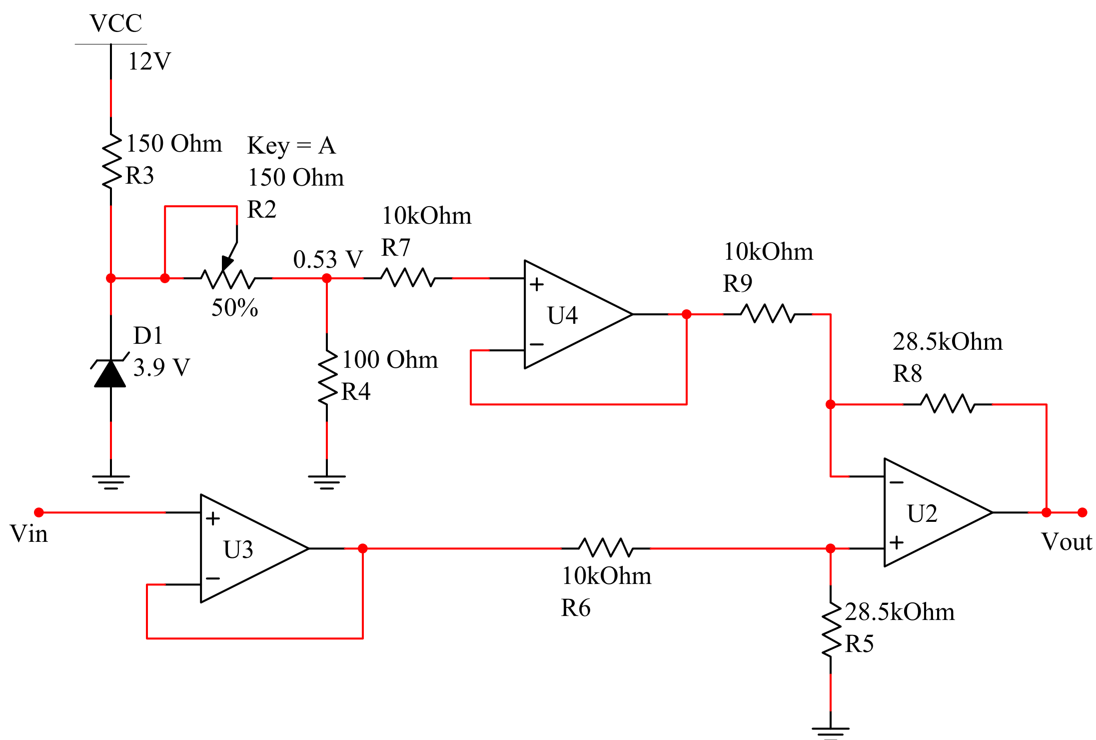
(a) The respective circuit is shown below. A gain of - 2.85 is given by R5/R1; however, since the gain is + 2.85, a gain of – 1 is given by R8/R6. The constant of - 1.52 is given by R2, R3, R4, D1 and the inverting amplifier with unity gain (R8/R9). Notice that due to the inverting amplifier we need to obtain + 1.52 V first. Voltage followers U3 and U4 prevent loading.



(b) In this case, the equation needs to be rearranged as:

$$V_{out} = 2.85\ Vin - 1.52 = 2.85\ (Vin - \frac{1.52}{2.85}) = 2.85\ (Vin - 0.53)$$

The respective circuit is shown below. The gain of the differential amplifier is determined by R8/R9 or R5/R6. The constant of - 0.53 is given by R2, R3, R4 and D1. Notice that since this constant voltage is connected to the inverting input of the differential amplifier, we need to obtain + 0.53 V first. Voltage followers U3 and U4 prevent loading.



2.29 What change(s) would you to the above circuits, the summing amplifier and the differential amplifier to implement the following equation:

$$V_{out} = 4.25\ Vin + 2.45$$

2.30 A differential amplifier has R_2 = 560 KΩ and R_1 = 3.9 KΩ. When Va = V_b = 2.8 V the output is 69 mV. Find the CMR and CMRR.

Solution

The amplifier gain is determined by Ad = R_2/R_1 = 560/3.9 = 144

The common-mode gain is determined by Acm = Vo/Vin = 69 mV/2.8 = 0.025

CMRR is the ratio between the differential gain (Ad) and the common-mode gain (Acm); thus,

$$CMRR = Ad/Acm = 144/0.025 = 5760$$

CMRR is given in dB. The equation is:

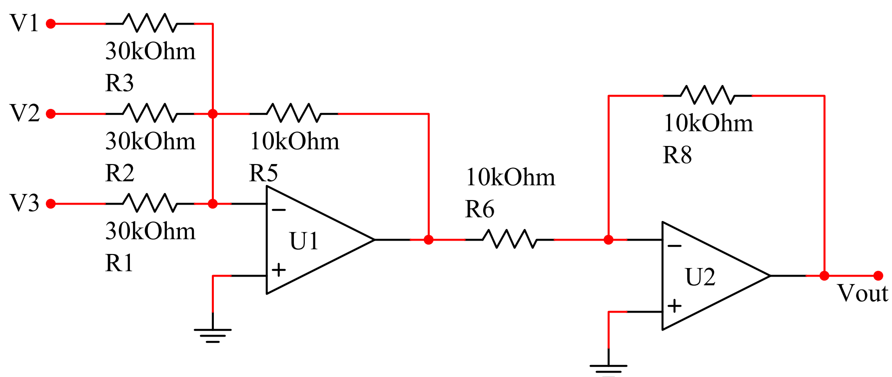
$$20 \log 10 (CMRR) = 20 \log 10 (5760) = 75.2 \text{ dB}$$

2.31 A differential amplifier has R_2 = 680 KΩ and R_1 = 4.7 KΩ. When Va = V_b = 3.2 V the output is 98 mV. Find the CMR and CMRR.

2.32 A control system needs the average of temperature from three locations. Sensors make the temperature information available as voltages, V_1, V_2, and V_3. Develop an op amp circuit that outputs the average of these voltages.

Solution

A solution is to use a summing amplifier with a gain of 1/3 on all inputs because there are three input signals, followed by a unity gain inverter to get the right polarity. Notice that R1, R2 and R3 are of the same value (30 kΩ) and R5 is 10 kΩ (1/3 of 30 kΩ). Since U1 is an inverter we need an inverting amplifier with unity gain. This is given by U2, R6 and R8.



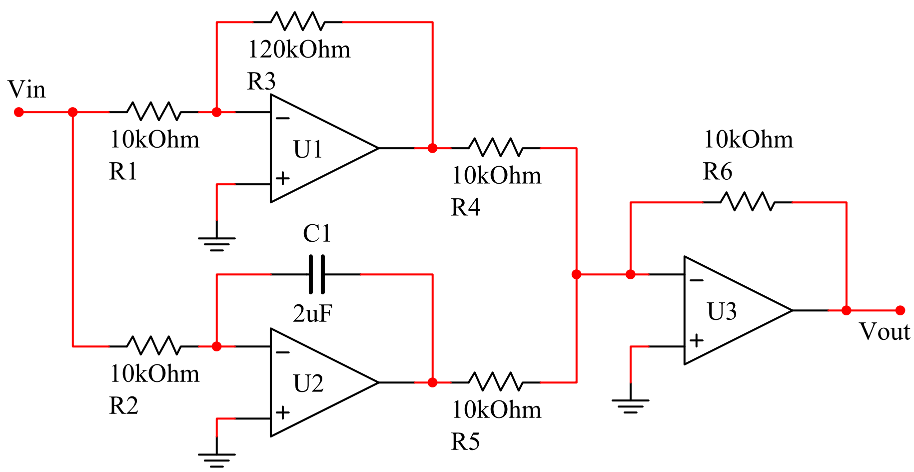
2.33 A control system needs the average of temperature from five locations. Sensors make the temperature information available as voltages, V_1, V_2, V_3, V_4, and V_5. Develop an op amp circuit that outputs the average of these voltages.

2.34 Use the appropriate circuits to implement an output voltage given by

$$Vout = 12V_{in} + 5\int V_{in}\, dt$$

Solution

This equation consists of the sum of a gain term and an integrator term. Thus, the circuit shown below meets the requirement. Resistors R3/R2 determine the gain of 12. The integrator gain is determined by 1/(R1 C1) = 1/(10 kΩ * 2 uF) = 1/(0.2) = 5.



2.35 What change(s) would you do to the above circuit to implement an output voltage given by

$$Vout = 10V_{in} + 4\int V_{in} dt$$

2.36 Develop signal conditioning for Problem 2.3 so the output voltage varies from 0 to 6 V as the resistance varies from 560 to 2500 Ω, where 0 V corresponds to 2500 Ω.

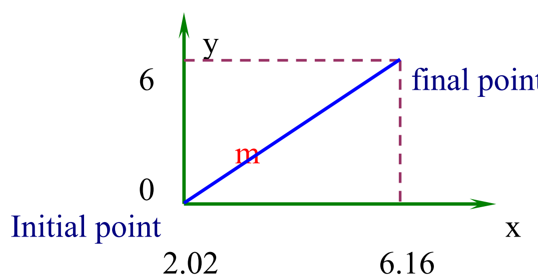
Solution

The input conditions and the requirements of this problem can be summarized as follows:

R	Vd = Vin	Vout
560 Ω	6.16 V	6 V
2500 Ω	2.02 V	0 V

The input voltage (6.16 V to + 2.02 V) is the independent variable while the output voltage (0 to 6V) is the dependent variable.

By plotting the independent variable (x axis) and the dependent variable (y axis), we have:



Connecting the intersection points, we find that the graph is a straight line,

$$y = mx + b \qquad (1)$$ **equation of the straight line.**

where:

$$m = \frac{y_1 - y_0}{x_1 - x_0} \qquad (2)$$ **slope of the straight line.**

Replacing values in the slope of the straight line, we have:

$$m = \frac{6 - 0}{6.16 - 2.02} = 1.45$$

To find the value of the constant (b), in the equation of the straight line we replace the variables (x, y) for the coordinates of the initial point (4.8, 0) or the coordinates of the final point (24, 3.5), through this linear equation:

$y = mx + b$ **equation of the straight line**

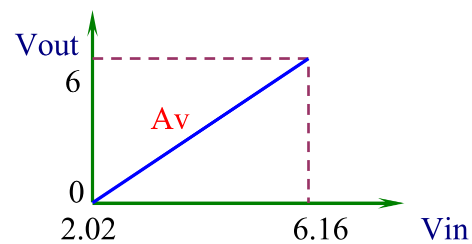
Use coordinates of the initial point → (2.02, 0) ➔ 0 = 1.45(2.02) + b ➔ **b = - 2.93**

Use coordinates of the final point → (6.16, 6) ➔ 6 = 1.45(6.16) + b ➔ **b = - 2.93**

The result is the same; however, it is simpler to use the initial point as seen above.

Replacing the variables and the constant of the linear equation for equivalent electronic terms we'll have:

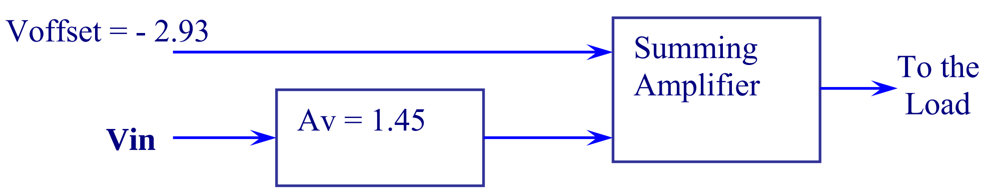
y = Vout
m = Av = 1.45
x = Vin
b = Voffset = - 2.93



The constant of the equation can be called any name; in this case we'll call it Voffset.

Then: Vout = Av (Vin) + Voffset (4)

Equation (4) indicates that we should use a circuit whose block diagram is:



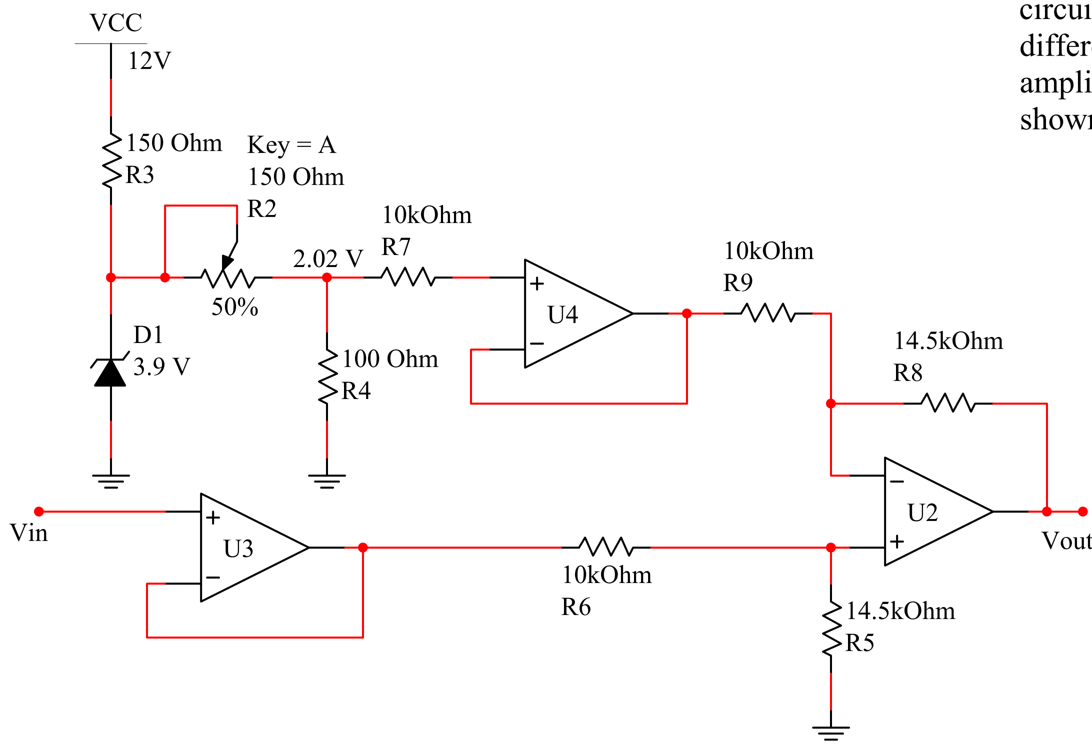
Replacing values in equation (4), we have:

Vout = Av(Vin) + Voffset (4)

Vout = 1.45 (Vin) – 2.93

Vout = 1.45 (Vin – 2.02) (5)

The respective circuit using a differential amplifier is shown below:



2.37 What change(s) would you to the above circuit if the output voltage varies from 0 to 8 V as the resistance varies from 470 to 2200 Ω, where 0 V corresponds to 2200 Ω.

2.38 Sensor resistance varies from 22 kΩ to 1.2 kΩ as a variable changes from C_{min} to C_{max}. Design a signal-conditioning system that provides an output voltage varying from -3 to + 3 V as the variable changes from min to max. Power dissipation in the sensor must be kept below 2.0 mW.

Solution

To begin with, we establish an equation relating Vout and R from the equation for a straight line,

$$Vout = mR + Voffset \qquad (1)$$

Using the given values,

$$-3 = 22000m + Voffset \qquad (2)$$

$$+3 = 1200m + Voffset \qquad (3)$$

Solving, we have

$$0 = 23200m + 2\ Voffset \rightarrow Voffset = -23200m/2 = -11600m \qquad (4)$$

Substituting Voffset (equation 4) into equation 3

$$+3 = 1200m - 11600m$$

$$+3 = -10400m \rightarrow m = 3/(-10400) = -2.89 \times 10^{-4} \qquad (5)$$

So we can find Voffset (equation 5 into equation 4),

$$Voffset = -11600m = -11600(-2.89 \times 10^{-4}) = 3.352\ V$$

The equation is then:

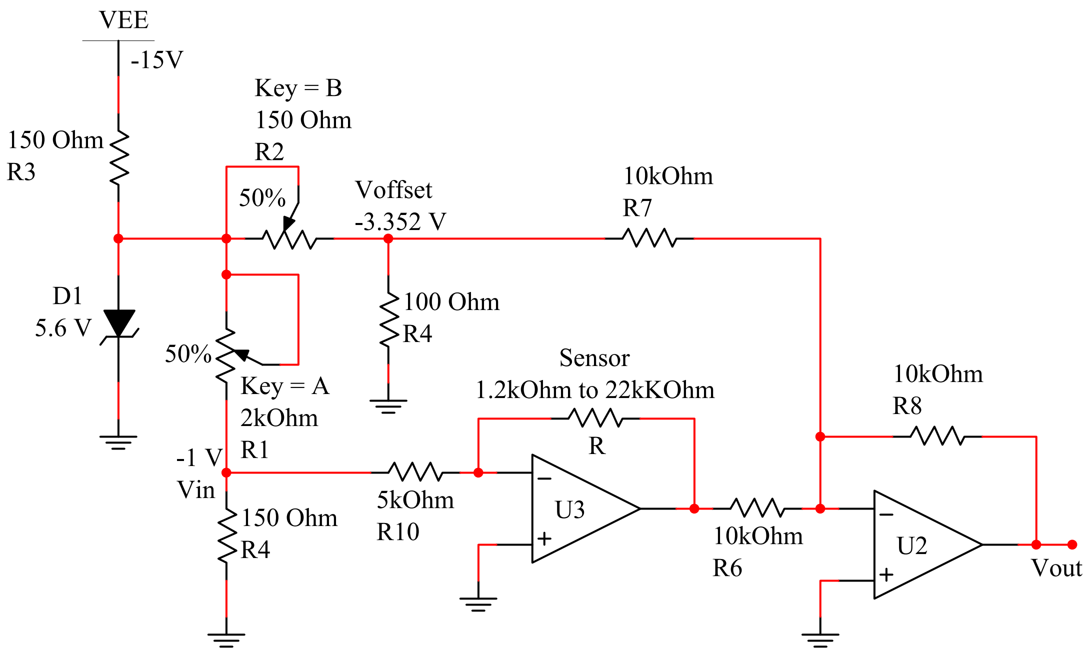
$$Vout = -2.89 \times 10^{-4} R + 3.352 \qquad (6)$$

Equation (6) can be implemented by using an inverting amplifier with R (sensor) in the op-amp feedback and a summing amplifier to provide the offset voltage. The current in the sensor resistor, R, must be kept below a limit so that the dissipation does not exceed 2.0 mW. This can be obtained by making the input resistance and fixed input voltage within certain limits since the current through the feedback resistor is the same as the current through the input resistor.

$$Pmax = 2.0mW = I^2\ Rmax$$

$$I^2 = 2.0\ mW/22000 = 9.09 \times 10^{-8} \rightarrow I = 0.3\ mA$$

Let's use an input current of 0.2 mA to be in the safe side. In the circuit below, the input divider voltage is - 1 V and the input resistor is 5 kΩ. Adjust R2 until Voffset = - 3.352 V and adjust R1 until Vin = - 1 V.



2.39 What change(s) would you to the above circuit if the sensor resistance varies from 18 kΩ to 0.8 kΩ as a variable changes from C_{min} to C_{max}. Design a signal-conditioning system that provides an output voltage varying from -2 to + 2 V as the variable changes from min to max. Power dissipation in the sensor must be kept below 3.0 mW.

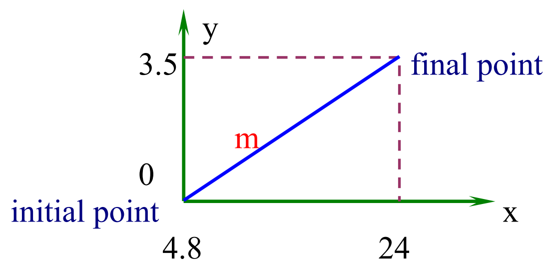
2.40 A pressure sensor outputs a voltage varying as 120 mV/psi and has a 2.0- KΩ output impedance. Develop signal conditioning to provide 0 to 3.5 V as the pressure varies from 40 to 200 psi.

Solution

As the pressure varies from 40 to 200 psi the sensor voltage will vary from (40 psi)(120 mV/psi) = 4.8 V to (200 psi)(120 mV/psi) = 24 V. The signal conditioning must convert this into 0 to 3.5 V.

The input voltage (4.8 V to + 24 V) is the independent variable while the output voltage (0 to 3.5 V) is the dependent variable.

By plotting the independent variable (x axis) and the dependent variable (y axis), we have:



Connect the intersection points, we find that the graph is a straight line, then:

$$y = mx + b \qquad (1)$$ **equation of the straight line.**

where:

$$m = \frac{y_1 - y_0}{x_1 - x_0} \qquad (2)$$ **slope of the straight line.**

Replace values in the slope of the straight line, we have:

$$m = \frac{24 - 4.8}{3.5 - 0} = 5.49$$

To find the value of the constant (b), in the equation of the straight line we replace the variables (x, y) for the coordinates of the initial point (4.8, 0) or the coordinates of the final point (24, 3.5), through this linear equation:

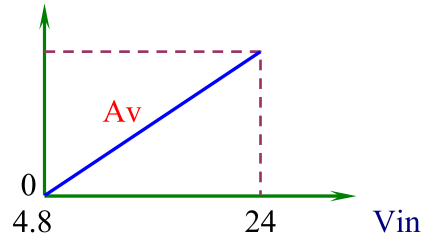
$y = mx + b$ **equation of the straight line**

Use coordinates of the initial point (4.8, 0) ➔ $0 = 5.49(4.8) + b$ ➔ **b = 26.35**

Replacing the variables and the constant of the linear equation for equivalent electronic terms we'll have:

y = Vout Vout
m = Av = 5.49 3.5

x = Vin
b = Voffset = 26.35



The constant of the equation can be called any name; in this case we'll call it Voffset.

Then: $\quad$ Vout = Av (Vin) + Voffset $\quad$ (4)

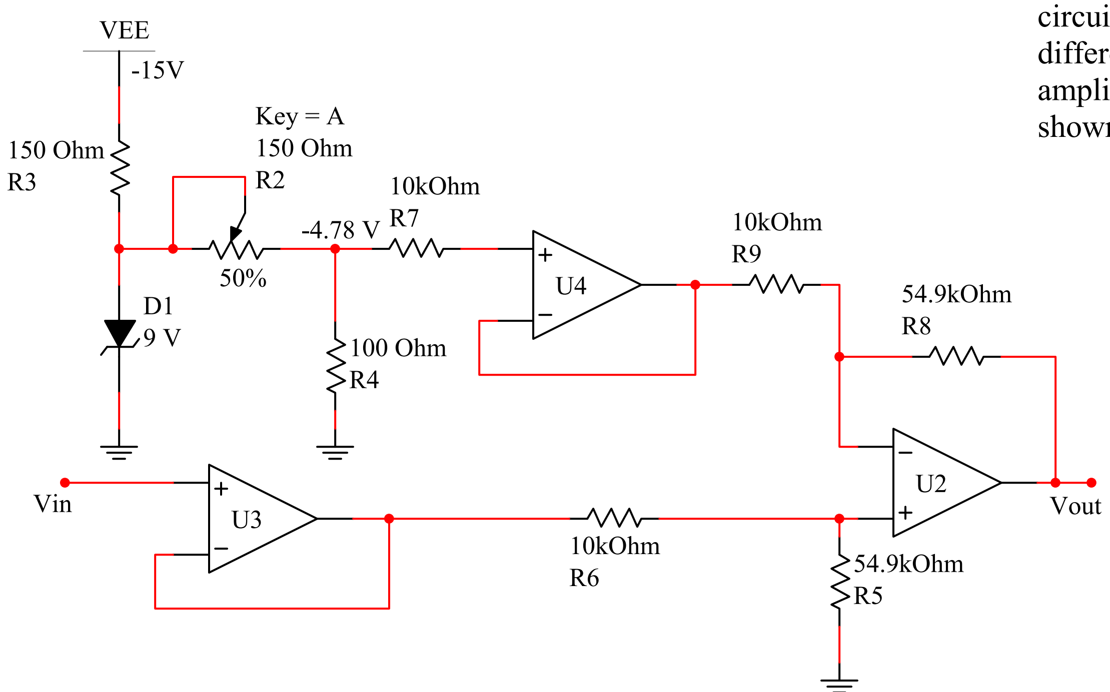
Replacing values in equation (4), we have:

Vout = Av(Vin) + Voffset $\quad$ (4)

Vout = 5.49 (Vin) + 26.25

Vout = 5.49 (Vin + 4.78) $\quad$ (5)

The respective circuit using a differential amplifier is shown below:



2.41 $\quad$ A pressure sensor outputs a voltage varying as 80 mV/psi and has a 1.0- KΩ output impedance. Design a signal conditioning circuit that provides 0 to 5 V as the pressure varies from 20 to 180 psi.

SAN JOSE STATE UNIVERSITY
Department of Aviation & Technology

Tech 167: Control Systems Dr. Julio R. Garcia

Digital Signal Conditioning

3.1 Convert the following binary numbers into decimal, octal, and hex:

a. 1011_2

b. 110101_2

c. 010101_2

Solution

The basic relations for conversions of binary are defined for a binary, $b_n b_{n-1} \ldots b_1 b_0$ where the b's are either a 1 or 0, then,

$$N_{10} = b_n 2^n + b_{n-1} 2^{n-1} + \ldots + b_1 2^1 + b_0 2^0$$

For octal we just arrange the binary number in three-bit groups starting from the decimal point and use the relations

$$111 = 7_8, \quad 110 = 6_8, \ldots\ldots\ldots, 001 = 1_8 \text{ and } 000 = 0_8$$

For hex we use groupings of four,

1000 = 8H	1001 = 9H	1010 = AH	1011 = BH
1100 = CH	1101 = DH	1110 = EH and	1111 = FH

so,

(a) $1011_2 = 2^3 + 2^1 + 2^0 = 8 + 2 + 1 = 11_{10}$

$1011_2 = 001 \;\; 011 = 13_8$

$1011_2 =$ BH

(b) $110101_2 = 2^5 + 2^4 + 2^2 + 2^0 = 32 + 16 + 4 + 1 = 53_{10}$

$110101_2 = 110\ \ 101 = 65_8$

$110101_2 = 0011\ \ 0101 = 35H$

(c) $010101_2 = 2^4 + 2^2 + 2^0 = 16 + 4 + 1 = 21_{10}$

$010101_2 = 010\ \ 101 = 25_8$

$010101_2 = 0001\ \ 0101 = 15H$

3.2 Convert the following binary numbers into decimal, octal, and hex:

a. 11011_2

b. 101001_2

c. 010011_2

3.3 Convert the following binary numbers into decimal, octal, and hex:

a. 1011010_2

b. 0.1001_2

c. 1101.0110_2

Solution

(a) $1011010_2 = 2^6 + 2^4 + 2^3 + 2^1 = 64 + 16 + 8 + 2 = 90_{10}$

$1011010_2 = 001\ \ 011\ \ 010 = 132_8$

$1011010_2 = 0101\ \ 1010 = 5AH$

(b) For this we must use the base 10 fractional to binary fractional relationship,

Given a binary fraction, $0.b_1b_2 \ldots b_n$ then

$$0.N_{10} = b_1 2^{-1} + b_2 2^{-2} + \ldots + b_n 2^{-n}$$

Octal and Hex fractional are found by the regular 3 and 4 groupings of bits. So,

$$0.\ 1001_2 \approx 2^{-1} + 2^{-4} = 0.5 + 0.0625 = 0.5625_{10}$$

$$0.\ 1001_2 = 0.100\ \ 100 = 0.44_8$$

$$0.\ 1001_2 = 0.9H$$

(c) 1101.0110_2 treating the whole and fractional parts separately,

$$1101 = 2^3 + 2^2 + 2^0 = 8 + 4 + 1 = 13_{10}$$

and $$0.0110 = 2^{-2} + 2^{-3} = 0.25 + 0.125 = 0.375_{10}$$

thus, $1101.0110 = 13.375_{10}$

$$1101.0110_2 = 001\ \ 101.011\ \ 000 = 15.3_8$$

$$1101.0110_2 = \text{D.6H}$$

3.4 Convert the following binary numbers into decimal, octal, and hex:

a. 1010101_2

b. 0.1101_2

c. 1011.0101_2

3.5 Convert the following decimal numbers into binary, octal, and hex:

a. 29_{10}

b. 530_{10}

c. 627_{10}

Solution

If we find binary first then the octal and hex can be found easily using the groupings of 3 and 4 bits

(a) 29/2 = 14 + Remainder = 1 so $b_0 = 1$

14/2 = 7 + Remainder = 0 so $b_1 = 0$

$7/2 = 3 + \text{Remainder} = 1$ so $b_2 = 1$

$3/2 = 1 + \text{Remainder} = 1$ so $b_3 = 1$

$1/2 = 0 + \text{Remainder} = 1$ so $b_4 = 1$

Therefore, $29_{10} = 11101_2$

and, $11101_2 = 011\ \ 101 = 35_8$

$11101_2 = 0001\ \ 1101 = 1DH$

(b) Lets do successive division by 8 instead of finding the octal first,

$530/8 = 66 + \text{Remainder} = 2$ so $d_0 = 2$

$66/8 = 8 + \text{Remainder} = 2$ so $d_1 = 2$

$8/8 = 1 + \text{Remainder} = 0$ so $d_2 = 0$

$1/8 = 0 + \text{Remainder} = 1$ so $d_3 = 1$

$530_{10} = 1022_8$

using binary groupings we see that,

$1022_8 = 001\ \ 000\ \ 010\ \ 010 = 10000010010_2$ and,

$10000010010_2 = 0100\ \ 0001\ \ 0010 = 412H$

(c) On this one let's successively divide by 16 to get the hex first,

$627/16 = 39 + \text{Remainder} = 3$ so $a_1 = 3_{10} = 3H$

$39/16 = 2 + \text{Remainder} = 7$ so $a_2 = 7_{10} = 7H$

$2/16 = 0 + \text{Remainder} = 2$ so $a_3 = 2_{10}$

$627_{10} = 273H$

Using groupings we get the binary and then the octal,

$273H = 001001110011 = 1001110011_2$

and $1001110011_2 = 001\ 001\ \ 110\ \ 011 = 1163_8$

3.6 Convert the following decimal numbers into binary, octal, and hex:

a. 56_{10}

b. 850_{10}

c. 1210_{10}

3.7 Find the 2s complement of

a. 1101_2

b. 10111101_2

Solution

(a) Complement of 1101 = 0010

$$\begin{array}{rr} \text{Complement of } 1101 = & 0010 \\ + & 1 \\ \hline \text{2's complement:} & 0011 \end{array}$$

(b) Complement of 10111101 = 01000010

$$\begin{array}{rr} \text{Complement of } 10111101 = & 01000010 \\ + & 1 \\ \hline \text{2's complement:} & 01000011 \end{array}$$

3.8 Find the 2s complement of

a. 10111_2

b. 11001001_2

3.9 Simplify the Boolean equation $AB + A(\overline{AB})$.

Solution

Let's assume that Y represents the output:

$$Y = AB + A(\overline{AB})$$

$$Y = AB + A(\overline{A} + \overline{B})$$

$$Y = AB + A\overline{A} + A\overline{B} \quad \text{but} \quad A\overline{A} = 0$$

$$Y = A(B + \overline{B}) \quad \text{but} \quad B + \overline{B} = 1$$

$$Y = A$$

3.10 Simplify the Boolean equation $AC + BC + C(\overline{AC})$

3.11 A process involves moving speed, load weight, and rate of loading in a conveyor system. The variables are provided as high (1) and low (0) levels for digital control. An alarm should be activated whenever any of the following conditions occur:

a. Speed is low; both weight and loading rate are high.

b. Speed is high; loading rate is low.

Find a Boolean equation describing the required alarm output. Let the variables be ***S*** for speed, ***W*** for weight, and ***R*** for loading rate.

Solution

(a) We have an alarm when speed (S) is low, weight (W) is high and loading rate (R) is high, so:

$$\bar{S}\,WR$$

(b) Speed is high and loading rate is low, $S \bullet \bar{R}$

The combination is OR'ed to give the Boolean equation,

$$Y = \bar{S}\,WR + S\bar{R}$$

3.12 A process involves moving speed, load weight, and rate of loading in a conveyor system. The variables are provided as high (1) and low (0) levels for digital control. An alarm should be activated whenever any of the following conditions occur:

a. Speed is high; both weight and loading rate are low.

b. Speed is low; loading rate is high.

Find a Boolean equation describing the required alarm output. Let the variables be ***S*** for speed, ***W*** for weight, and ***R*** for loading rate.

3.13 Implement Problem 3.11 with

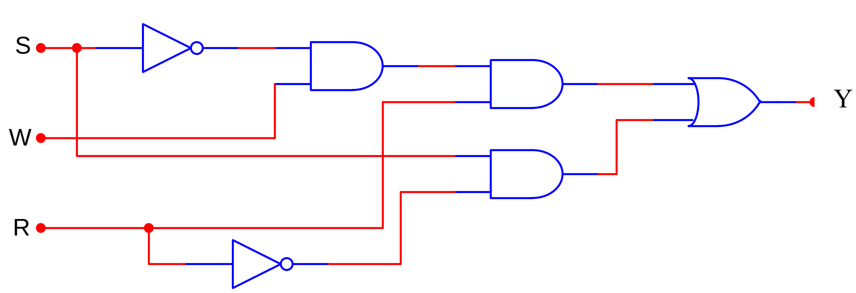
a. AND/OR logic and

b. NAND/NOR logic

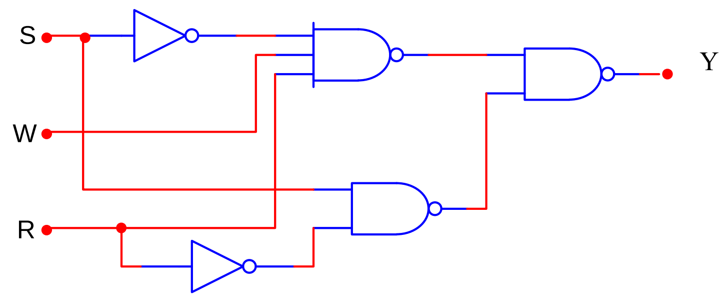
Solution

The equation $Y = \bar{S}\,WR + S\bar{R}$ is implemented as follows,

(a) AND/OR logic



(b) in NAND/NOR logic we have,



3.14 Implement Problem 3.12 with

a. AND/OR logic and

b. NAND/NOR logic

3.15 A tank shown in the Figure below (Figure 3.1) has the following Boolean variables: flow rates, QA, QB, and QC; pressure, P; and level, L. All are high if the variable is high and low otherwise. Devise Boolean equations for two alarm conditions as follows:

a. OV = overfill alarm

1. If either input flow rate is high while the output flow rate is low, the pressure is low and the level is high.
2. If both input flow rates are high while the output flow rate is low and the pressure is low.

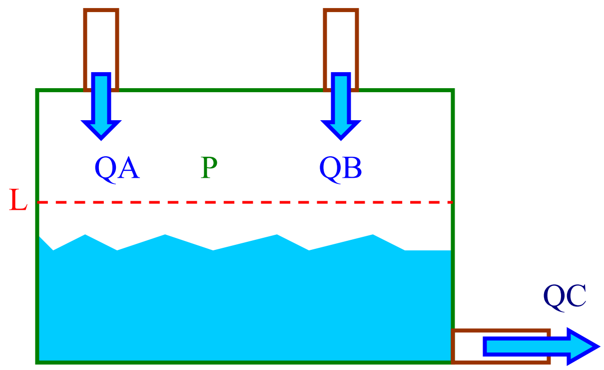


Figure 1

b. EP = empty alarm

1. If both input flow rates are low, the level is low and the output flow rate is high.
2. If either input flow rate is low, the output flow rate is high and the pressure is high.

Solution

We simply translate the statements directly into Boolean expressions

a. OV: 1. $(QA + QB)\,\overline{QC}\,L\,\overline{P}$

2. $QA\,QB\,\overline{QC}\,\overline{P}$

$$OV = (QA + QB)\,\overline{QC}\,L\,\overline{P} + QA\,QB\,\overline{QC}\,\overline{P}$$

b. EP: 1. $\overline{QA}\,\overline{QB}\,\overline{L}\,QC$

2. $(\overline{QA} + \overline{QB})\,QC\,P$

$$EP = \overline{QA}\,\overline{QB}\,L\,QC + (\overline{QA} + \overline{QB})\,QC\,P$$

3.16 A tank shown in the Figure above (Figure 1) has the following Boolean variables: flow rates, QA, QB, and QC; pressure, P; and level, L. All are low if the variable is high and high otherwise. Devise Boolean equations for two alarm conditions as follows:

a. OV = overfill alarm

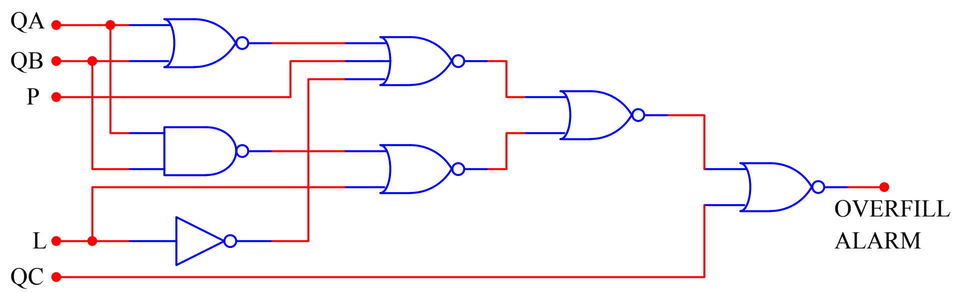
1. If either input flow rate is low while the output flow rate is high, the pressure is high and the level is high.
2. If both input flow rates are low while the output flow rate is high and the pressure is low.

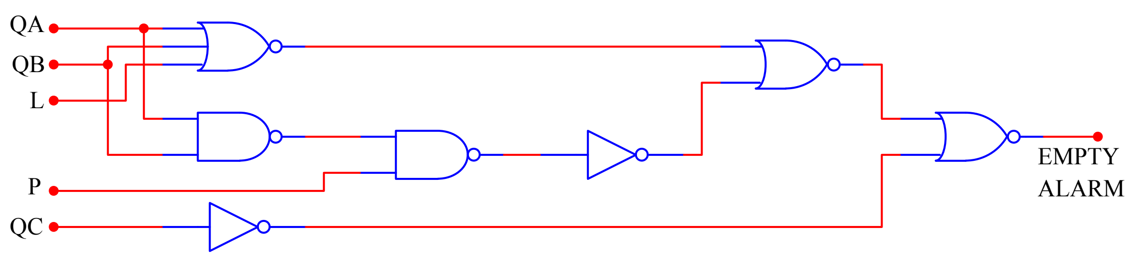
b. EP = empty alarm

1. If both input flow rates are high, the level is high and the output flow rate is low.
2. If either input flow rate is high, the output flow rate is low and the pressure is low.

3.17 Devise logic circuits using NAND/NOR logic that will provide the two alarms of problem 3.15.

The following logic circuits will provide the needed alarms.





3.18 Devise logic circuits using NAND/NOR logic that will provide the two alarms of problem 3.16.

3.19 A sensor provides temperature data as 430 μV/°C. Develop a comparator circuit that goes high when the temperature reaches 620°C.

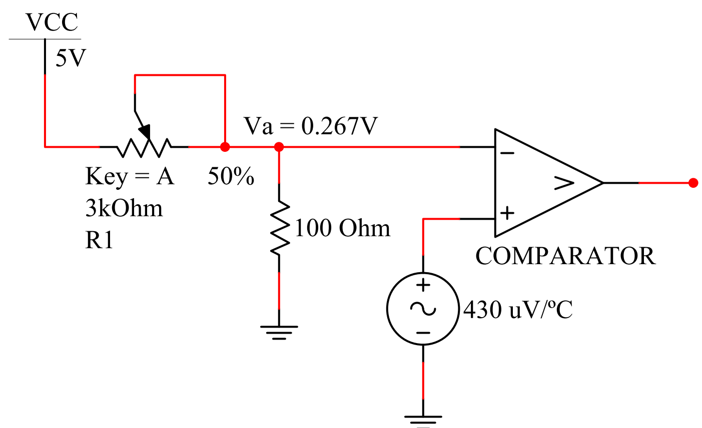
Solution

If a transfer function is 430 uV/ºC then a temperature of 620 ºC will result in an output voltage of,

$$V = (430 \times 10^{-6}\ \text{V/ºC})(620\ \text{ºC})$$

$$V = 0.2666 \text{ volts or } 0.267 \text{ to three significant figures.}$$

We can construct a divider from a + 5 volt supply to obtain this required alarm voltage for the comparator. One possible circuit then is shown below. Adjust R1 until Va = 0.267 V.



3.20 What change(s) would you do to the circuit shown above if the sensor provides temperature data as 560 μV/°C and the comparator circuit should go high when the temperature reaches 965°C.

3.21 An 8-bit DAC has an input of 10100101_2 and uses an 8.0-V reference.

a. Find the output voltage produced.

b. Specify the conversion resolution.

Solution

For the 8-bit DAC with a 10100101_2 input and an 8.0 V reference,

(a) The output is given by,

$$Vout = V_{ref}\,(b_0\, 2^{-1} + b_0\, 2^{-2} + b_0\, 2^{-3} + \ldots\ldots\ldots\ b_0\, 2^{-8} +)$$

$$Vout = 8(2^{-1} + 2^{-3} + 2^{-6} + 2^{-8})$$

$$= 5.156\text{V}$$

(b) The resolution is $\Delta V = V_{ref}2^{-n}$ so

$$\Delta V = (8)(2^{-8})$$

$$= 0.031\ \text{V}$$

3.22 A 10-bit DAC has an input of 1011100101_2 and uses a 6.0-V reference.

a. Find the output voltage produced.

b. Specify the conversion resolution.

3.23 A 6-bit DAC must have a 10.00-V output when all inputs are high. Find the required reference.

Solution

We have $V_{max} = V_{ref}(2^{-1} + 2^{-2} + 2^{-3} + 2^{-4} + 2^{-5} + 2^{-6})$

$10 = V_{ref}(0.5 + 0.25 + 0.125 + 0.1625 + 0.031 + 0.016)$

$10 = Vref\,(1.085)$

Thus, $Vref = 10/1.085 = 9.217$ V

3.24 An 8-bit DAC must have a 12.00-V output when all inputs are high. Find the required reference.

3.25 A 10-bit ADC with a 12.0-V reference has an input of 4.869 V. (a) Find the digital output word. (b) What range of input voltages would produce this same output? (c) Suppose the output of the ADC is 1110110111_2. What is the input voltage?

Solution

(a) The ratio of input to reference is, (4.869/12) = 0.406

This fraction of the total counting states will provide the output as,

$$(0.406)(2^{10}) = 415.744$$

but since the output is the integer part only it will be just 415, so

$$415 \approx 19FH \text{ or } 0110011111_2$$

(b) This same output would be produced by input voltages which range from,

$$12(415/1024) = 4.863 \text{ V to } 12(416/1024) = 4.875 \text{ V}$$

(c) An output of $1110110111_2 = 951_{10}$ so the input is at least 12(951/1024) = 11.145 volts but could be as high as 12(952/1024) = 11.156 volts.

3.26 An 8-bit ADC with a 10.0-V reference has an input of 3.453 V. (a) Find the digital output word. (b) What range of input voltages would produce this same output? (c) Suppose the output of the ADC is 11011001_2. What is the input voltage?

3.27 An ADC that will encode pressure data is required. The input signal is 548.4 mV/psi.

a. If a resolution of 0.4 psi is required, find the number of bits necessary for the ADC. The reference is 8.0 V.

b. Find the maximum measurable pressure.

Solution

The pressure transducer converts pressure to voltage at 548.4 mV/psi or 0.5484 V/psi.

(a) We need a resolution of 0.4 psi with an 8.0 volt reference. This means a voltage resolution of (0.4 psi)(548.4 mV/psi) = 219.4 mV. So,

$$\Delta V = .2194\ V = V_{ref}2^{-n} = (8)2^{-n}$$

$$.2194/8 = 2^{-n}$$

$$0.027 = 2^{-n}$$

Taking logarithms,

$$\log(0.027) = -\ n \log(2)$$

$$-1.569 = -\ 0.30303n$$

$$n = 5.178$$

So, we must use a 6-bit ADC.

(b) The maximum measurable pressure occurs when the output is 111111_2, so we can use

$$V_{max} = V_{ref}(2^{n-1}/2^n),$$

$$V_{max} = 8(63/64) = 7.875 \text{ volts for a pressure of,}$$

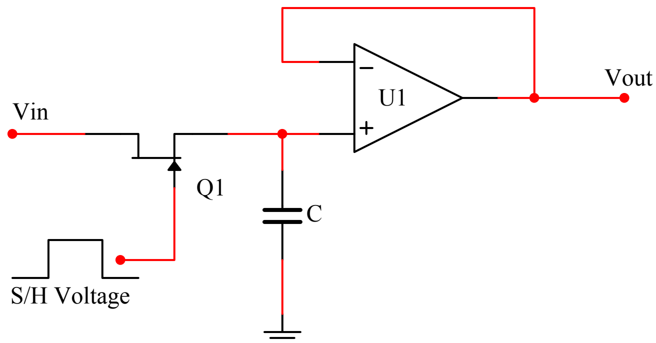
$$P_{max} = (7.875V)/(0.5484 \text{ V/psi}) = 14.36 \text{ psi}$$

3.28 An ADC that will encode pressure data is required. The input signal is 635.8 mV/psi.

a. If a resolution of 0.5 psi is required, find the number of bits necessary for the ADC. The reference is 10.0 V.

b. Find the maximum measurable pressure.

3.29 A sample-and-hold circuit like the one shown below has C = 0.56 μF, and the ON resistance of the FET is 50 Ω. (a) For what signal frequency is the sampling capacitor voltage down 3 dB from the signal voltage? (b) How does this limit the application of the sample hold?



Solution

(a) A model of the "ON" FET and capacitor shows that the system acts like a low-pass filter of R = 50 Ω and C = 0.56 μF. The voltage appearing across the capacitor is down 3 dB at the critical frequency of the filter, $f_c = \frac{1}{2\pi RC}$, so,

$$fc = \frac{1}{2\pi(50)(0.56 \text{ x } 10^{-6})} = 5684 \text{ Hz}$$

(b) The limitation is the fact that the system cannot be used to sample signals with a frequency greater than about 5.684 kHz due of attenuation.

3.30 A sample-and-hold circuit like the one shown above has C = 0.068 μF, and the ON resistance of the FET is 60 Ω. For what signal frequency is the sampling capacitor voltage down 3 dB from the signal voltage?

3.31 A S/H and ADC combination has a throughput expressed as 50,000 samples per second. Explain the consequences of using this system to take samples every 5 ms.

Solution

A throughput of 50,000 samples per second means that there must be at least (1/50,000) = 20 μs between samples. If samples are taken every 5 ms = 5000 μs then the time available for signal processing between samples is 5000 μs - 20 μs = 4980 μs.

3.32 A S/H and ADC combination has a throughput expressed as 40,000 samples per second. Explain the consequences of using this system to take samples every 2 ms.

3.33 A data-acquisition system has ten input channels to be sampled continuously and sequentially. The multiplexer can select and settle on a channel in 4.2 μs, the ADC converts in 29 μs, and the computer processes a single channel of data in 325 μs. What is the minimum time between samples for a particular channel?

Solution

The total time for selecting, inputting and processing one channel is,

$$t = (4.2 + 29 + 325)\ \mu s = 358.2\ \mu s$$

Therefore the total time for all 10 channels is,

$$T = 10t = 10(358.2\ \mu s) = 3582 \mu s$$

This is the minimum time between samples of a particular channel.

3.34 A data-acquisition system has twelve input channels to be sampled continuously and sequentially. The multiplexer can select and settle on a channel in 3.1 μs, the ADC converts in 18 μs, and the computer processes a single channel of data in 265 μs. What is the minimum time between samples for a particular channel?

3.35 A 10-bit ADC has a 12.0-V reference.

a. Find the output for inputs of 4.3 V and 8.2 V.

b. What range of inputs could have caused the output to become A5H?

Solution

Given a 10-bit ADC with a 12.0 volt reference.

(a) For an input of 4.3 volts we find the output as,

$$N_{10} = \frac{V_{in}}{V_{ref}}(2^n) = \frac{4.3}{12}(2^{10}) = 366.933 \approx 366 \approx 16EH$$

For an input of 8.2 volts the output is;

$$N_{10} = \frac{V_{in}}{V_{ref}}(2^n) = \frac{8.2}{12}(2^{10}) = 699.733 \approx 699 \approx 2BBH$$

(b) For A5H we first find that A5H = 165_{10} Then,

$$Vin = \frac{V_{ref}(\text{Input in decimal})}{2^n}$$

$$Vin = \frac{(12)(165)}{2^{10}} = \frac{(12)(165)}{1024} = 1.934\text{ V}$$

But the output will stay A5H until the input changes by the voltage of one LSB,

$AV = \frac{V_{ref}}{2^n} = \frac{12}{2^{10}} = 0.012\text{V}$, so the range is 1.934 V to (1.934 + 0.012) = 1.946 V.

3.36 A 12-bit ADC has a 10.0-V reference.

a. Find the output for inputs of 3.8 V and 6.8 V.

b. What range of inputs could have caused the output to become B8H?

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TECH 167: Control Systems   Dr. Julio R. Garcia

Thermal Sensors

1. (a) What is a sensor?

A sensor is a transducer that converts a physical variable such as pressure, temperature, flow, etc., into an analog quantity (voltage or current) or in resistance.

(b) Provide an example of a temperature sensor:_______________________________

2. Describe an RTD and a thermistor.

RTD (Resistance-temperature detector): variation of metal resistance with temperature.

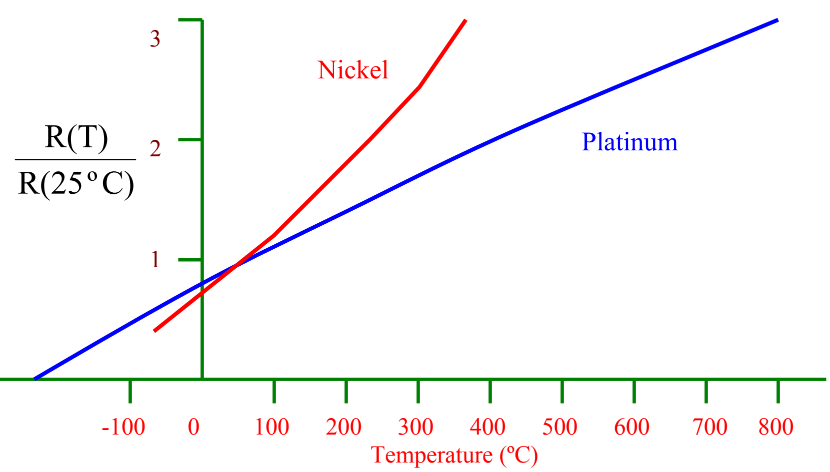
Thermistor: variation of semiconductor resistance with temperature. Two types:

NTC (Negative Coefficient Temperature): Resistance decreases when temperature increases

PTC (Positive Coefficient Temperature): Resistance increases when temperature increases.

3. Provide two types of NTC thermistors and type of PTC thermistor.

4. See the following Figure and answer the following questions:



a) Are the two curves nearly linear? →Yes.

b) Which metal has a better linear response with temperature? → Platinum.

5. An RTD has α (25 °C) = 0.006/°C. If R= 108 Ω at 25°C, find the resistance at 35°C.

   Solution

   The equation to be used is: $R(T) = R(T_0)[1 + \alpha_0(T-T_0)]$

   Where

   $R(T)$ is the approximation of resistance at temperature T

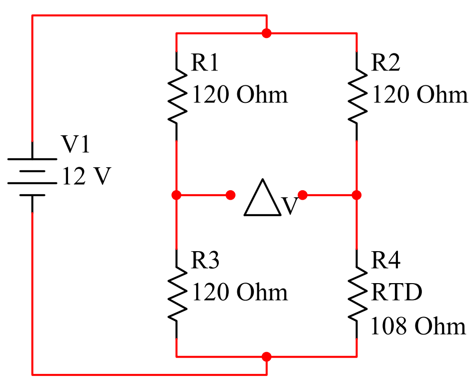
   $R(T_0)$ is the resistance at temperature T_0

   α_0 is the fractional change in resistance per degree of temperature at T_0

   Therefore: R(35°C) = 108[1 + 0.006(35 - 25)] = 114.48 Ω

6. If α (25 °C) = 0.005/°C and R = 112 Ω at 25°C, Find the resistance at 20 °C:______________ and at 30 °:______________________________

7. The RTD of question 5 is used in the bridge circuit shown below. Calculate the voltage the detector must be able to resolve in order to resolve a 1.0°C change in temperature.



Solution

Note that the bridge is not nulled at 25°C since the RTD is 108 Ω at that temperature, not 120 Ω. We find the off-null voltage at 25 °C and then the voltage at 26 °C. The difference will be the required detector resolution for a 1°C change.

We use the equation: $$\Delta V = V\left(\frac{R3}{R1+R3} - \frac{R4}{R2+R4}\right)$$

$$\Delta V(25) = V\left(\frac{12}{120+120} - \frac{108}{120+108}\right) = 0.316\ V$$

The RTD resistance at 26 °C is,

$R(26\ °C) = 108[1 + 0.006(26 - 25)] = 108.648\ \Omega$

So the off-null voltage is,

$\Delta V = 12[120/240 - 108.648/228.648] = 0.298$ V.

Thus the difference, which is the required resolution, is

$V_{Res} = 0.316\ V - 0.298\ V = -\ 0.018\ V$ or - 18 mV

8. If in problem 7, we need to resolve a 1.5°C change in temperature calculate the voltage the detector must be able to resolve.

9. Use the values of RTD resistance versus temperature shown in the table to find the equations for the linear approximation of resistance between 95°C and 125°C. Assume $T_0 = 110$ °C.

T(ºC)	R(Ohm)
90.0	553.45
95.0	569.63
100.0	574.70
105.0	579.82
110.0	585.31
115.0	590.16
120.0	595.42
125.0	603.21
130.0	606.81

Solution

We use the following equation:

$$\alpha_0 = [1/ R(T_0)]\ [(R_2-R_1)/(T_2-T_1)]$$

Where:

R_2 is the resistance at temperature T_2.

R_1 is the resistance at temperature T_1.

here, $T_0 = 110$°C, $T_1 = 95$ °C, $T_2 = 125$ °C and the corresponding resistances (from the table) are,

$R_0 = 585.31\ \Omega$, $R1 = 569.63\ \Omega$ and $R2 = 603.21\ \Omega$ so,

$\alpha_0 = (1/585.31)[(603.21 - 569.63)/(125 - 95)] = .001912$

$\alpha_0 = 0.0019$ /°C

Thus, the equation for the linear approximation of resistance between 95°C and 125°C is:

$$R(T) = 585.31\ [1 +0.0019(T - 110)]$$

10. Find the equations for the linear approximation of resistance between 90°C and 130°C. Assume T_0 = 110 °C.

11. Suppose the RTD of Problem 5 has a dissipation constant (P_D) of 30 mW/°C and is used in a circuit that puts 10 mA through the sensor. If the RTD is placed in a bath at 120°C, (a) what resistance will the RTD have? (b) What then is the indicated temperature?

Solution

(a) In a bath at a temperature of 120°C the resistance of the RTD should be,

$R(120°C) = 108[1 + 0.006(120 - 25)] = 169.56\ \Omega$

However, if there are 10 mA through the sensor then the self heating will cause a temperature rise from the power dissipation. The power dissipated is,

$P = I^2R = (0.01)^2(169.56) = 0.017$ W = 17 mW

Thus the temperature rise will be,

$\Delta T = P/P_D$ = 17 mW/30 mW/°C = 0.567 °C

So the resistance will be,

$R(120.567\ °C) = 108[1 + 0.006(120.567 - 25)] =$ **169.927 Ω**

(b) If you didn't know about the self-heating temperature rise you would think the temperature was 120.0°C. The temperature is actually 120°C + 0.567 °C = **120.567 °C**.

12. If in problem 11 the dissipation constant (P_D) is 20 mW/°C, the current through the sensor is 15 mA and the RTD is placed in a bath at 130°C, (a) what resistance will the RTD have? (b)What then is the indicated temperature?

13. Using an RTD with α = 0.0045/°C and R = 110 Ω at 20 °C, design a bridge and op amp system to provide a 0.0- to 12.0-V output for a 20 °C to 130 °C temperature variation.

Solution

First we find the resistance of the RTD at the two temperature extremes,

R(20 °C) = 110 Ω (given)

R(130 °C) = 110[1 + .0045(130 - 20)] = 164.45 Ω

If we use this in a bridge with all arms at 110 Ω then it will null at 20 °C, which is good.

The equation to be used is:

$$\Delta V = \frac{VR_3}{R_1 + R_3} - \frac{VR_4}{R_2 + R_4}$$

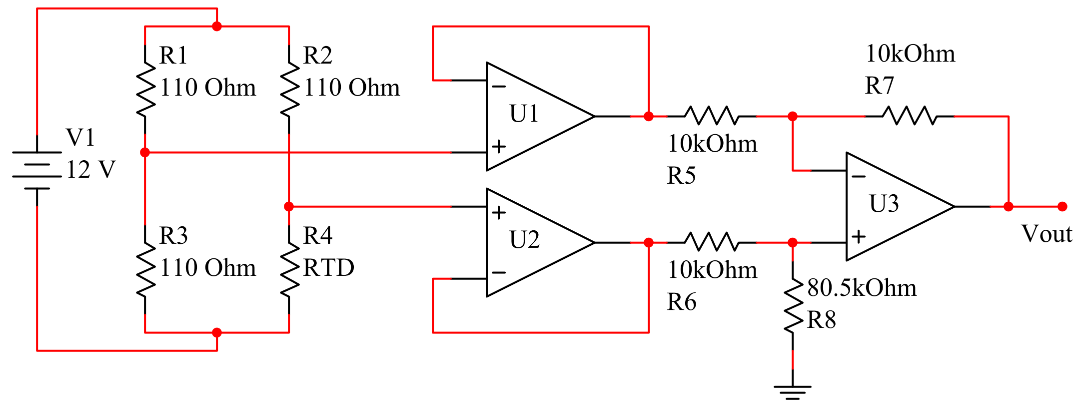
Assuming a 15 volt bridge excitation voltage, we find the off-null voltage at 130 °C as,

$$\Delta V = 15\left(\frac{110}{110+110} - \frac{164.45}{110+164.45}\right) = -\,1.49\text{ V}$$

So, to get the required output of 12 volts we need a gain of,

Av = 12/1.49 = 8.05

The following circuit will provide this result.



14. If α = 0.0035/°C and R = 120 Ω at 25 °C, design a bridge and op amp system to provide a 0.0- to 10.0-V output for a 25 °C to 125 °C temperature variation.

15. A calibrated RTD with $\alpha = 0.0056/°C$, $R = 295.8\ \Omega$ at 20°C, and $P_D = 25$ mW/°C will be used to measure a critical reaction temperature. Temperature must be measured between 40 and 120°C with a resolution of 0.1 °C. Devise a signal conditioning system that will provide an appropriate digital output to a computer.

Solution

From the conditions of the problem, 40 to 120 °C is a span of 80 °C and a resolution of 0.1°C means 80/0.1 = 800 increments. A 9-bit computer provides only 512 but a 10-bit provides 1024, so we must use a 10-bit ADC, unipolar and with a 5.000 V reference. A 10-bit ADC is common so we are in good shape.

The expected resistance variation will be,

$$R_{40} = 295.8\,[1 + 0.0056\,(40 - 20)] = 328.9\ \Omega$$

$$R_{120} = 295.8\,[1 + 0.0056\,(120 - 20)] = 461.5\ \Omega$$

Let's use a bridge for the RTD (although an op amp circuit could be used). We must keep the self-heating below 0.01°C to maintain the 0.1°C resolution. Thus, $P/P_D = 0.01°C$, and

$$P = P_D(0.01) = (25\text{ mW})(0.01) = 0.25\text{ mW}.$$

At the maximum temperature, 120 °C, R = 461.5 Ω; thus,

$$P = I^2 R \ \rightarrow I = \sqrt{P/R} = \sqrt{0.00025/461.5} = 0.74\text{ mA}$$

Thus the bridge voltage across the RTD should be about, Vamax = (461.5 Ω)(0.74 mA) ≈ 0.34 volts. We design so that Va = 0.34 volts at 40°C, which means Vb will be 0.34 volts also so that the output is AV = 0 volts. This is shown in the schematic below for the bridge.

At 40 °C, RTD = 328.9 Ω.

$$\text{Va} = \frac{\text{RTD}}{\text{RTD} + \text{R1}}\text{V} = 0.34\text{V} \rightarrow \frac{328.9}{328.9 + \text{R1}}5\text{V} = 0.34\text{V} \rightarrow \text{R1} = 4.502\text{ k}\Omega.$$

Assuming R4 = 1 kΩ,

$$\text{Vb} = \frac{\text{R4}}{\text{R2} + \text{R4}}\text{V} = 0.34\text{V} \rightarrow \frac{1\text{k}}{\text{R2} + 1\text{k}}5\text{V} = 0.34\text{V} \rightarrow \text{R2} = 13.8\text{ k}\Omega.$$

Now, at 120 °C we will have a bridge offset voltage of,

$$\Delta V = \text{Va} - \text{Vb} = 5(461.5)/(461.5 + 4502) - 0.34 = 0.125\text{ V}$$

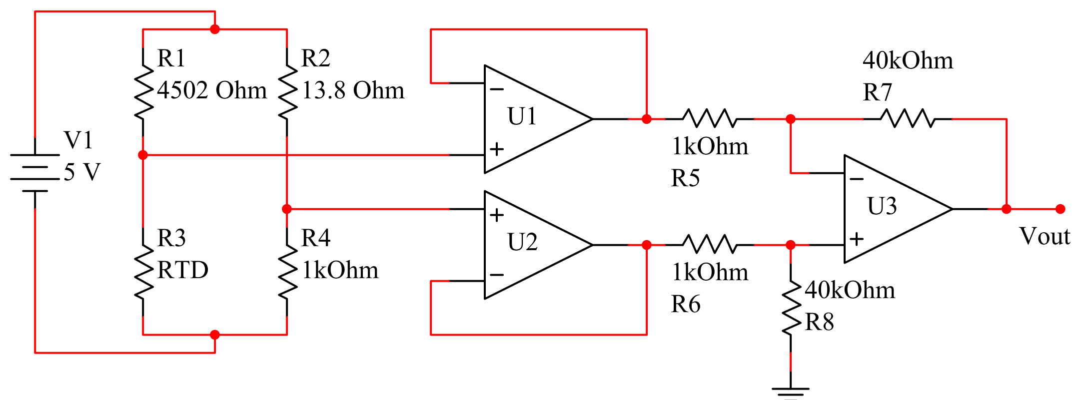
Since the input to the ADC needs to be, 5.000 - 5.000/2^{10} ≈ 5.000 V, thus an amplifier with a gain of = 5.000/0.125 = 40 is required. The whole equation is,

$$Vout = Av\ (Va - Vb)$$

$$Va = \frac{RTD}{RTD + R1} V = \frac{5RTD}{RTD + 4502} \text{ and } Vb = 0.34 \text{ V, so}$$

$$Vout = 40\left[\frac{5RTD}{RTD + 4502} - 0.34\right]$$

And the circuit is given below.



16. If in Problem 15 the temperature must be measured between 50 and 150°C with a resolution of 0.1 °C; what change(s) would you do?

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Optical Sensors

- Sensors should have negligible effect on the measured environment (the process).
- Example: Heat developed by an RTD can alter the environmental temperature.
- Electromagnetic (EM) radiation allows that transducers do not affect the process-variable measurements. No physical contact is made.
- In process control, EM radiation in either the visible or infrared band is frequently used in measurement applications.
- The techniques of such applications are called ***optical*** because such radiation is close to visible light.
- Fundamentals of EM Radiation
- EM radiation is a form of energy that is always in motion, that is, it propagates through space.
- An object that releases or ***emits*** such radiation ***loses*** energy.
- An object that ***absorbs*** radiation ***gains*** energy

Frequency and Wavelength

- **Frequency**: oscillations per second.
- **Wavelength**: spatial distance between two successive maxima or minima of the wave in the direction of propagation.
- **Speed of Propagation**: EM radiation propagates through a vacuum at a constant speed independent of both the wavelength and frequency.

$c = \lambda f$
$c = 3 \times 10^8$ m/s (speed of EM radiation in a vacuum)
λ = wavelength in meters
f = frequency in Hz or cycles/sec (S^{-1})

1. Determine the wavelength for an EM radiation frequency of 500 kHz.

Solution

$$c = \lambda f \Rightarrow \lambda = \frac{c}{f} = \frac{3\,(10^8\,\text{m/s})}{5\,(10^5\,\text{s}^{-1})} = 600\text{ m.}$$

2. If the wavelength is 250 m determine the radiation frequency.

- When such radiation moves through a nonvacuum environment, the propagation velocity is reduced to a value less than c.
- The new velocity is indicated by the **index of refraction** (n)

$$n = c/v$$

v = velocity of EM radiation in the material (m/s)

3. A certain material has an index of refraction of n = 1.26. Find the velocity of EM radiation in this material.

Solution

$$n = \frac{c}{v} \Rightarrow v = \frac{c}{n} = \frac{3\,(10^8\,\text{m/s})}{1.26} = 2.38 \times 10^8 \text{ m/s}$$

4. A certain material has a velocity of EM radiation of 1.46×10^7 m/s. Find the index of refraction in this material.

5. A certain source of light has a frequency of 4.0×10^{12} Hz. What is its wavelength in nm, um, and Å?

Solution

$$c = \lambda f \Rightarrow \lambda = \frac{c}{f} = \frac{3\,(10^8\,\text{m/s})}{4\,(10^{12}\,\text{s}^{-1})} = 75\ \mu\text{m} = 75{,}000 \text{ nm} = 750{,}000\text{Å}$$

$1 \text{ Å} = 10^{-10}$ m

Wavelength Units

Angstrom (Å) = 10^{-10} m or 10^{-10} m/Å

6. A certain source of light has a frequency of 2.8×10^{12} Hz. What is its wavelength in Å, um, and nm?

Characteristics of Light

- **Photon**: EM radiation at a particular frequency can propagate only in *discrete* quantities of energy.
- These discrete units or *quanta* are called photons.

$Wp = hf = hc/\lambda$ Wp = photon energy (J)

$h = 6.63 \times 10^{-34}$ J-s   (Planck's constant)

The energy of one photon is very small compared to electron energy.

7. A microwave source emits a pulse of radiation at 1.3 GHz with a total energy of 0.8 J. Determine:

   a) The energy per photon.

   Solution $Wp = hf = (6.63 \times 10^{-34} \text{ J-s})(1.3 \times 10^{9} \text{ s}^{-1}) = 8.62 \times 10^{-25} \text{ J}$

   b) The number of photons in the pulse.

   Solution $N = \dfrac{W}{Wp} = \dfrac{0.8\text{J}}{(8.62)(10^{-25}\text{ J/photon})} = 9.28 \times 10^{23}$ photons

8. A microwave source emits a pulse of radiation at 3.1 GHz with a total energy of 1.2 J. Determine (a) the energy per photon and (b) the number of photons in the pulse.

Intensity

I = P/A

I = Intensity in W/m^2

P = Power in W

A = Beam cross-sectional area in m^2.

Intensity is better expressed in mW/cm^2

Divergence

- Radiation travels in straight lines.
- Intensity of the light may change even though the power remains constant.

9. Calculate the intensity of a 12-watt source whose radius is 0.04 m at (a) the source in W/m^2 and mW/cm^2 and (b) 1.3 meters away if the divergence is 1.8º.

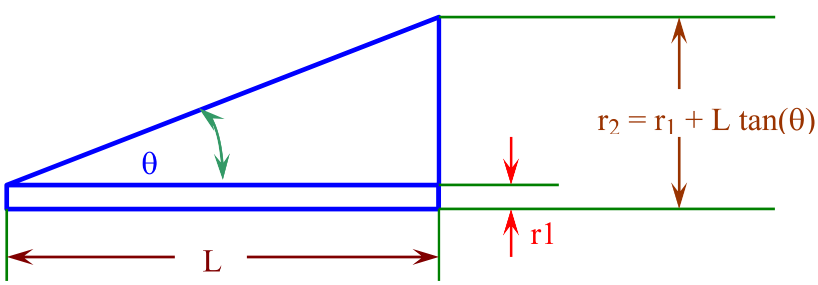
Solution

a) At the source in W/m^2 and mW/cm^2.

$$I = \frac{P}{A_1} = \frac{12W}{\pi\, r_1^2} = \frac{12W}{\pi\,(0.04m)^2} = 2388.5\ W/m^2$$

$$2388.5\ \frac{W}{m^2}\ \frac{1{,}000mW}{W}\ \frac{m^2}{10{,}000cm^2} = 238.85\ mW/cm^2$$

b) 1.3 meters away if the divergence is 1.8º.



R2 = 0.04 m + (1.3 m)(tan 1.8°) = 0.0808 m.

$$I = \frac{P}{A^2} = \frac{12W}{\pi\, r_2^2} = \frac{12W}{\pi\,(0.0808m)^2} = 585.071\ W/m^2$$

10. Calculate the intensity of a 20-watt source whose radius is 0.05 m (a) at the source in W/m^2 and mW/cm^2 and (b) 2.1 meters away if the divergence is 2.4º.

Photodetectors

- In most process-control-related applications, the radiation lies in the range from IR through visible and sometimes UV bands.
- The measurement sensors are called *photodetectors*
- Four types of photodetectors:

  –Photoconductive

  –Photovoltaic

  –Photoemissive

  –Photodiode

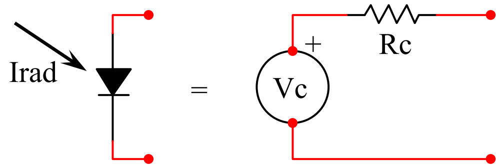
Photoconductive Detectors

- Also called photo resistive cells
- Resistance changes with light intensity
- As intensity increases, the semiconductor resistance decreases, making the resistance an inverse function of radiation intensity.

Photovoltaic Detectors

- They generate a voltage that is proportional to incident EM radiation intensity
- They convert the EM energy into electrical energy

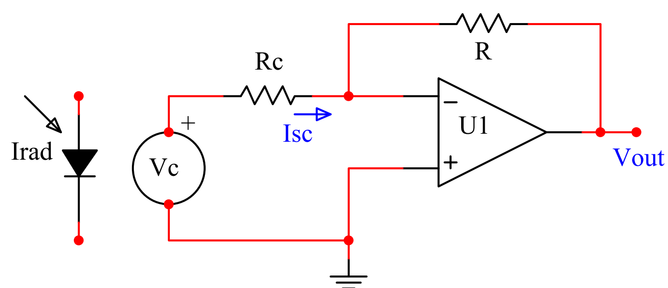
Equiv Circuit for a photovoltaic cell



- Photovoltaic cells have a range of spectral response within which a voltage will be produced
- Vc varies with light intensity in an approximately logarithmic fashion
- The internal resistance of the cell also varies with light intensity. This complicates the design of systems to derive maximum power from the cell, since R_L optimum = Rc.

Signal Conditioning

Error!



- ISC (short-circuit current) can be obtained by connecting the cell directly to an op-amp.
- Since the current is linearly proportional to light intensity, so is the output voltage

11. A CdS cell has a dark resistance of 120 kΩ and a resistance in a light beam of 25 kΩ. The cell time constant is 60 ms. Design a system to trigger a 2-volt comparator within 6 ms of the beam interruption.

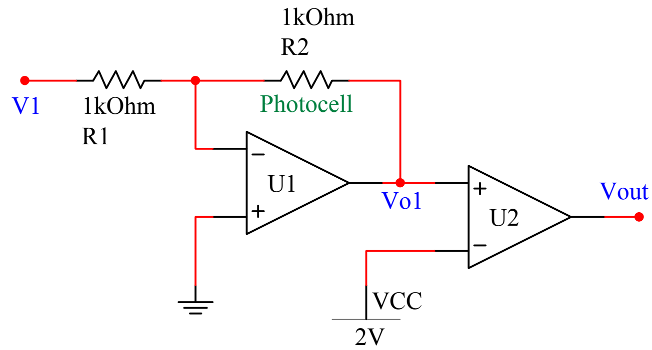
Solution

The equation to be used is:

$$R(t) = Ri + (Rf - Ri)[1 - e^{-t/\tau}]$$

$$R\,(6\text{ ms}) = 25\text{ K}\Omega + (120 - 25)\text{ K}\Omega\,[1 - e^{-6/60}] = 34.04\text{ K}\Omega$$

This means that at 6 ms, the CdS's resistance is 34.04 KΩ. The circuit that can be used is:



$$Vo1 = 2\ V = \frac{-R2}{R1} V1 \qquad\qquad +2\ V = \frac{-34.04\ K}{R1} V1$$

Assume V1 and determine R1.

Example, If V1 = -1 V, then $R1 = \dfrac{(-34.04\ K)(-1\ V)}{2V} = 17.02\ K\Omega$

12. A CdS cell has a dark resistance of 150 kΩ and a resistance in a light beam of 20 kΩ. The cell time constant is 50 ms. Design a system to trigger a 1.2-volt comparator within 4 ms of the beam interruption.

13. A photovoltaic cell is to be used with radiation of intensity from 4 to 15 mW/cm^2. Measurements show that its unloaded output voltage ranges from 0.15 to 0.45 volts over this intensity while it delivers current from 0.4 to 1.9 mA into an 80 Ω load. (a) Determine the range of short-circuit current. (b) Develop signal conditioning to provide a linear voltage from 0.3 to 1.5 V as the intensity varies from 4 to 15 mW/cm^2.

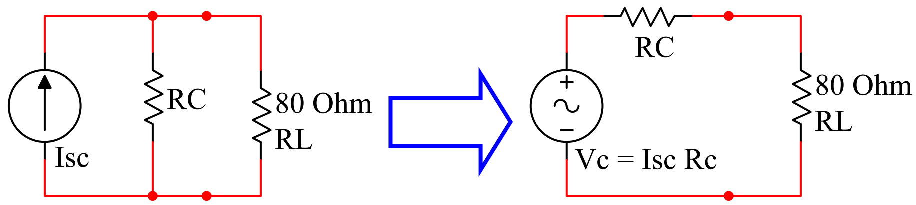
Solution

a) Determine the range of short-circuit current.

Intensity = 4 to 15 mW/cm^2

Vc (no load) = 0.15 to 0.45 V

I = 0.4 to 1.9 mA



$$I_L = \frac{Vc}{Rc + 80}$$

$$Rc\ I_L + 80\ I_L = Vc \longrightarrow Rc = \frac{Vc - 80\ I_L}{I_L}$$

At 4 mW/cm^2, $Vc = 0.15$ V & $I_L = 0.4$ mA

$$Rc = \frac{0.15 - 80(0.4\text{mA})}{0.4\text{mA}} = 295\ \Omega$$

At 15 mW/cm^2, $Vc = 0.45$ V & $I_L = 1.9$ mA

$$Rc = \frac{0.45 - 80(1.9\text{mA})}{1.9\text{mA}} = 157\ \Omega$$

The short-circuit current (Isc) is given by $Isc = \dfrac{Vc}{Rc}$

At 4 mW/cm^2, $Vc = 0.15$ V & $Rc = 295\ \Omega$

$$Isc = \frac{Vc}{Rc} = \frac{0.15\text{ V}}{295\ \Omega} = 0.51\text{ mA}$$

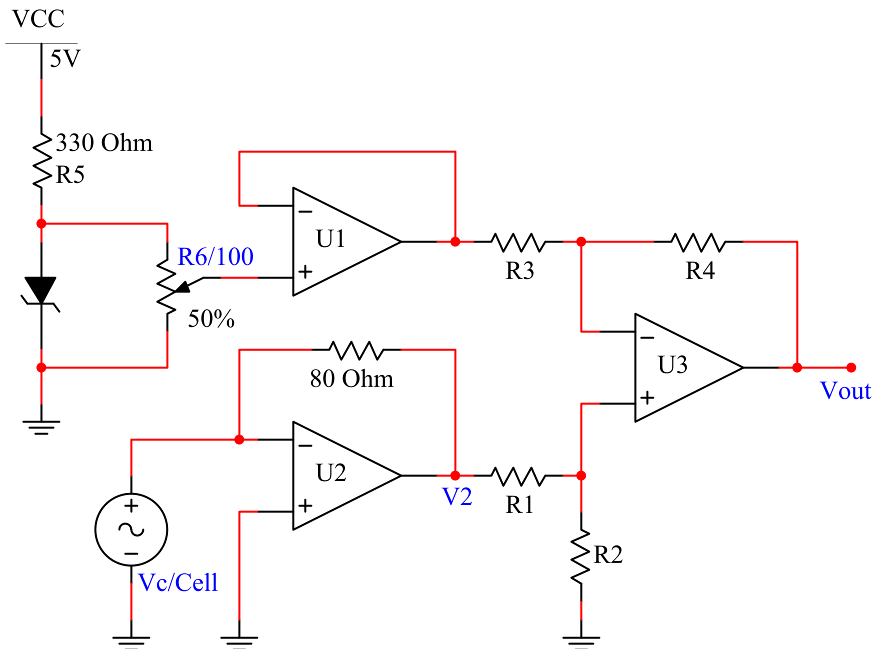
At 15 mW/cm^2, $Vc = 0.45$ V & $Rc = 157\ \Omega$

$$Isc = \frac{Vc}{Rc} = \frac{0.45\text{ V}}{157\ \Omega} = 2.87\text{ mA}$$

The range of short-circuit current is from 0.51 mA to 2.87 mA.

b) Develop signal conditioning to provide a linear voltage from 0.3 to 1.5 V as the intensity varies from 4 to 15 mW/cm^2.

The circuit that we will use is shown below:



At 4 mW/cm^2, Isc = 0.51 mA

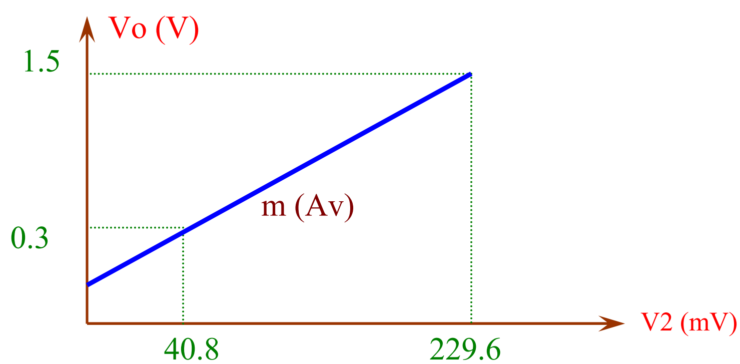
We need to obtain Vout = 0.3 V (condition of the problem)

$$V2 = (0.51 \text{ mA})\ (80) = 40.8 \text{ mV}$$

At 15 mW/cm^2, Isc = 2.87 mA

We need to obtain Vout = 1.5 V (condition of the problem)

$$V2 = (2.87 \text{ mA})\ (80) = 229.6 \text{ mV}$$



Vout = Av V2 + Voffset (1)

$$Av = \frac{1.5 - 0.3}{(229.6 - 40.8)mV} = 6.356$$

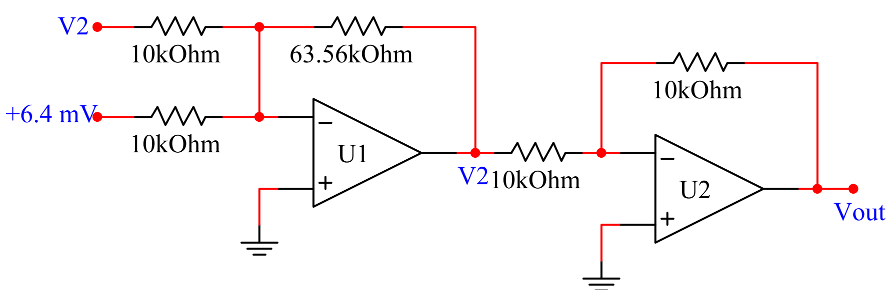
0.3 = 6.356 (40.8mV) + Voffset

Voffset = 40.68 mV

From Eq. (1): Vout = 6.356 V2 + 40.68 mV = 6.356 (V2 + 6.4 mV)

- Adjust R6 until Voffset = - 6.4 mV
- Make R1 = R3 = 1 kΩ
- Make R2 = R4 = 6.356 kΩ

Another solution:



14. A photovoltaic cell is to be used with radiation of intensity from 6 to 20 mW/cm^2. Measurements show that its unloaded output voltage ranges from 0.24 to 0.56 volts over this intensity while it delivers current from 0.3 to 2.5 mA into a 60 Ω load. (a) Determine the range of short-circuit current and (b) Develop signal conditioning to provide a linear voltage from 0.2 to 2.0 V as the intensity varies from 6 to 20 mW/cm^2.

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Final Control

1. A 4 - 20-mA control signal is loaded by a 100 Ω resistor and must produce a 20 - 40 V motor drive signal. Find an equation relating the input current to the output voltage.

Solution

The 100 Ω resistor provides Va = 100 I so as I varies from 4 mA to 20 mA, this voltage will vary from 0.4 V (Va = 100 Ω x 4 mA = 400 mV = 0.4 V) to 2.0 volts (Va = 100 Ω x 20 mA = 2 V). There must be a linear circuit that converts this voltage variation into 20 to 40 volts. So,

$$V_{out} = mV_a + V_o \qquad \text{(Eq. 1)}$$

Using the given conditions provide the equations,

$$20 = 0.4m + V_o$$
$$40 = 2.0m + V_o$$

subtracting,

$$20 = 1.6m \quad \text{or} \quad m = 20/1.6 = 12.5 \text{ then,}$$
$$20 = (0.4)(12.5) + V_o$$
$$V_o = 20 - 5 = 15$$

Therefore, from Eq 1:

$$V_{out} = 12.5\ V_a + 15 \qquad \text{(Eq. 2)}$$

Since, Va = 100 I

then, $V_{out} = 1250\ I + 15$ (I in amperes)

2. Implement the equation of Problem 1 if a power amplifier is available that can output 0-100 V and has a gain of 10.

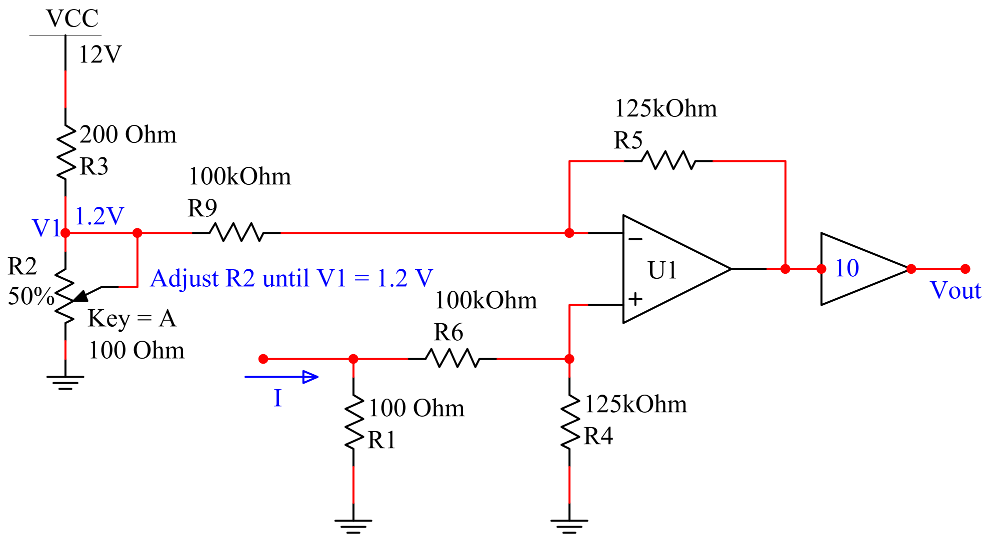
Solution

Since the power amplifier has a gain of ten, the equation above can be reduced by a factor of ten. Using equation 2,

$$V_{out} = 1.25\ V_a + 1.5$$

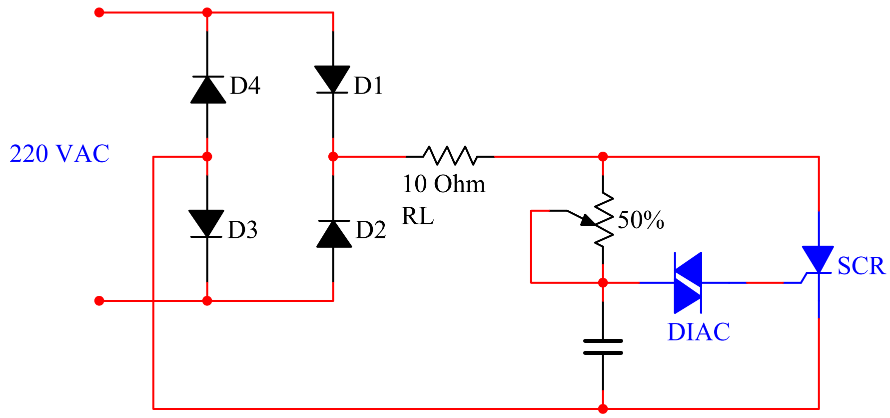
Or $V_{out} = 1.25\ (V_a + 1.2)$

This can be provided by a differential amplifier as follows,



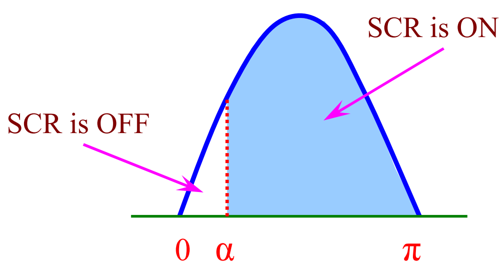
3. Implement the equation of Problem 1 if a power amplifier is available that can output 0-80 V and has a gain of 12.

4. The power in the load must be 2 kW, determine the triggering angle, α.



Solution

Since the SCR will work as a full-wave device due to the bridge rectifier,



$$V_L = Vav = \frac{1}{\pi}\int_{\alpha}^{\pi} Vmax\ sinwt\ dwt$$

$$V_L = Vav = \frac{-V\,max}{\pi}(\cos\pi - \cos\alpha) \qquad \text{(Eq. 3)}$$

The power across the load is calculated as:

$$P_L = \frac{(V_L)^2}{R_L}, \text{ where}$$

$$V_L = \sqrt{P_L\ R_L} = \sqrt{(2000)(10)} = 141.4V$$

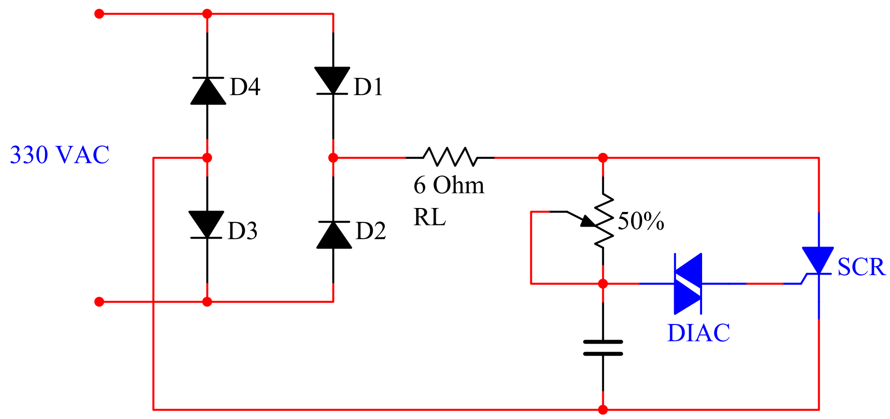
From equation 3:

$$141.4\ V = \frac{-220\sqrt{2}}{\pi}(-1 - \cos\alpha)$$

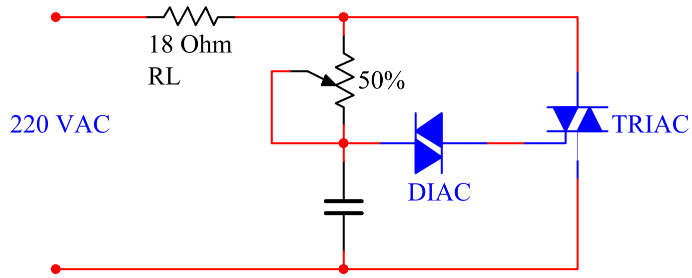
$$141.4\ \pi\ V = 220\sqrt{2} + 220\sqrt{2}\ \cos\alpha$$

The triggering angle, α is: $\alpha = \cos^{-1}\left(\frac{141.4\,\pi - 220\sqrt{2}}{220\sqrt{2}}\right) = 64.5°$

5. The power in the load must be 4.2 kW. Determine the triggering angle, α.



6. Calculate the power dissipated in the load. α = triggering angle = 50°



Solution

A TRIAC is a full-wave device. Thus, the equation for calculating the P_L or Vav is the same as shown in Eq. 3:

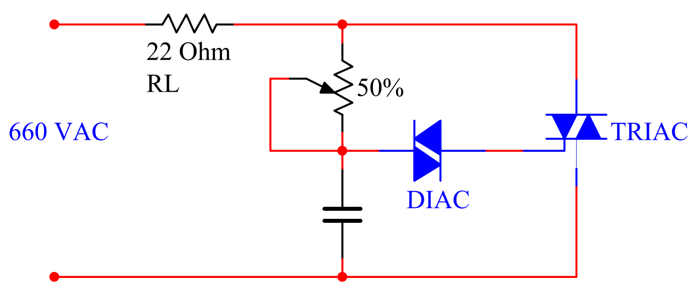
$$V_L = Vav = \frac{-V\max}{\pi}(\cos\pi - \cos\alpha)$$

$$V_L = Vav = \frac{-220\sqrt{2}}{\pi}(\cos\pi - \cos 50°) = 162.70\ V$$

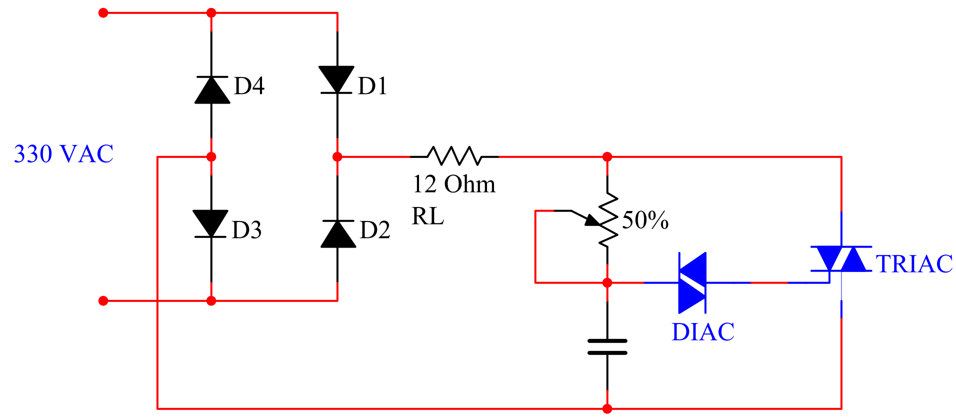
The power across the load is:

$$P_L = \frac{(V_L)^2}{R_L} = \frac{(162.70)^2}{18\Omega} = 1{,}470.6\ W$$

7. Calculate the power dissipated in the load. α = 63°



8. In the following circuit, α = triggering angle = 35°. (a) Calculate P_L (b) If D1 and D3 open find P_L (c) If D2 opens determine P_L. (d) If it is required that P_L = 1200 W, calculate α.



Solution

a) Calculate P_L

From Eq. 1:

$$V_L = Vav = \frac{-330\sqrt{2}}{\pi}(\cos\pi - \cos 35°) = 270.2 \text{ V}$$

$$P_L = \frac{(V_L)^2}{R_L} = \frac{(270.2)^2}{12\Omega} = 6{,}084 \text{ W}$$

b) If D1 and D3 open find P_L.

If D1 and D3 open, then the TRIAC will function as a half-wave device. Therefore,

$$V_L = Vav = \frac{-V\max}{2\pi}(\cos\pi - \cos\alpha)$$

$$V_L = Vav = \frac{-330\sqrt{2}}{2\pi}(\cos\pi - \cos 35°) = 135.1 \text{ V, and}$$

$$P_L = \frac{(V_L)^2}{R_L} = \frac{(135.1)^2}{12\Omega} = 1{,}521 \text{ W}$$

c) If D2 opens determine P_L.

If D2 opens, the solution is the same as part (b)

d) If it is required that $P_L = 1200$ W, calculate α.

$$P_L = \frac{(V_L)^2}{R_L} \Rightarrow (V_L)^2 = P_L\,R_L$$

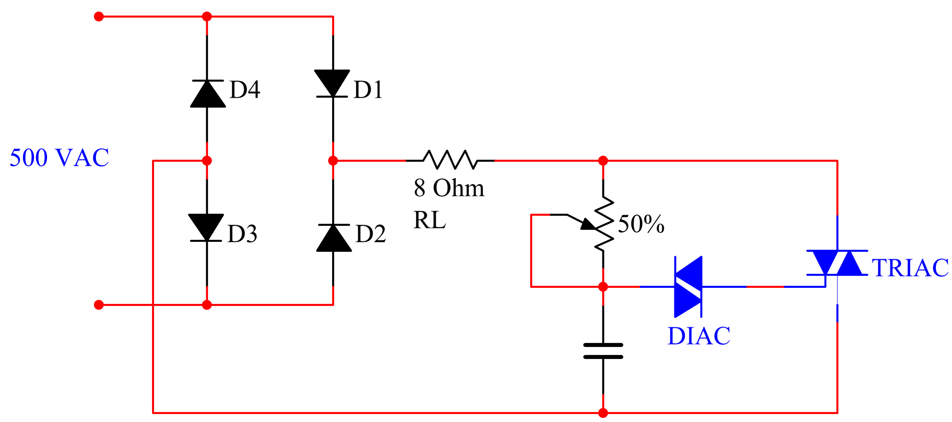
$$V_L = \sqrt{P_L\,R_L} = \sqrt{(1200)(12)} = 120\text{V}$$

From Eq 1:

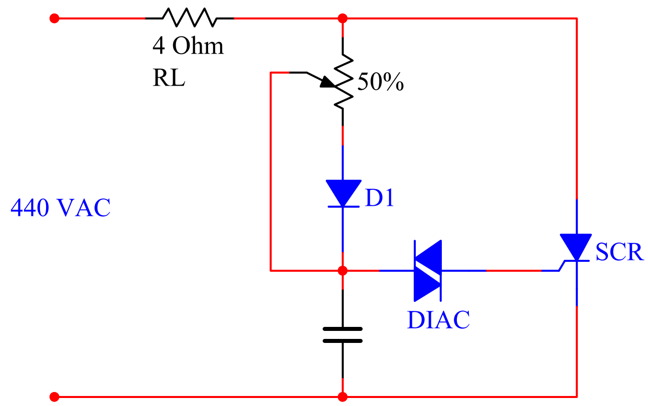
$$120\text{ V} = \frac{-330\sqrt{2}}{\pi}(\cos\pi - \cos\alpha) = \frac{-330\sqrt{2}}{\pi}(-1 - \cos\alpha)$$

$$\alpha = \cos^{-1}\left(\frac{120\,\pi - 330\sqrt{2}}{330\sqrt{2}}\right) = 101°$$

9. In the following circuit: (a) Calculate P_L, (b) If D3 opens determine P_L. α = triggering angle = 48°



10. In the circuit shown below: (α = triggering angle = 35°). (a) Determine P_L. (b) If the diode shorts, calculate P_L. (c) If D1 diode opens, calculate P_L.



Solution

a. Determine P_L.

The SCR is a half-wave device.

$$V_L = Vav = \frac{1}{2\pi}\int_{\alpha}^{\pi} V\max \sin wt \, dwt$$

$$V_L = Vav = \frac{-V\max}{2\pi}(\cos\pi - \cos\alpha)$$

$$V_L = Vav = \frac{-440\sqrt{2}}{2\pi}(\cos\pi - \cos 35°) = 180.16 \text{ V, and}$$

$$P_L = \frac{(V_L)^2}{R_L} = \frac{(180.16)^2}{4\Omega} = 8{,}114.4 \text{ W}$$

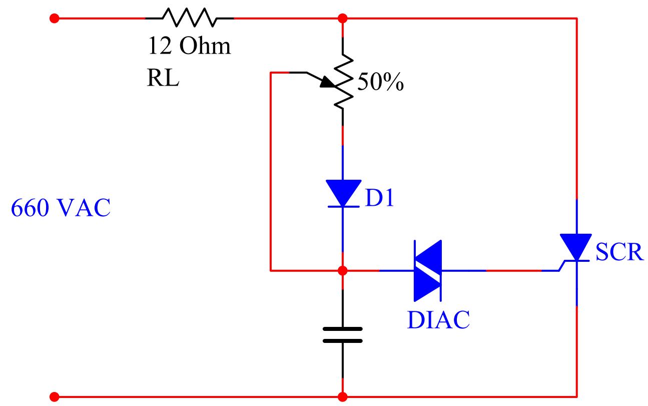
b. If the diode shorts, calculate P_L.

If the diode shorts, the SCR's gate will receive both positive and negative voltages. The SCR cannot withstand large negative voltages at its gate, therefore, the SCR will blow up. Thus, $P_L = 0$

c. If the diode opens, calculate P_L.

If the diode opens, the SCR won't receive any excitation at its gate. Thus, the SCR won't conduct and no current will flow through the load. Therefore, $P_L = 0$.

11. In the circuit shown below: (α = triggering angle = 35°)



a. Determine P_L.

b. If D1 diode opens, find P_L.

c. If D1 diode is reversed, find P_L.

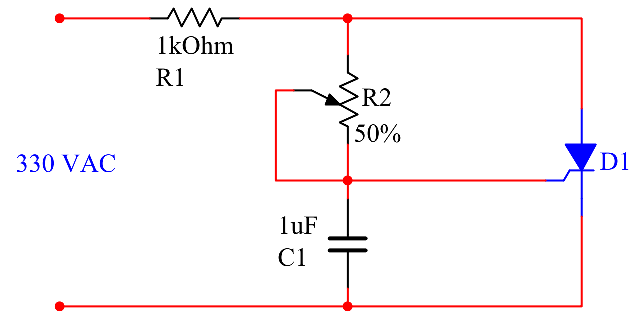
d. If DIAC opens, find P_L.

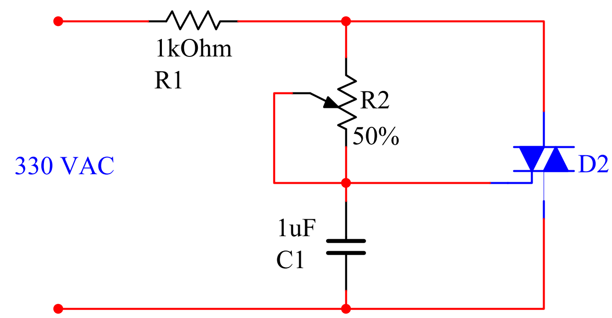
e. If SCR shorts between A and K, find P_L.

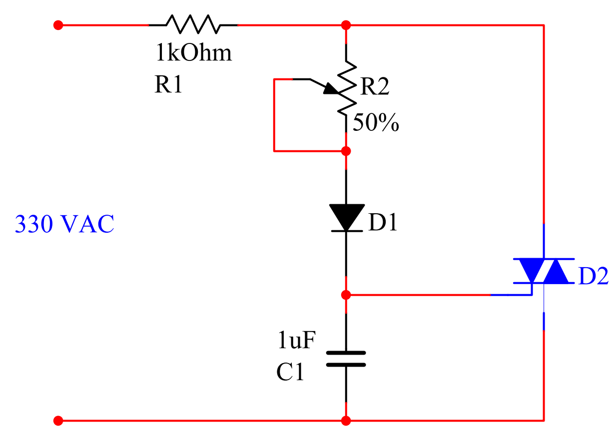
f. If the SCR is replaced by a TRIAC, find P_L.

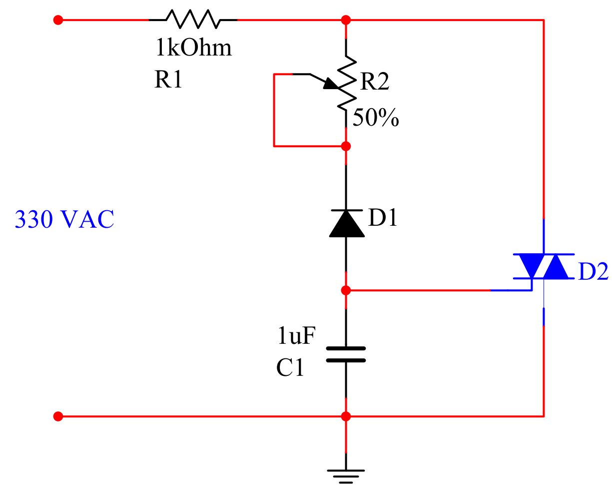
g. If the load shorts, find P_L.

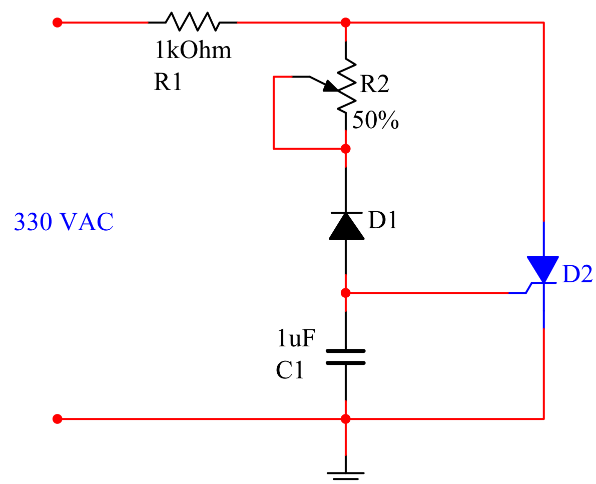
12. For each circuit identify the formula that you would use to find Vav and P_{R1} (load).

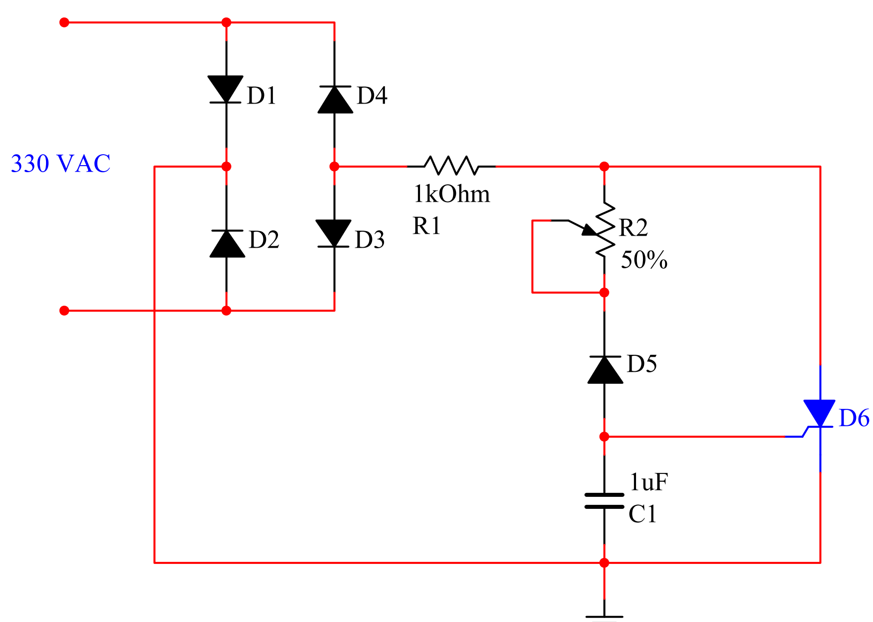


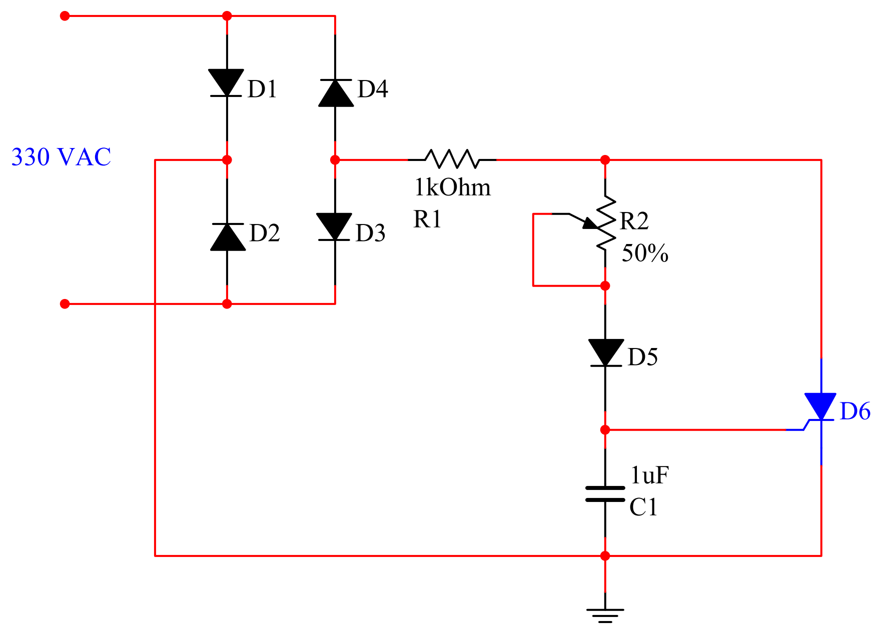


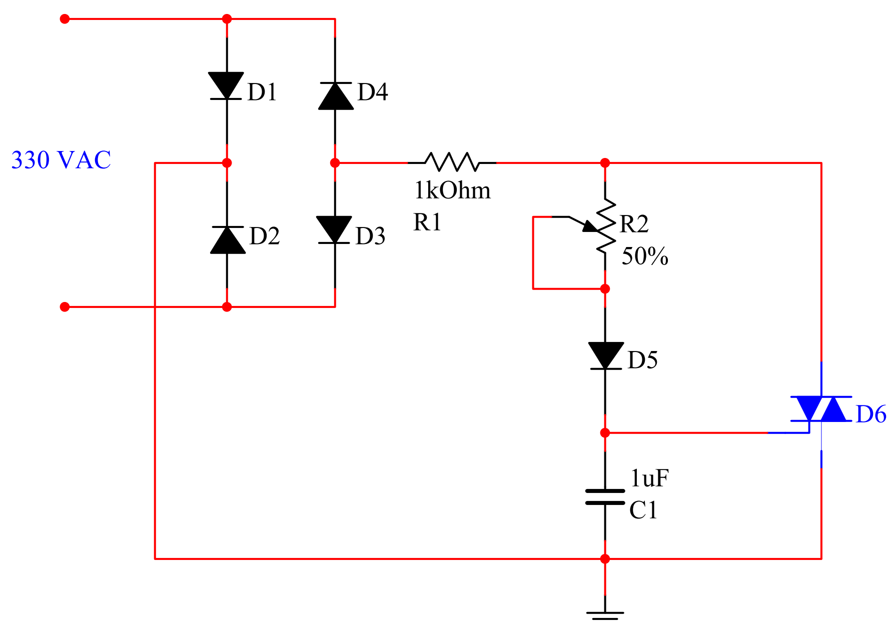



1kOhm
R1
R2
50%
330 VAC
D1
D2
1uF
C1


1kOhm
R1
R2
50%
330 VAC
D1
D2
1uF
C1


D1
D4
330 VAC
D2
D3
1kOhm
R1
R2
50%
D5
D6
1uF
C1


D1
D4
330 VAC
1kOhm
R1
R2
50%
D2
D3
D5
D6
1uF
C1

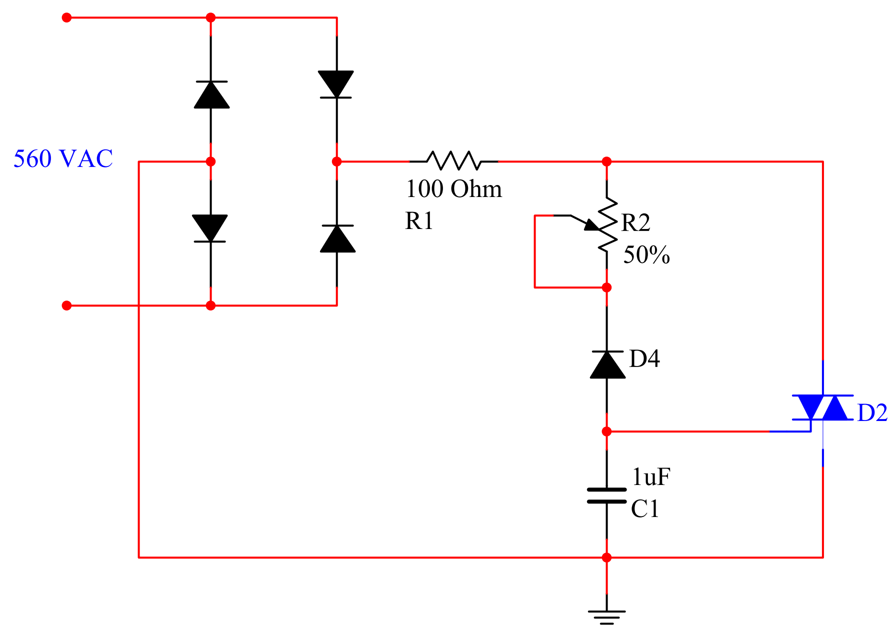

D1
D4
330 VAC
1kOhm
R1
R2
50%
D2
D3
D5
D6
1uF
C1

13. (a) If diode D4 opens and θ = 42° then the SCR is =________________________

(b) If diode D4 shorts and θ = 55° then the SCR is =________________________

(c) If R1 opens and θ = 60° then the SCR is =______________________________

Select:
(a) working as a λ/2
(b) working as a λ
(c) open
(d) shorted.

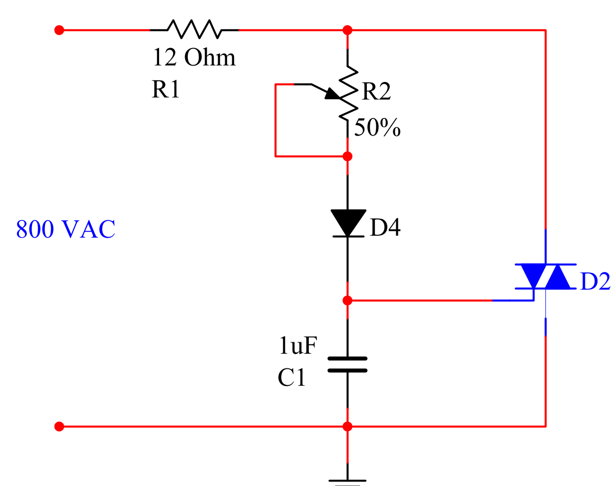


14. (a) TRIAC is____

(b) If D4 is reversed then TRIAC is__________________________

(c) If D4 is shorted then TRIAC is__________________________

Select:
(a) working as a λ/2
(b) working as a λ
(c) open
(d) shorted.



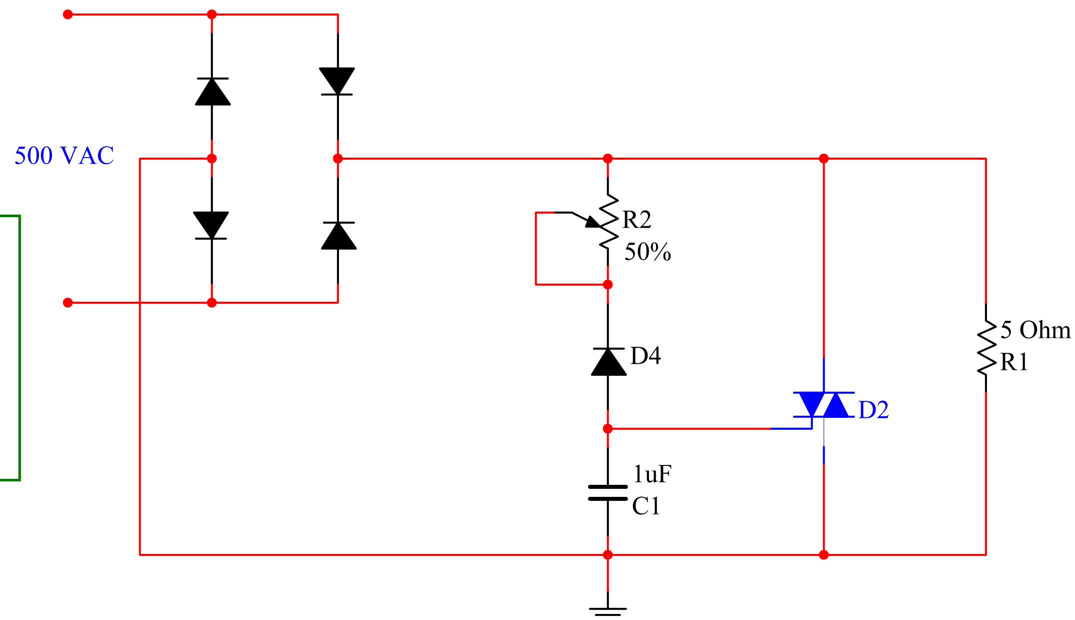
15. (a) P_{R1} is____

(b) If D4 opens then P_{R1} is______________________________

(c) If D4 shorts then P_{R1} is______________________________

(d) If R1 opens then TRIAC______________________________

Select:
(a) zero
(b) greater than zero
(c) less than zero
(d) blows up
(e) remains intact



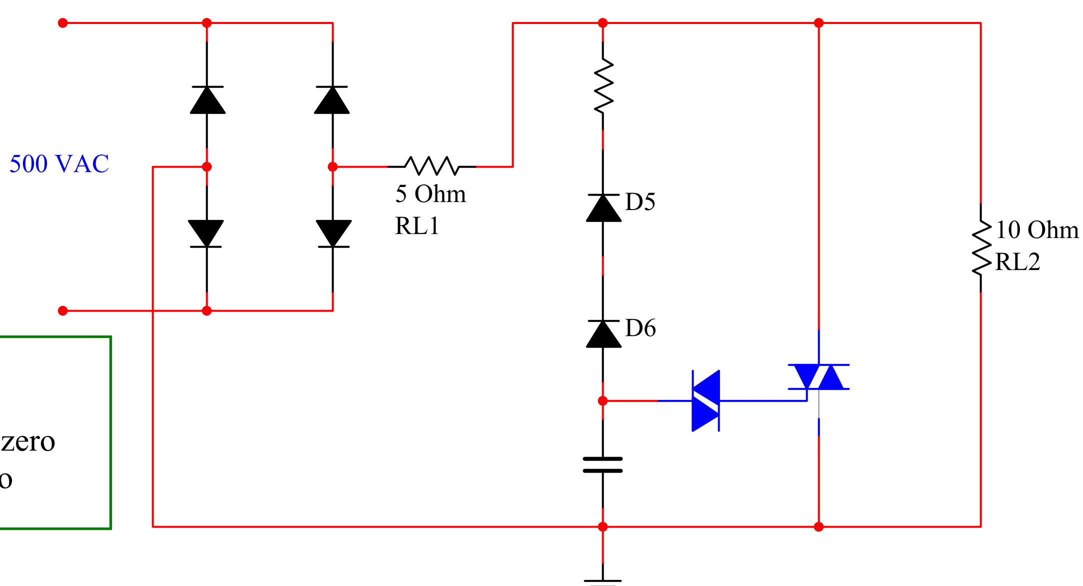
16. In the following circuit ($\alpha = 48°$)

(a) P_{RL1} is ____

(b) P_{RL2} is ____

(c) If D5 shorts then P_{RL1} is _____________________________________

(d) If D5 and D6 open then P_{RL2} is ________________________________



Select:
(a) zero
(b) greater than zero
(c) less than zero

17. In the following circuit ($\alpha = 98°$)

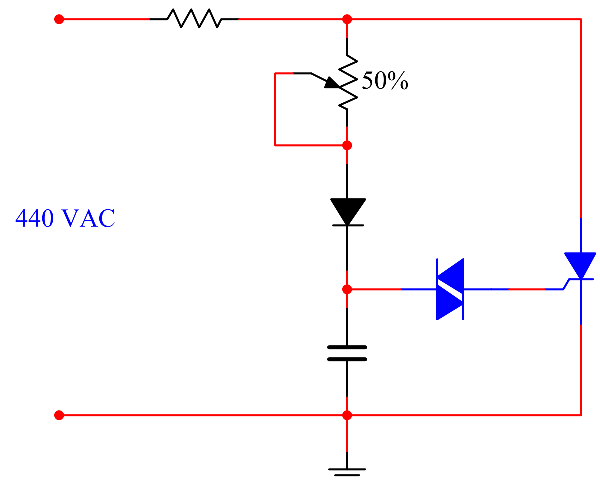
(a) P_L is ______________________________

(b) SCR is ______________________________

(c) If diode shorts then SCR is______________________________

(d) If diode opens then P_L is ______________________________

Select:
(a) zero
(b) greater than zero
(c) less than zero
(d) blows up
(e) remains intact
(f) working as a $\lambda/2$
(g) working as a λ



SAN JOSE STATE UNIVERSITY
Department of Aviation & Technology

TECH 167: Control Systems Dr. Julio R. Garcia

Controller Principles

1. What is a control system?

   A control system is a group of properly arranged devices and components that maintain a certain process at a desired level.

2. **Provide two examples of a control system.**

3. **Why is the control in industrial processes very critical?**
   The control in industrial processes is very critical because some areas are very hazardous or impossible for human operators to work in such as high-temperature environments and high-voltage surroundings.

4. What is the classification of Control Systems?

Process Being Controlled	Temperature control systems → Temperature Flow control systems → Fluid flow Level control systems → Height of material in holding bins or reservoirs
Nature of Controlling Components	Analog Digital
Feedback	Open-loop Closed-loop

5. **Closed-loop control system.** Figure 1 below shows a typical closed-loop control system

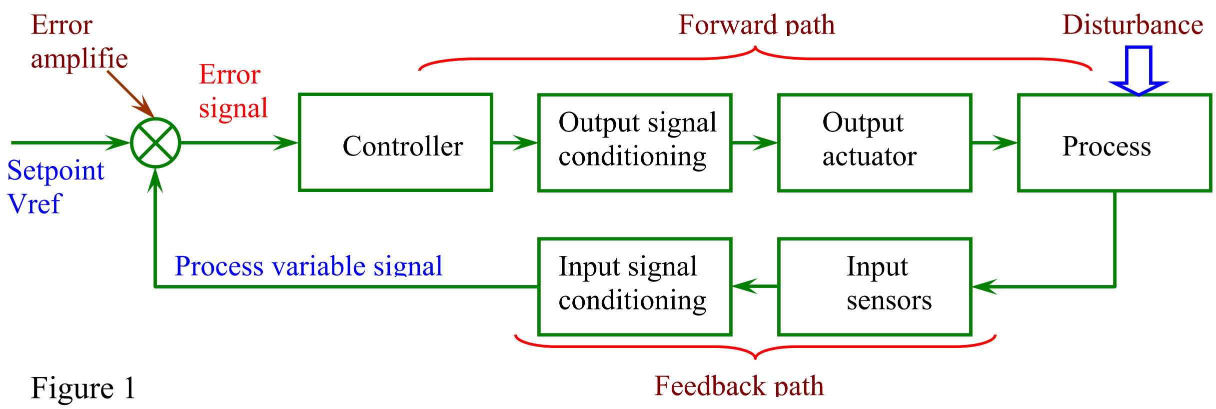


Figure 1

a. Is this a closed-loop or an open-loop control system? Why?

b. What is V_{ref} and with what other names is also called?

V_{ref} is the desired operating point for the process. Other names are Set-point, Command, or Reference.

c. What does v_f represent and with what other names is also called?
v_f is the signal that represents current process status. Other names are process variable, measured value or controlled variable.

d. What does the Error Amp represent? How can we implement the Error Amp?

The Error Amp is a circuit that represents whether the process is under control. The Error Amp can be implemented through an Error detector, Comparator or Summing amplifier.

e. What is v_ε, what other names is also called and what is the equation?

v_ε is the Error Amplifier output. Other names are Error signal or System deviation signal. The equation is:

$$v_\varepsilon = A_v\,(v_{ref} - v_f);\;\; \text{If}\;\; A_v = 1 \Rightarrow v_\varepsilon = v_{ref} - v_f$$

f. Briefly describe the Controller, Output signal conditioning, Output actuator, Input sensor and Input signal conditioning:

The Controller provides a corrective signal. Output will depend on v_{ε}.

The Output signal conditioning or Signal conditioner is the interface between the controller output (a signal) to the output actuator.

The Output actuator or Final correcting device directly affects a process change: motor, heater, solenoid, etc.

The Input sensor detects any changes in the process respect to the set-point.

The Input signal conditioning converts the output from the input sensor to a process variable signal.

6. What is the Controller?

The Controller is the heart of any electronic control system and possesses the following characteristics:

a. It maintains the process variable within acceptable limits of the set point.
b. The smaller the variations of the process from the set point the better the controller.
c. The faster the controller responds when the process variable deviates from the set point the better the controller.

7. What are the types of Controllers?

- ON-OFF
- Proportional
- Integral
- Derivative
- Proportional-Integral
- Proportional-Integral Derivative (PID)
- Digital Proportional-Integral

Selection of type of controller depends on speed of response, allowable system error and process dynamics.

ON/OFF Controllers. (Two-position controllers)

a. Output is fully ON or fully OFF. It is inexpensive but limited.

	Direct acting controller (Process variable and controller output move in the same direction)	**Inverse acting controller** (Process variable and controller output move in the opposite direction)
Process variable > Setpoint	**ON**	**OFF**
Process variable < Setpoint	**OFF**	**ON**

b. An ON/OFF controller must have some degree of hysteresis. Otherwise, the output will oscillate. This may destroy the system.

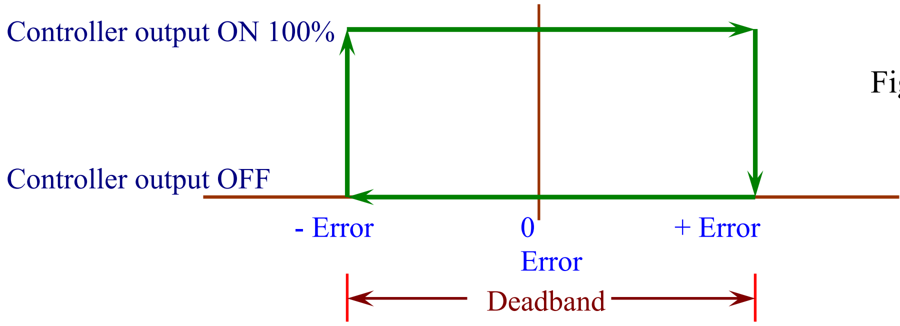
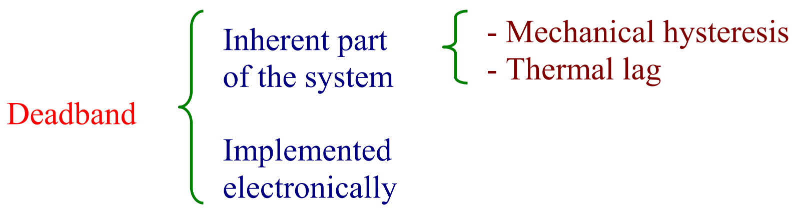


Figure 2

The controller output will remain OFF until the error signal decreases to the level of -Error. When this level is reached the controller output is ON. The output will remain ON until the error signal reaches the level of +Error. At this point, the controller output is OFF.

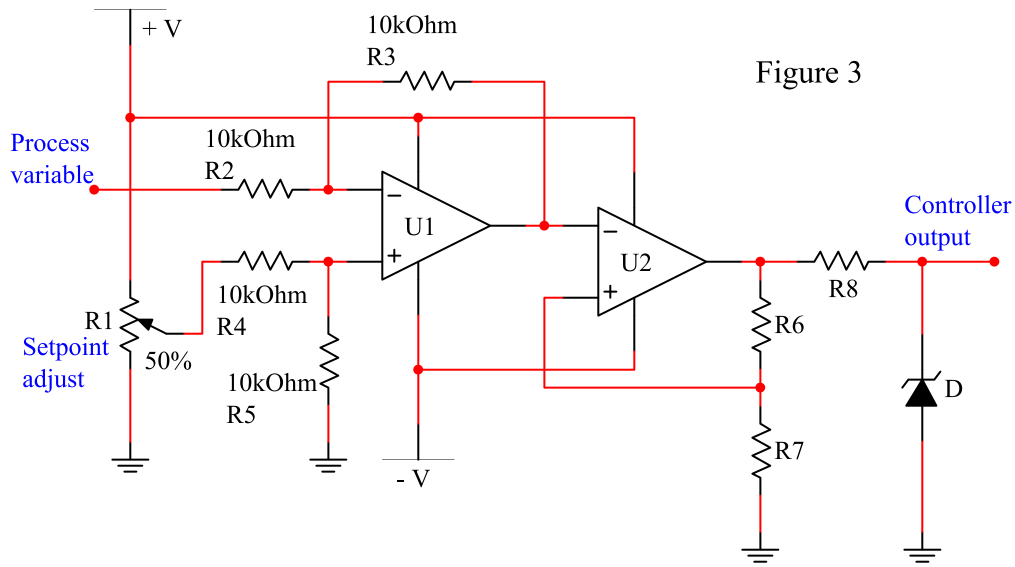
$$\text{Deadband} = \text{Error}_{\text{ON}} - \text{Error}_{\text{OFF}}$$

The deadband is the difference between the error signal that turns the controller output fully ON and the error signal that turns the controller output fully OFF.



Analyze Figure 3.

Error!



U1 and associated components

Error amplifier with unity gain.

vo_1 = Error signal = Av_1 (Vset-point - Vprocess variable) = Av_1 $(V_{REF} - v_f)$

Since $Av_1 = 1 \Rightarrow vo_1$ = Vset-point - Vprocess variable = $V_{REF} - v_f$

U2 and associated components

Comparator

$V_{UTP} = \dfrac{R7}{R6 + R7}(+\,Vsat)$ $\qquad V_{LTP} = \dfrac{R7}{R6 + R7}(-\,Vsat)$

When Error signal > $V_{UTP} \Rightarrow vo_2 = -$ Vsat

When Error signal < $V_{LTP} \Rightarrow vo_2 = +$ Vsat

$$\text{Deadband} = V_{UTP} - V_{LTP} = 2\,|Vsat|\left(\frac{R7}{R6 + R7}\right)$$

Controller output is between – 0.7 V and + Vz.

In actual applications, the controller output must be limited between 0 and V^+ or 0 and V^-. R8 and D serve this purpose.

Problem 1. See Figure 3. If $\pm$ V = $\pm$ 18 V, R_6 = 120 kΩ, R_7 = 27 kΩ and D = 5.6 V.

a. Find the circuit Deadband.

b. Draw the circuit Transfer Curve.

Solution

a.) $\text{Deadband} = 2\,|\text{Vsat}|\left(\frac{R7}{R6+R7}\right) = 2\,|16\text{ V}|\left(\frac{27}{120+27}\right) = 6.8\text{ V}$

b)

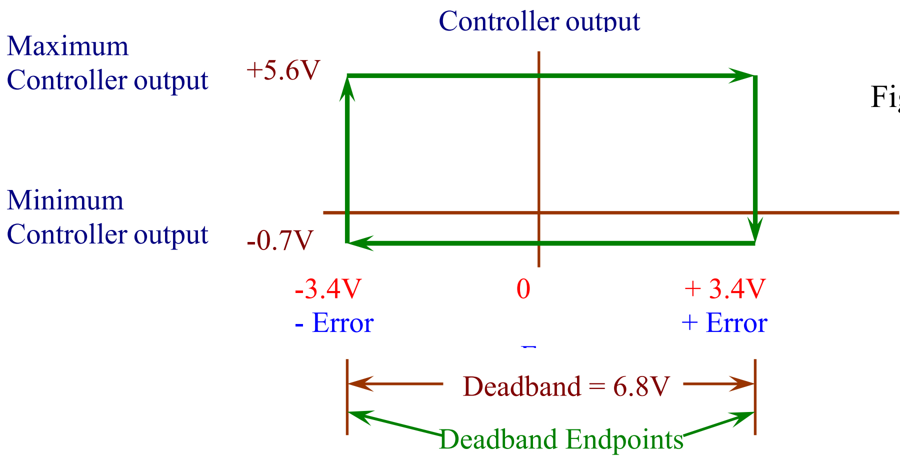


Figure 4

Problem 2. See Figure 3. If $\pm$ V = $\pm$ 15 V, R_6 = 150 kΩ, R_7 = 33 kΩ and D = 6.8 V.

a. Find the circuit Deadband.

b. Draw the circuit Transfer Curve.

Proportional Controllers
In many applications, the ON/OFF controller output is not acceptable. The output of a *proportional controller* varies between fully ON and fully OFF depending on the magnitude of the error signal. A proportional controller usually has a linear response.

Analyze Figure 5.

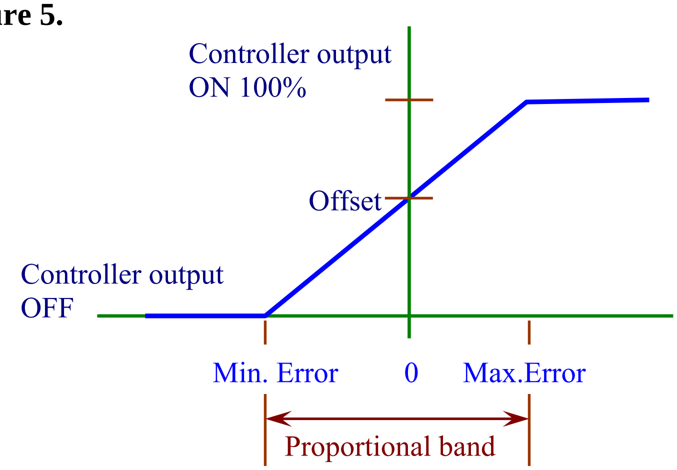


Figure 5

$$\text{Proportional band} = \frac{\text{Vout}_{,max} - \text{Vout}_{,min}}{\text{Av}}, \ \text{Av = controller gain}$$

3 points of interest

Max Error: Magnitude of error signal that makes output = full-ON.

Min Error: Magnitude of error signal that makes output = full-OFF.

Offset: Point where the curve crosses the Y-axis or controller output when Error = 0. Offset does not affect the magnitude of the proportional band.

$$\text{Error, max} = \frac{\text{Vout}_{,max}}{\text{Av}} - \text{Voffset}$$

$$\text{Error, min} = \frac{\text{Vout}_{,min}}{\text{Av}} - \text{Voffset}$$

Analyze Figure 6.

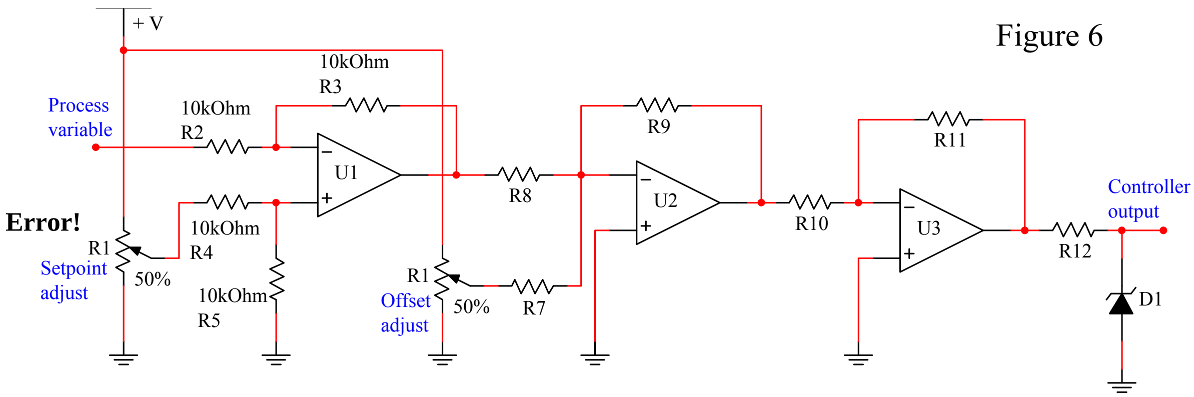


Figure 6

U1 and associated components

Similar to Figure 3.

U2 and associated components

Inverting summing amplifier

$vo_2 = -(\text{Verror} + \text{Voffset}) \neq 0$ (always)

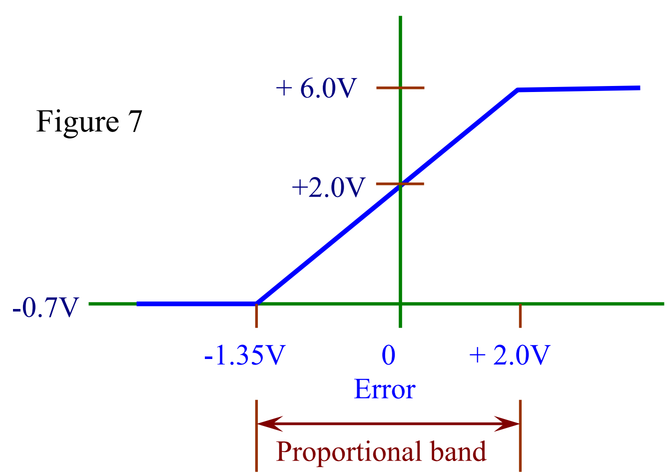
The offset facilitates correction of the process variable, but it will not allow the controller to maintain an error of zero.

Gain of U_2 determines the slope of the line.

Magnitude of the offset positions the entire curve above the zero-error point.

Analyze Figure 7. This is a typical proportional controller response curve

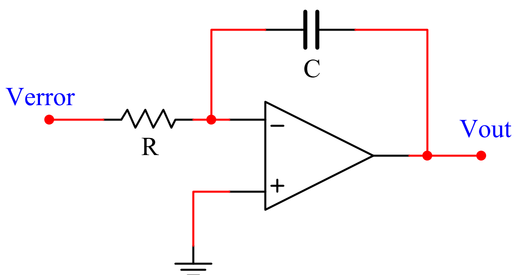
Figure 7



Integral Controllers

The advantage of an *integral controller* respect to an ON/OFF controller is that an integral controller can drive the error to zero and maintain it. An ON/OFF controller will never stabilize at the desired set point; therefore, some error is expected.

1. The principal circuit of an integral controller is ______________________________.
2. The output equation of the circuit shown below is:



If Verror is a steady DC, then

Therefore, as *t* increases, Vout increases (ramp).

Analyze Figure 8.

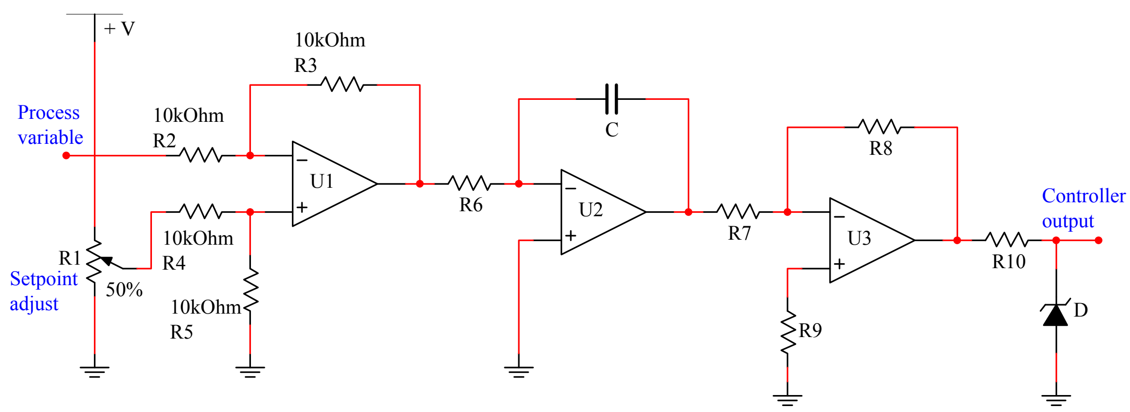


Figure 8

Note: Unless Verror is a simple step function, Vout may become very difficult to calculate. See Figure 9.

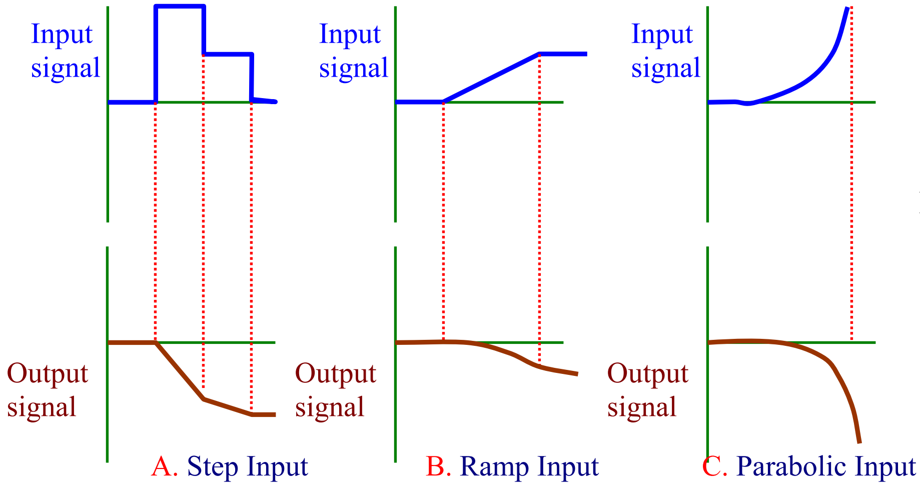
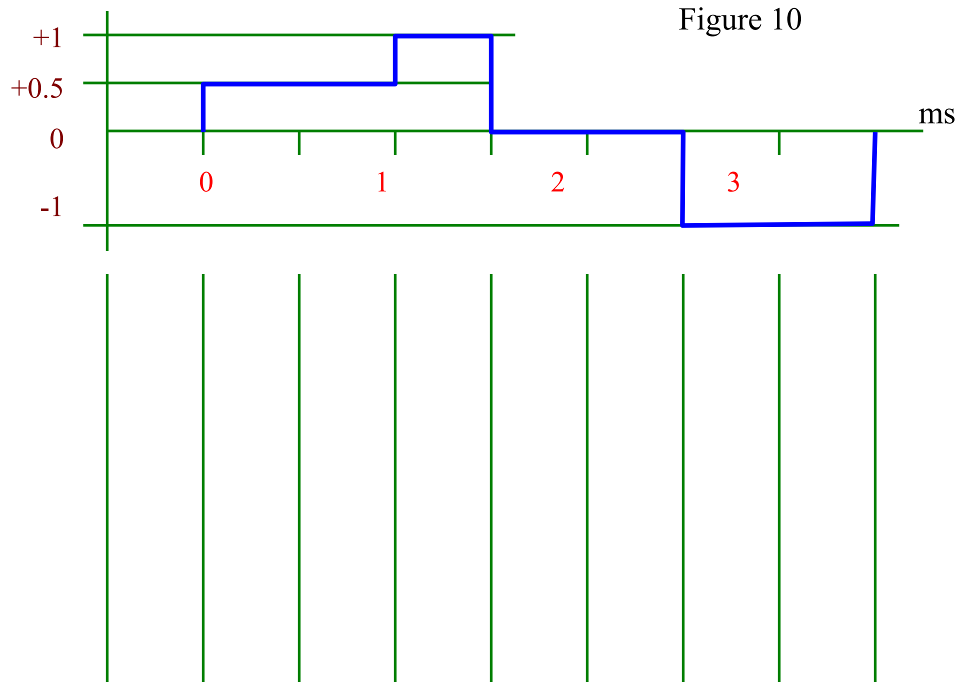


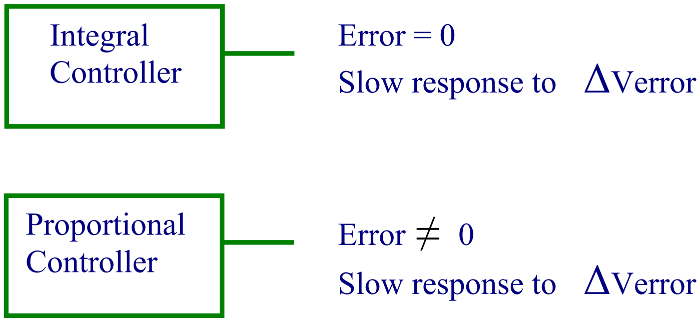
Figure 9

Problem 1.
The error signal indicated below appears at the integral controller input. R = 20 kΩ and C = 0.02 uF. If C has an initial voltage of + 1 V, determine the controller output.

Figure 10

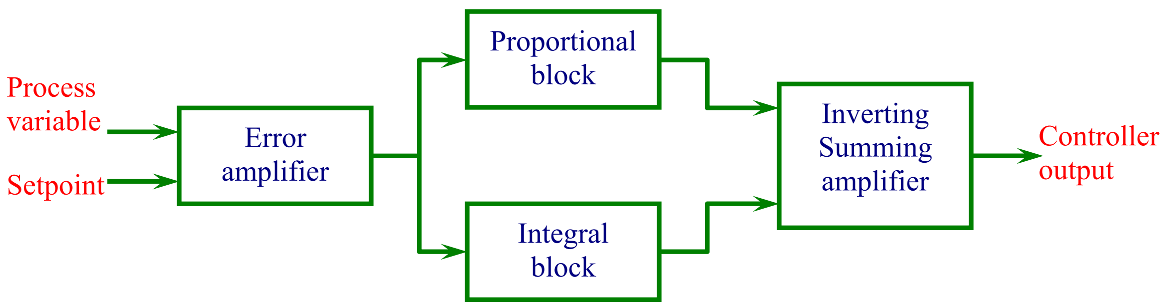


Proportional-Integral Controller

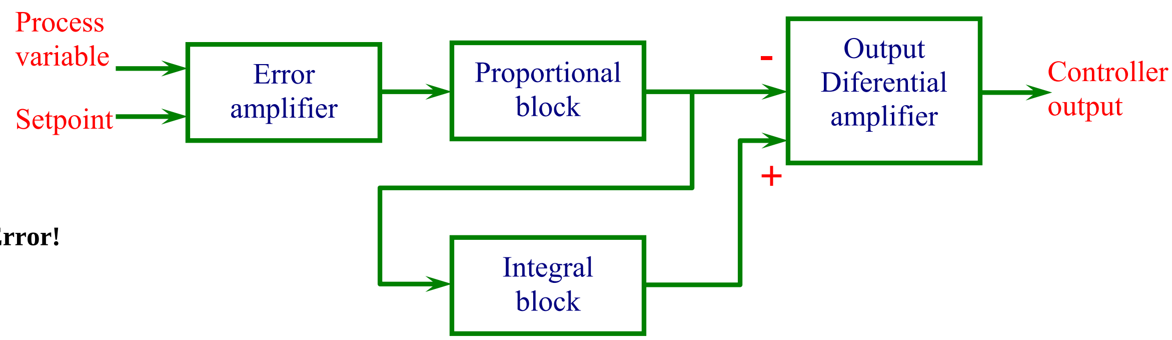


By combining these two controllers it is possible to obtain Error = 0 and a Fast response to ΔVerror.

Analyze Figure 11.



A. Parallel arrangement Figure 11



Error!

B. Series arrangement

The series arrangement responds faster than the parallel arrangement to ΔVerror. This is because the integral block receives an amplified error signal. Therefore, it forces the error to zero more rapidly.

Analyze Figure 12. Response of Parallel Proportional-Integral Controller to a Step Input.

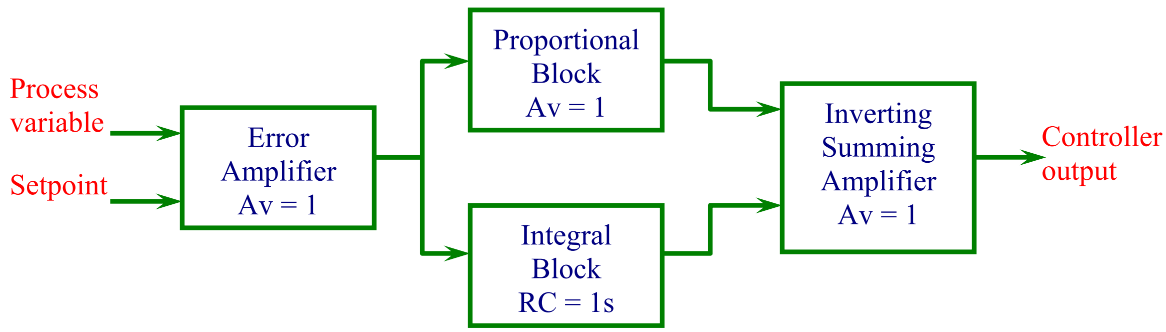
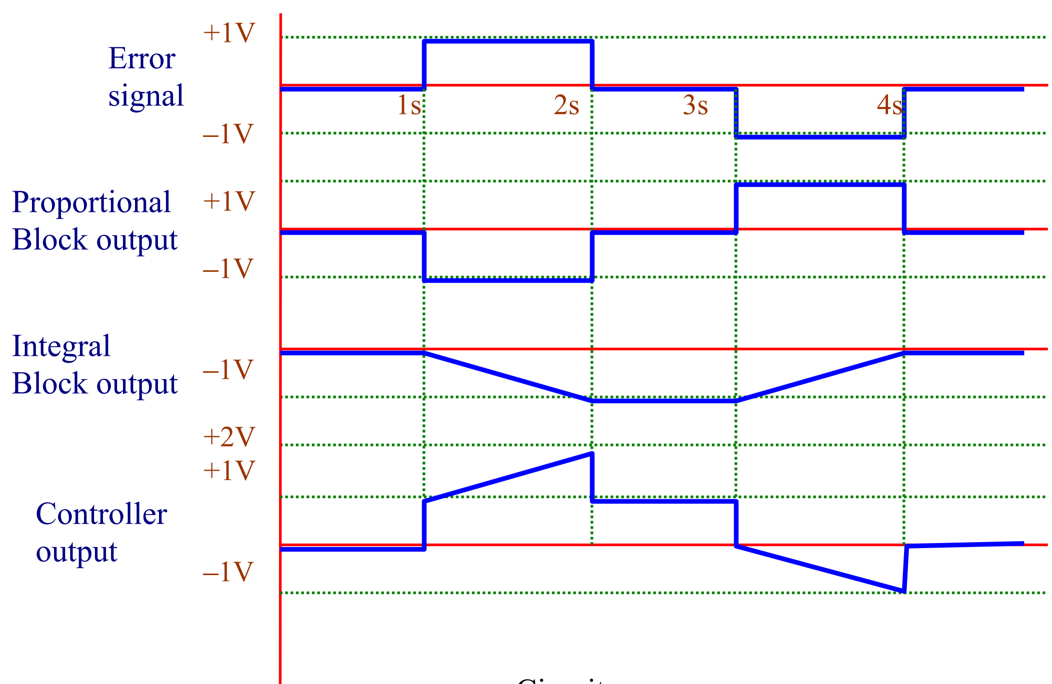


Figure 12



Circuit response

Analyze Figure 13. The gain of the proportional block = - 2, the RC of the integral block = 1 second, and the gain of the differential amplifier is 1.

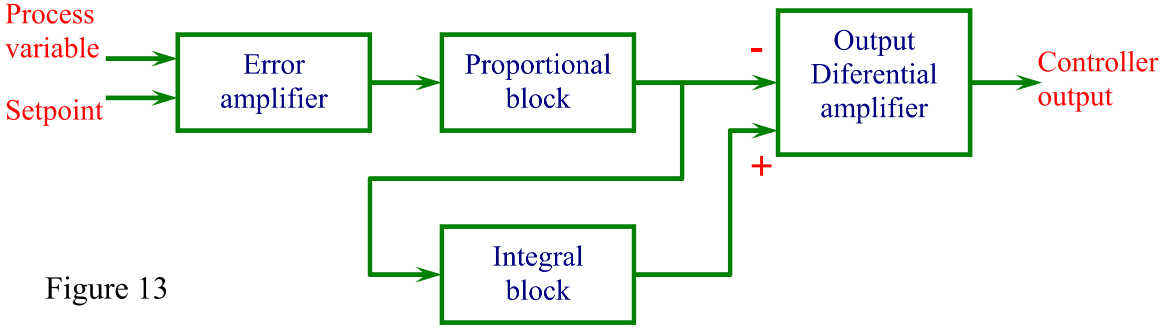
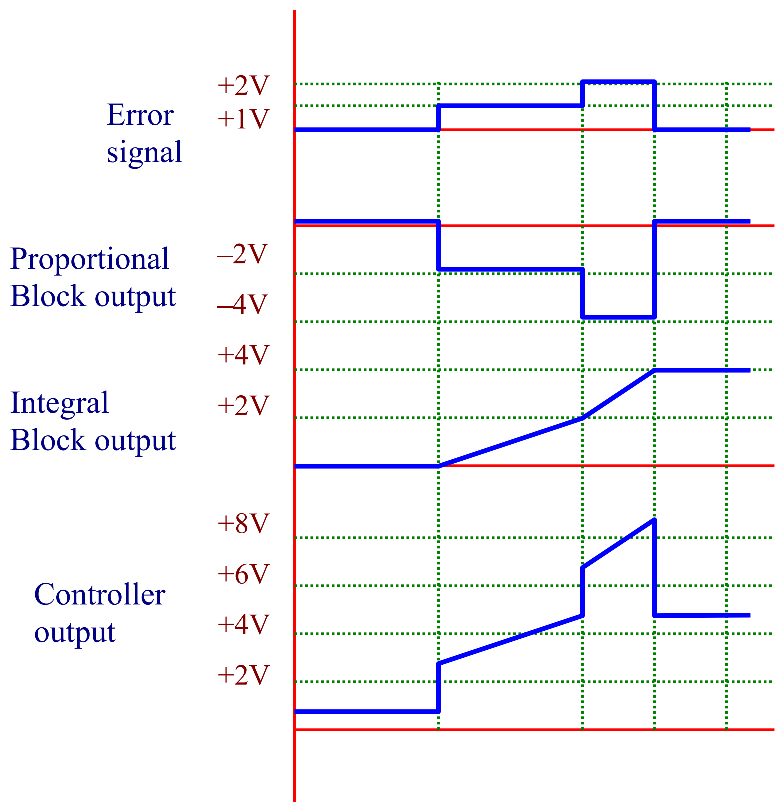


Figure 13

B. Series arrangement



Derivative Controllers

In many cases, a process has an inherent inertia or hysteresis. This means that a disturbance will not produce a deviation from the set point immediately. It also means that there is a lag from the time the process deviates from the set point and the corrective action.

To overcome this sluggish response and prevent oscillations the controller must produce a large corrective action signal initially but tapers off as time goes on. A Derivative Controllers does this job.

1. The basic element of a Derivative Controller is a ______________________________.
2. Analyze Figure 14. Ideal Differentiator Output Responses.

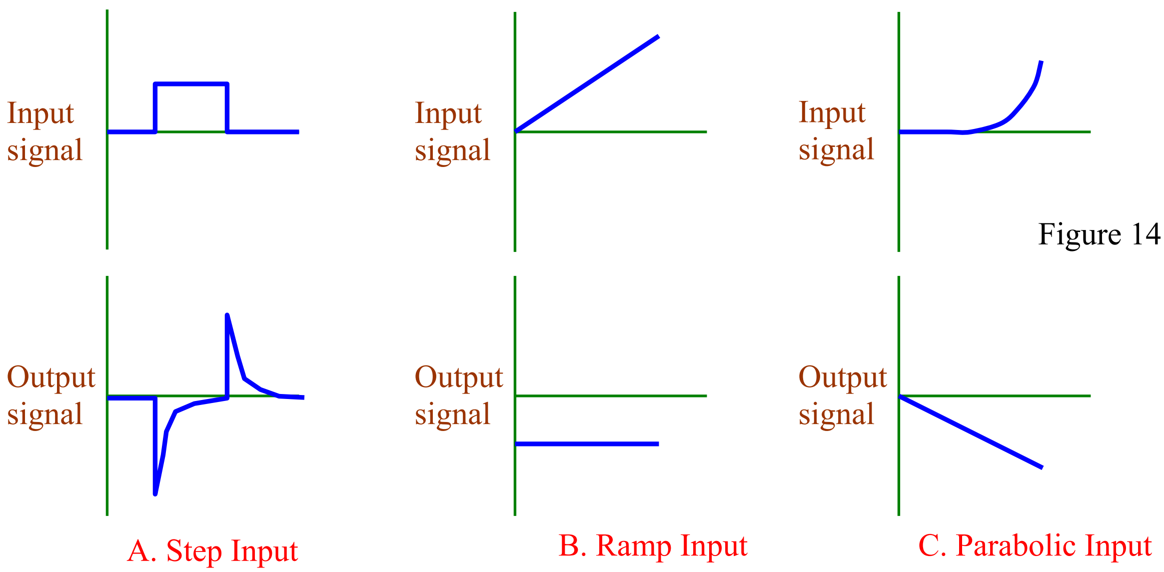


Figure 14

Disadvantages

a. Noise (high-frequency transients) will produce larger outputs that can saturate the amplifier. This action can be reduced by inserting a resistor in series with the input capacitor.

b. The Derivative controller responds only to changes in the error signal. It will not produce a corrective signal if the system has a steady-state error.

Derivative Controllers are never used alone. Proportional-Integral- Derivative (PID) Controllers are the industry standard.

Proportional-Integral- Derivative (PID) Controllers

Fast response to system disturbances.
Error = 0
Overcomes lag time without sarurating amp.

Analyze Figure 15.

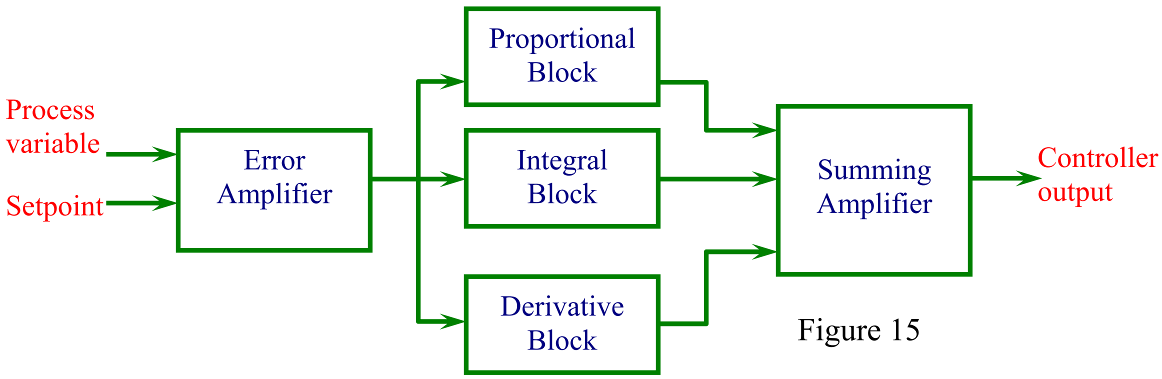


Figure 15

Several PID variations are possible.
In this case, a parallel configuration is shown.
Each block receives the same error signal and their outputs are added through a summing amp.

Tuning is the process of adjusting each of the 3 blocks. Tuning depends on:

a. the configuration of the controller,
b. the characteristics of the process being controlled, and
c. the desired controller performance.

Tuning is not a simple procedure. Computer simulation programs make this task easier but accuracy of the results depends on how the system response can be modeled.

Precautions

The action of the integral or derivative block can mask the effect of the other blocks in the controller.

a. A sudden change (step) in error will saturate the derivative block causing a saturation in the summing amp. The result may be an overcompensation and this will make the process to oscillate.
c. If a large error is present in the system for a large period of time, the output of the integral block may be forced into saturation and will remain in this state even though the error becomes zero. This output will make the process to overshoot. This condition is corrected when the resultant negative error brings the integral block out of saturation.

Analyze Figure 16. The gain of the proportional block = - 1, the RC of the integral block = 1 second, the RC of the derivative block = 0.2 seconds, and the gain of the summing amplifier is - 1.

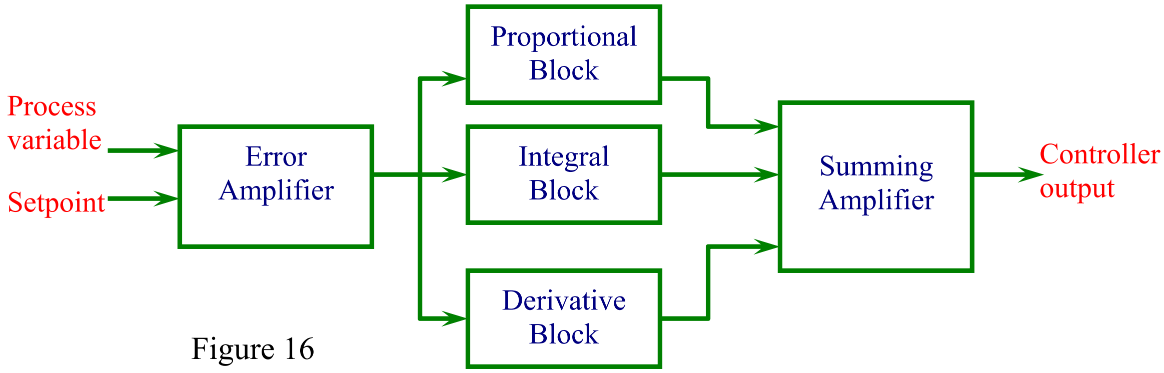
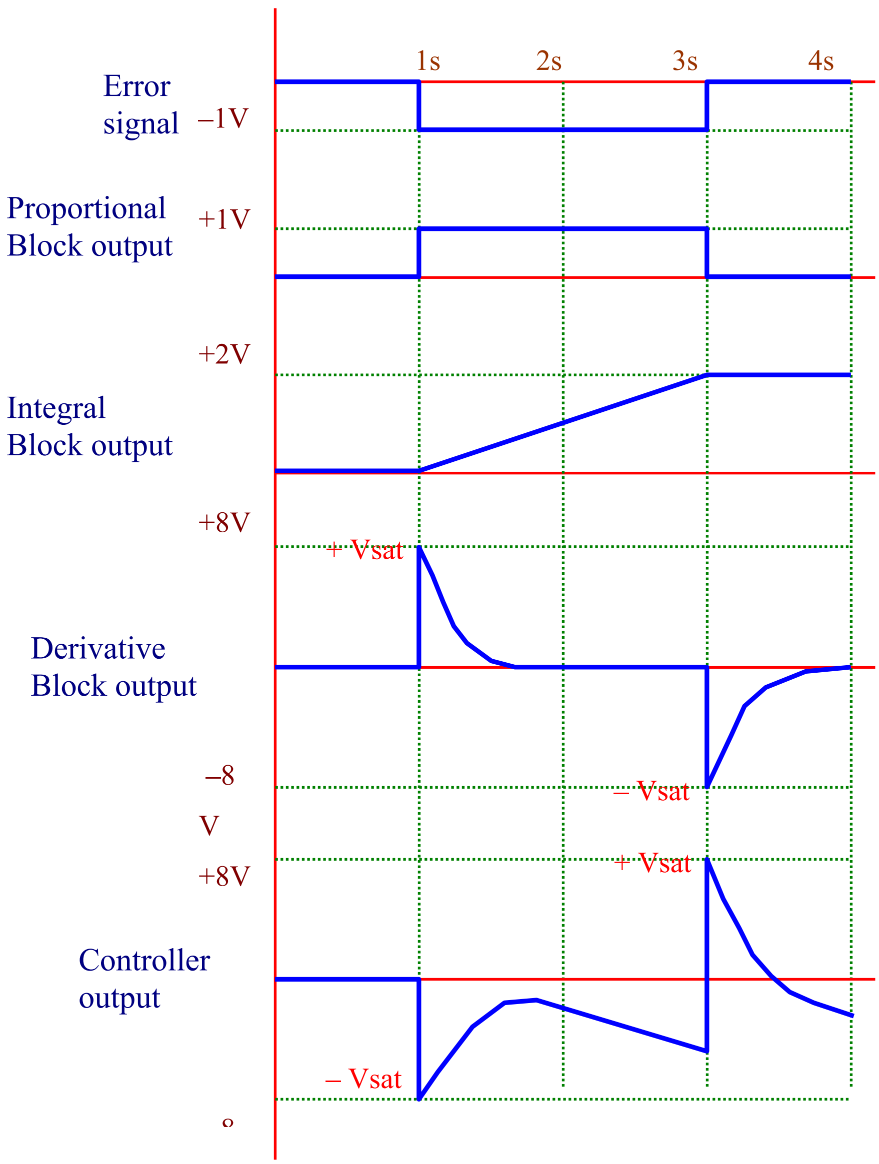


Figure 16



Points to consider

Verror is applied to the three blocks simultaneously.
The integral block output is given by:

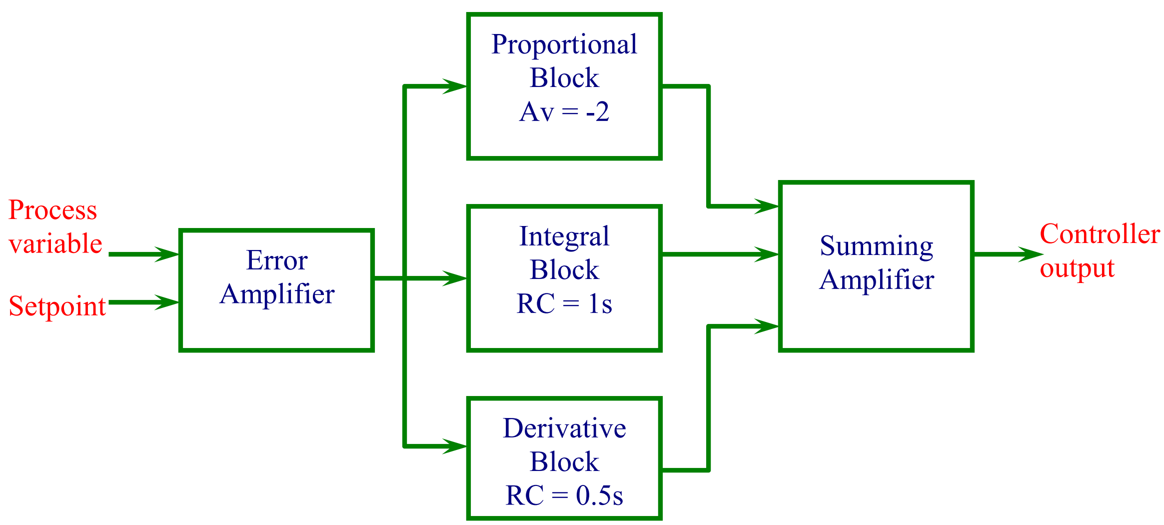
The derivative block is driven to:

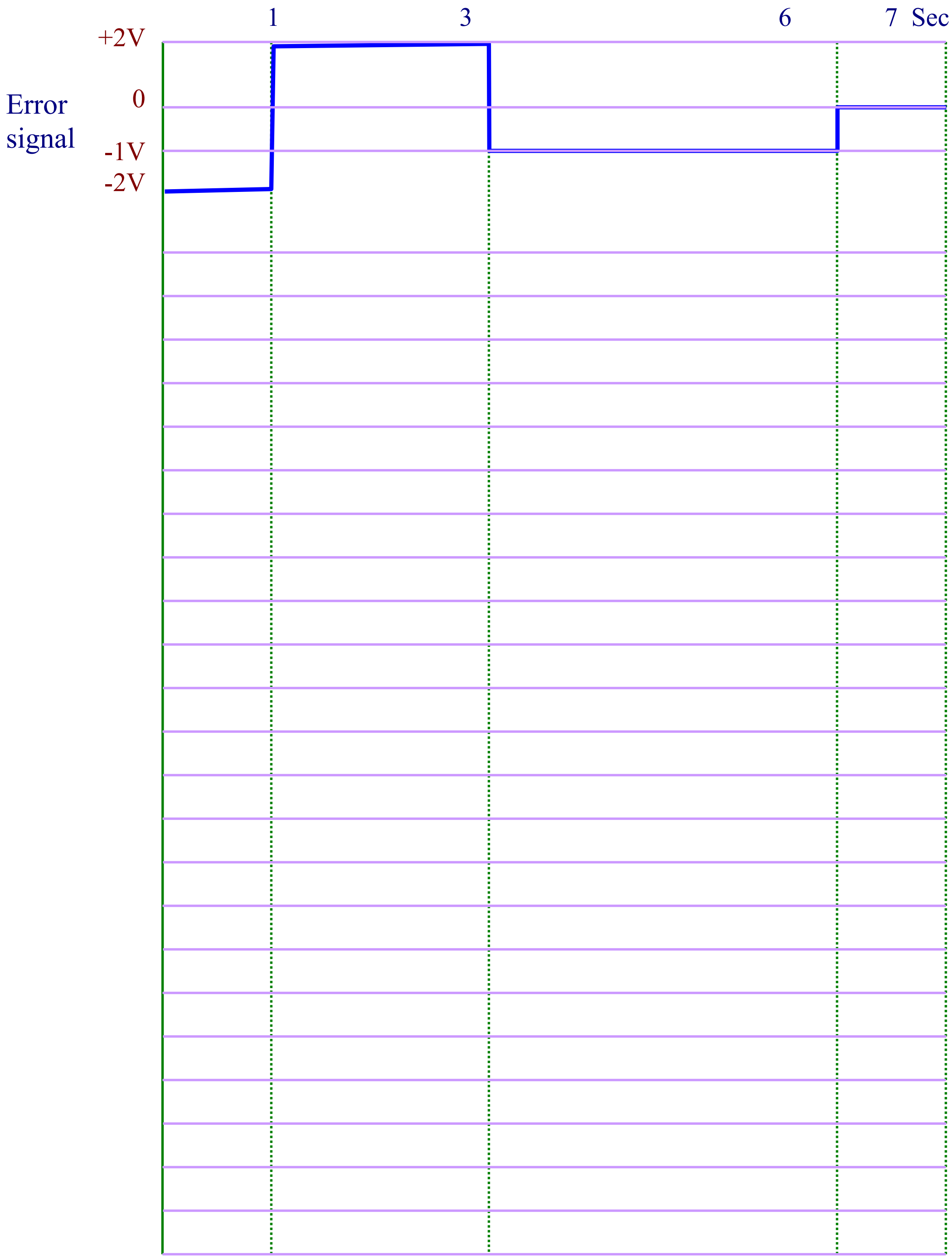
a. Positive saturation in response to a negative step.
b. Negative saturation in response to a positive step.

Since RC = 0.2 S, the capacitor will charge in_________________. At this time, the output is 0.

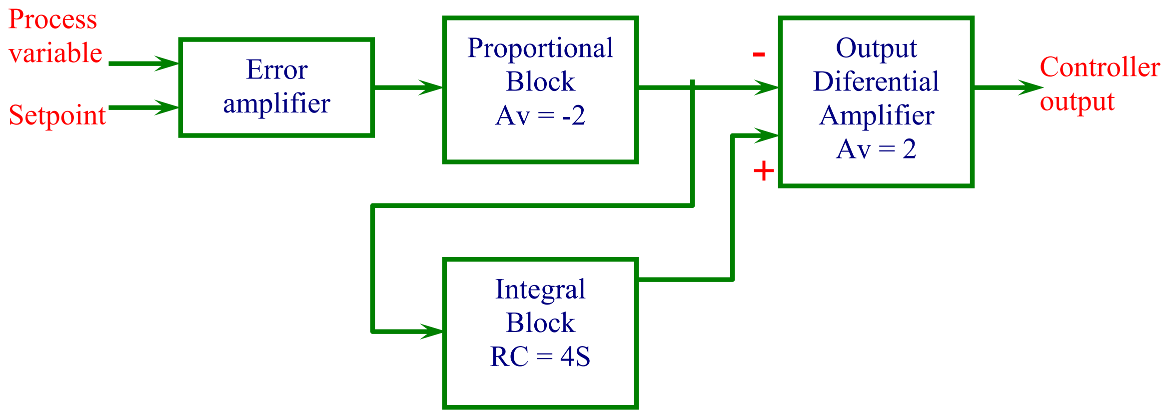
1. Draw the controller output.

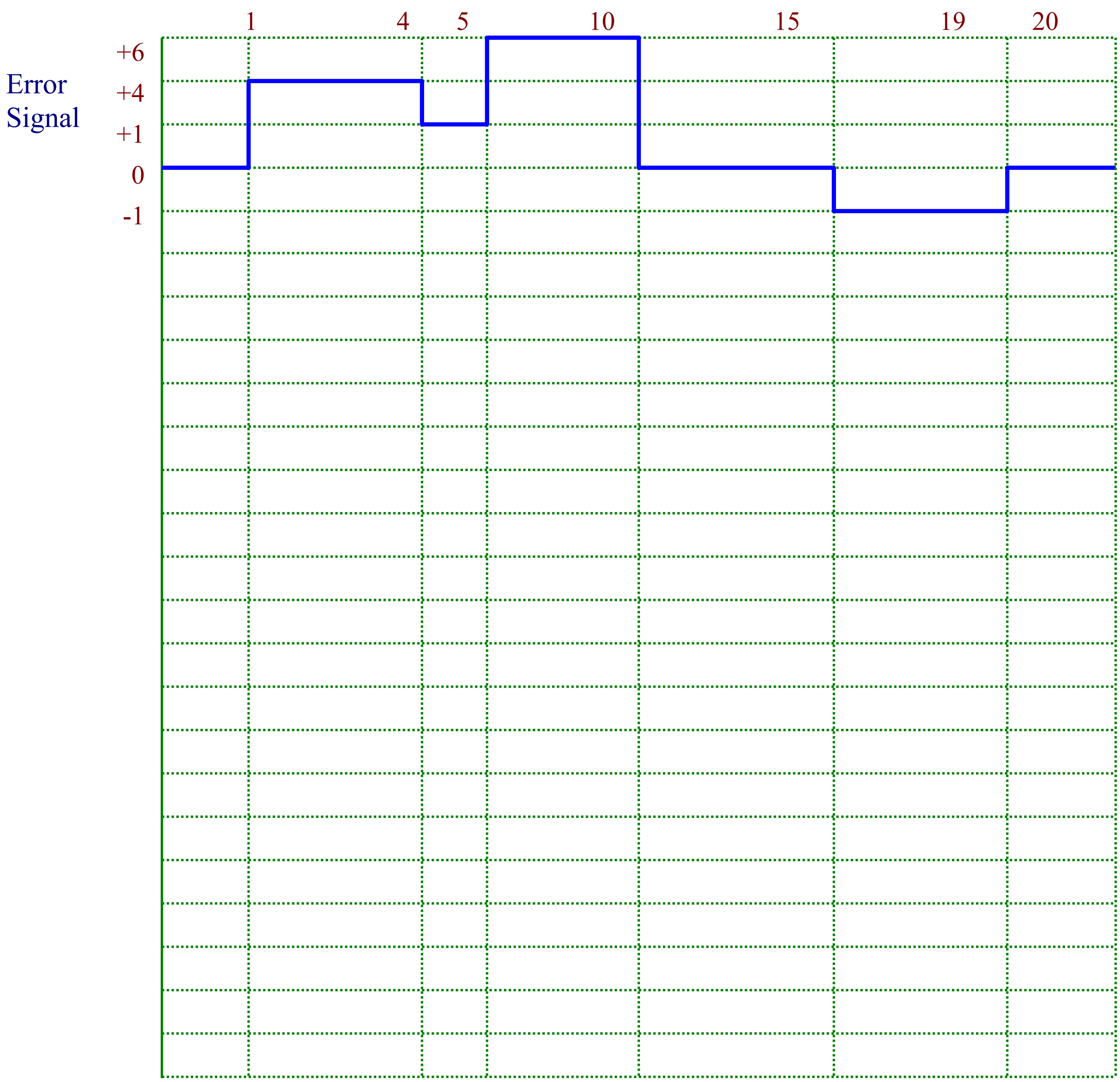
   The initial voltage in the integrator block is - 1 V. ± Vsat = ± 16 V.




1
3
6
7 Sec
+2V
Error
signal
0
-1V
-2V

2. Draw the controller output. (time in seconds).





SAN JOSE STATE UNIVERSITY

Department of Aviation & Technology

Tech 167: Control Systems Dr. Julio R. Garcia

Closed-Loop Systems

1. In the figure 1 shown below:

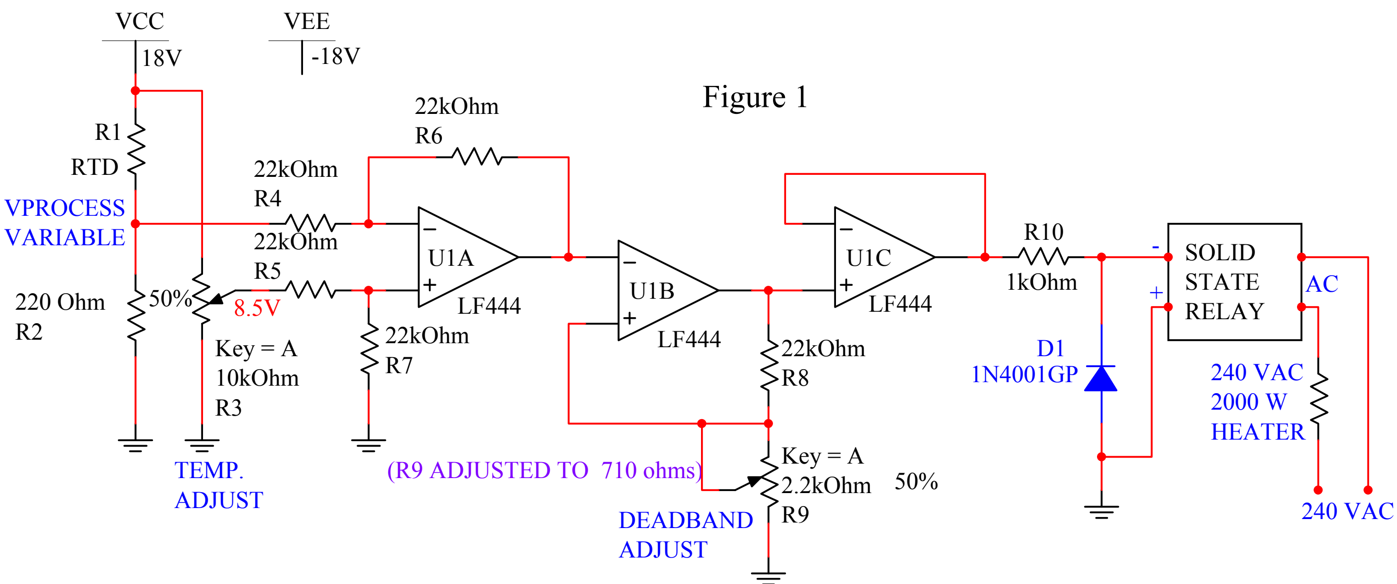


Figure 1

Analyze the circuit.

The circuit is an ON/OFF temperature control. This circuit controls the temperature of a reaction chamber shown in Figure 2.

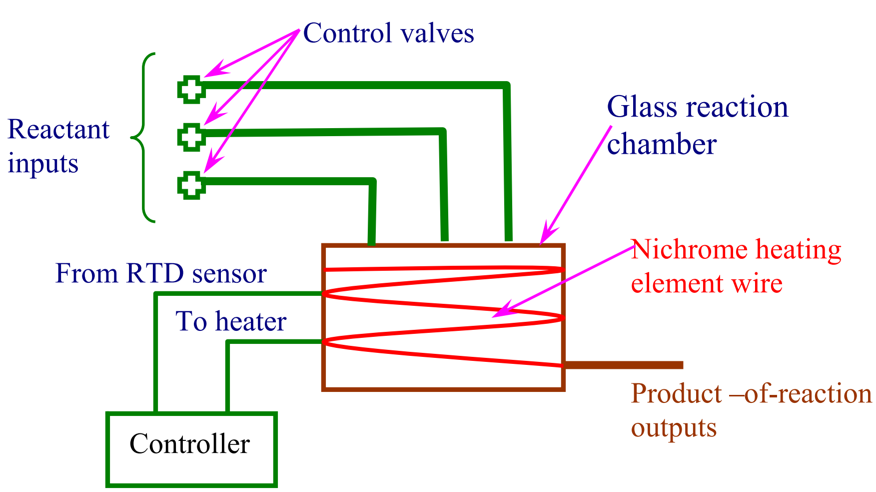


Figure 2

The internal temperature must be between 300°C and 500°C throughout the reaction.

U_{1A}: Differential amplifier, Gain = 1 because $R_4 = R_5 = R_6 = R_7 = 22$ kΩ.

U_{1B}: Window comparator

U_{1C}: Voltage follower (buffer)

Vprocess variable

Process-variable feedback is provided by R_1 (RTD sensor) assembly suspended inside the reaction chamber.

RTD: Resistance Temperature detector

R_1-R_2: voltage divider

R_1: RTD sensor. R = 100 Ω at 0°C.

PTC = 0.385Ω/°C → resistance increases 0.385Ω/°C

Usable temperature = - 200°C to 750°C, see Figure 3.

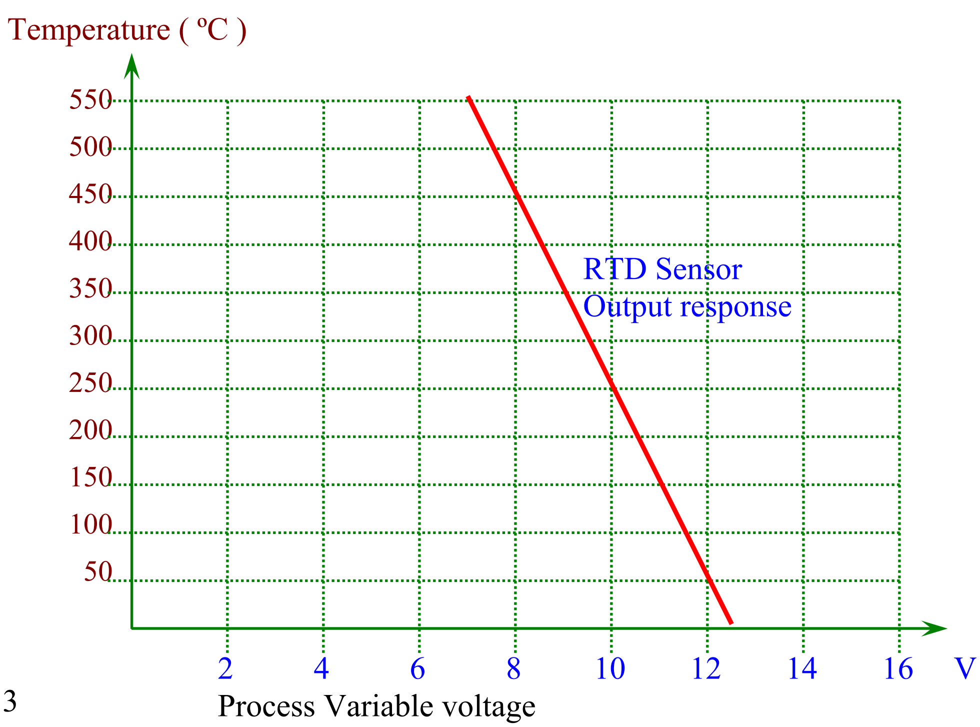


Figure 3

Vprocess variable = $[R_2/(R_1 + R_2)]\ (V_{CC})$

As $T \uparrow \Rightarrow R_1 \uparrow \Rightarrow$ Vprocess var $\downarrow$

R_1 = 100 Ω + 0.385Ω/°C (Temp in °C)

However, due to the overshoot in ON/OFF controllers, the thresholds are established between 350 °C to 450 °C.

When the heater is shut off at 350°C it will actually fall below this value maybe closer to 300°C. Likewise, when the heater is shut off at 450°C, the temperature will continue to rise to maybe 500°C.

From Figure 3 the Vprocess variable for 350°C is 9 V and for 450°C is 8 V.

Vtemp adj

Knowing these values, the Vtemp adj is adjusted to 8.5 V to allow the error voltage to vary – 0.5 V at 350°C to + 0.5 V at 450°C.

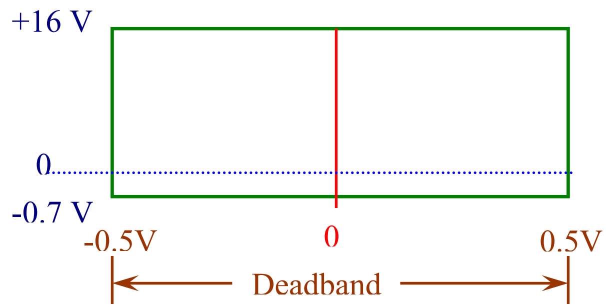
Window Comparator (U_{1B})

To maintain the 350°C - 450°C temperature range, the comparator must switch when one of these two thresholds (UTP = +0.5 V and LTP = -0.5 V) is reached.

$UTP = [R_9/(R_8 + R_9)]\ (+\ Vsat) = [710/(22k + 710)](16\ V) = +\ 0.5\ V$

$LTP = [R_9/(R_8 + R_9)]\ (-\ Vsat) = [710/(22k + 710)](-\ 16\ V) = -\ 0.5\ V$

The deadband is:



Buffer (U_{1C})

It isolates the load from U_{1B} to prevent asymmetrical saturation voltages.

Solid-state relay (ZVS = Zero Voltage Switching)

DC input: 3 V – 32 V, I = 5 mA

Output: controls from 24 VAC to 280 VAC, Iout = 10 A.

ZVS: Output will not switch into conduction unless the load potential at the time of triggering is about 10 VAC.

Output limiter: $R_{10} – D_1$.

System Operation

Let's assume that the system has been OFF for a period of time.

This means that Vo, $_{U1C}$ = - Vsat = - 16V

→ Vout, comparator = - 16 V → Vpin 5, $_{U1B}$ = LTP = - 0.5 V.

a) Vprocess var = + 13 V (See Figure 3, T = 25°C)

b) V_{error} = Vtemp adj – Vproc var = 8.5 – 13 = - 4.5 V

c) Since the voltage at pin 6 of comparator (U_{1B})= - 4.5 V (Verror) and the voltage at pin 5 of comparator = - 0.5 V, → Vout, comparator = + Vsat = + 16 V.

Thus,

1) The heater is turned ON, and
2) The voltage at pin 5 of comparator becomes UTP = + 0.5 V.

d) See Figure 3. As T ↑ ⇒ Vprocess var ↓ ⇒ Verror ↑ (Verror = 8.5 V – Vproc var)

e) When T > 450°C ⇒ Vprocess var < 8 V ⇒ Verror > + 0.5 V ⇒ Vout, comparator = - Vsat = - 16 V.

1) Heater is OFF. However, chamber temperature may continue to rise slightly, and
2) The voltage at pin 5 of comparator is LTP = - 0.5 V.

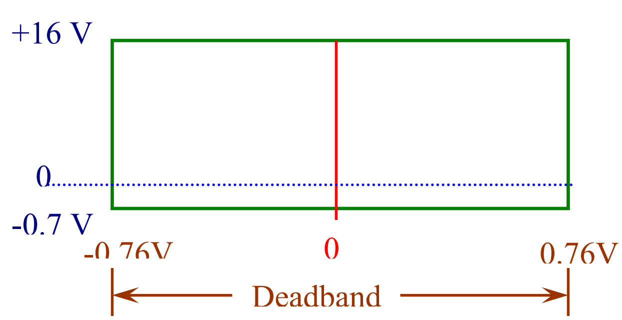
Problem 1: If the R_9 wiper is adjusted to 50% draw the transfer curve.

Solution

50% of R9 = 50% (2.2 kΩ) = 1.1 kΩ

$V_{UTP} = [R_9/(R_8 + R_9)] (+ Vsat) = [1.1/(22 + 1.1)] (16 V) = 0.76 V$

$V_{LTP} = [R_9/(R_8 + R_9)] (- Vsat) = [1.1/(22 + 1.1)] (- 16 V) = - 0.76 V$



Problem 2: If the R_9 wiper is adjusted to 70% draw the transfer curve.

Problem 3: If R_1 is substituted by an NTC thermistor, explain the circuit operation.

Solution
Heater will be ON at high temperatures and OFF at low temperatures. To correct this problem, switch the positions between R_1 and R_2.

Problem 4: What change(s) would you do to control the temperature between 200°C and 450°C.

Solution
We want 200°C $\leq$ Temp $\leq$ 450°C

Due to overshoot we need to control temperature between 250°C and 400°C.

From Figure 14-3:

250°C $\rightarrow$ V $\approx$ 10 V

400°C $\rightarrow$ V $\approx$ 8.6 V

Setpoint (Temp Adj) = (10 + 8.6)/2 = 9.3 V

Deadband = ± (10 – 9.3) = ± 0.7 V

Adjust R_9 until voltage at pin 5 of U_{1B} = ± 0.7 V

Problem 5: What change(s) would you do to control the temperature between 250°C and 400°C.

Problem 6: If the wipers of all potentiometers have been adjusted to 50% respect to ground and the temperature is 150°C, indicate the voltages and/or waveforms that appear at the following test points: (assume that the heater has been OFF for a long time).
U_{1A}: Pin 1, U_{1B}: Pin 7, U_{1C}: Pin 8

Solution

R_3 at 50% produces $V_{temp\ adj}$ = 9 V. (1/2 of V_{CC}, ½ of 18 V = 9 V)

At 150°C, $V_{process\ variable}$ = 11 V (See Figure 3)

Vout of Error Amp = 9 – 11 = - 2 V ⇒ **$U_{1A,\ pin\ 1}$ = - 2 V**.

Since the heater has been OFF for a long time, the voltage at pin 7 of U_{1B} = - Vsat. Thus, voltage at pin 5 of U_{1B} = - 0.76 V See problem 1).

Voltage at pin 6 of U_{1B} = - 2 V. This makes the output **(pin 7) of U_{1B} = + Vsat = + 16 V.**

Since U_{1C} is a voltage follower, $U_{1C,\ pin\ 8}$ = **+ Vsat = + 16 V.**

Problem 7: If the wipers of all potentiometers have been adjusted to 70% respect to ground and the temperature is 200°C, indicate the voltages and/or waveforms that appear at the following test points: (assume that the heater has been OFF for a long time).
U_{1A}: Pin 1, U_{1B}: Pin 7, U_{1C}: Pin 8

Problem 8: What would happen if the gain of U_{1A} were increased?

Solution

Unless some changes are made, the heater's temperature span will be lower than the 350°C and 450°C.

Problem 9: What would happen if R_8 opens?

Solution
Comparator (U_{1B}) will switch between +Vsat to –Vsat with a few mV at pin 6. Therefore, the circuit cannot effectively control the temperature at the reaction chamber.

Problem 10: What would happen if D_1 opens?

Solution
Solid-state relay will damage due to the excessive negative voltage applied to its internal LED when Vo of U_{1C} (pin 8) reaches – Vsat. D_1 protects the internal LED of the relay against high negative voltage.

Problem 11: If diode D1 were reversed, what would happen with the operation of the circuit?

Solution

If diode D_1 were reversed then solid-state relay will be damaged during the –Vsat swing from the output of U_{1C} (pin 8).

Problem 12: If diode D1 were shorted, what would happen with the operation of the circuit?

Solution

If diode D_1 were shorted, op-amp U_{1C} might overheat, solid-sate relay will be OFF all the time and the heater will be OFF.

See Figure 4 below.

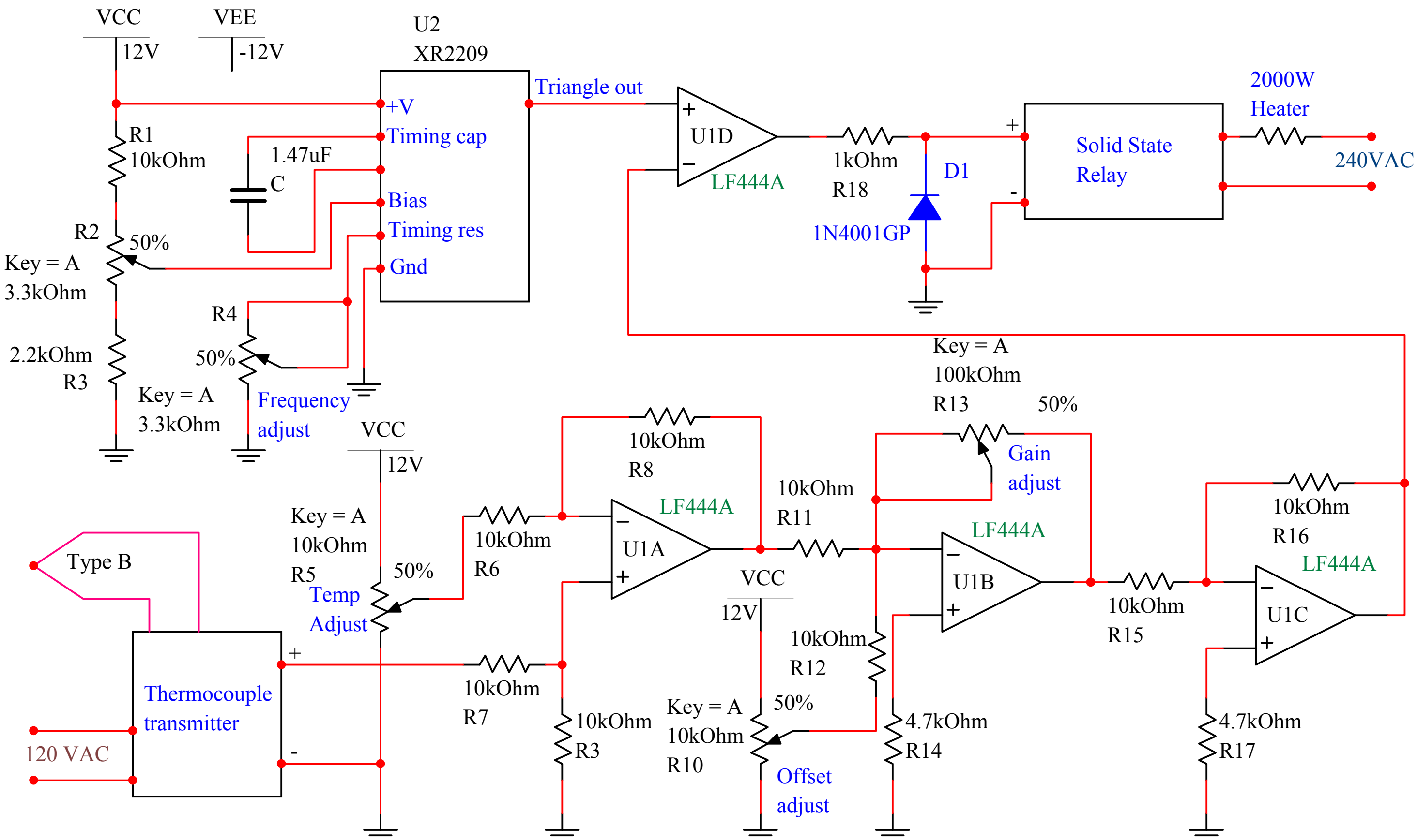


Figure 4

Analyze the circuit.

This circuit is a PWM Temperature controller. This circuit will maintain the temperature in the reaction chamber much closer to a set-point by varying the ratio of ON time to total cycle time (ON time + OFF time) for the solid-state relay.

U_{1A}: Error amplifier. Gain = 1

U_{1B}: Inverting summing amplifier. Gain = - 1.

U_{1C}: Inverting amplifier. Gain = - 1.

Note: U_{1B} and U_{1C} constitute a non-inverting summing amplifier with Gain = 1.

U2: Triangle wave oscillator

U_{1D}: Pulse-width modulator

Thermocouple sensor

1) Type E thermocouple
2) Thermocouple transmitter
    a) Produces linear output over selected temperature range.
    b) Provides cold-junction compensation for the thermocouple.
3) Provides DIP switches and trim pots for temperature range and output.
    a) Current loop: 4 – 20 mA, etc
    b) Voltage: 0 – 5 V, 0 –10 V, etc.

In this case, the thermocouple transmitter has been configured for an output of 0 – 10 V over a temperature range of 0°C - 600°C. See Figure 5.

Summing Amp, Inverting Amp (U_{1B}, U_{1C})

Form a non-inverting summing amp. They provide an output offset adjustment to the controller. This adjustment is critical because it prevents the controller from turning OFF the heater completely when error is zero (0).

R_{13}: adjust controller gain and sensitivity to temperature changes.

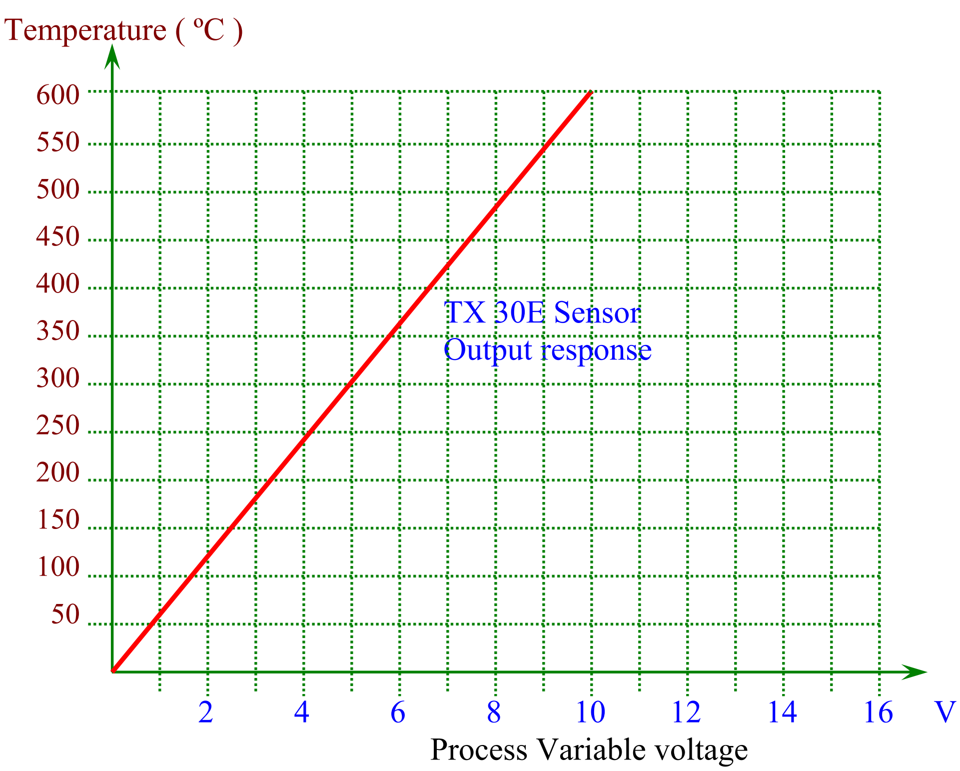


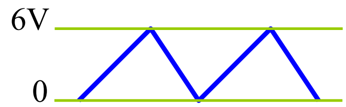
Figure 5

Triangle-wave oscillator.

U_2 = XR2209 or equivalent such as XR 2206. It is actually a square/triangle oscillator.

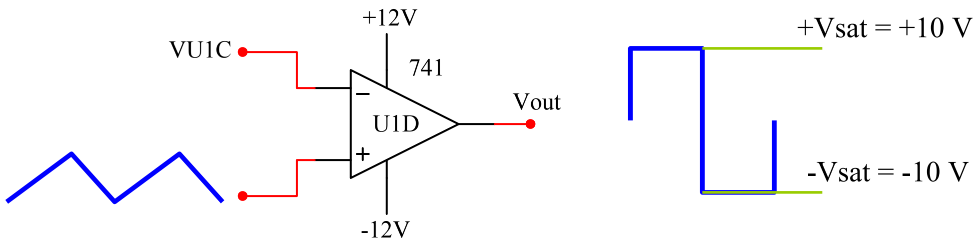
$F = 1/(R_4 C)$. In this case, R_4 is adjusted to obtain a freq of 6 Hz.

Vout =



½ Vcc = 6 V

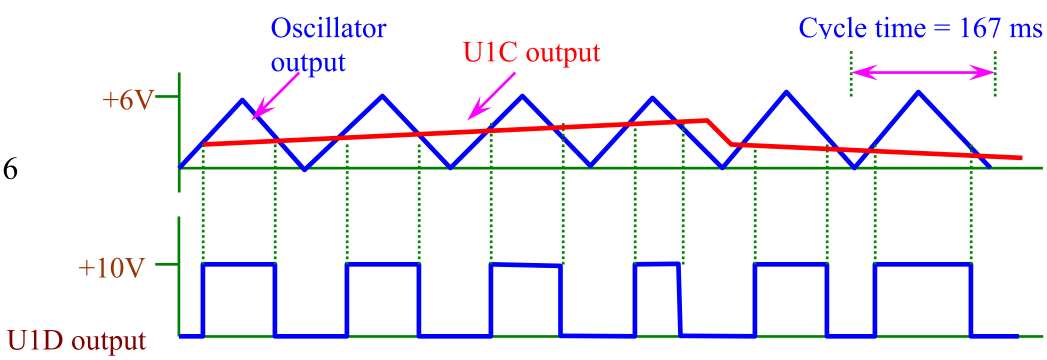
Pulse-width modulator



When V > V_{U1C} → Vout = + Vsat = + 10 V (See Figure 6)

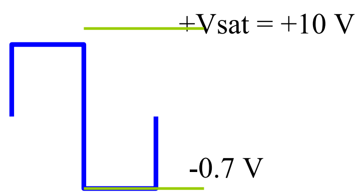
When V < V_{U1C} → Vout = - Vsat = - 10 V

Figure 6



Output Limiter

R_{18} – D.



Solid-State Relay

Similar to the one described in Figure 2.

The duty cycle of output U_{1D} related to load voltage is shown in Figure 7. The duty cycle is variable between 0 and 100% in increments of 5%.

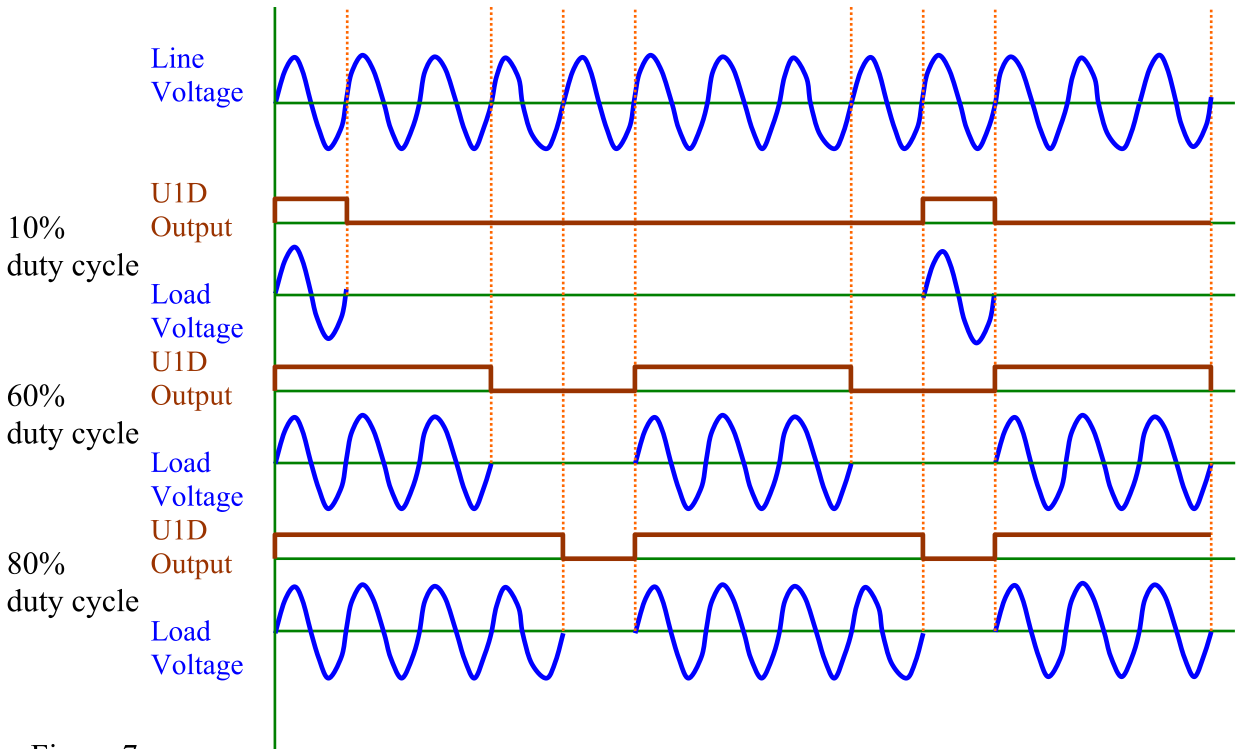


Figure 7

System Operation

1. Let's assume the following:
   a) The heater has returned to ambient temperature (25°C)
   b) Vtemp adj = 6 V (R_5)
   c) Voffset adj = 1.5 V (R_{10})
   d) R_{13} = 20 kΩ (This yields a gain of 2)

2. At ambient temperature (25°C), Vproc var = 0.5 V (see Figure 5)

3. Verror = Vproc var – Vtemp adj= 0.5 – 6 = - 5.5 V

4. V_{U1C} = Av (Verror + Voffset adj) = 2 (- 5.5 + 1.5) = - 8 V

   Since $V_{\wedge\wedge}$ > V_{U1C} → V_{U1D} = + Vsat → Heater ON

   Mathematically, the output of U_{1C} is:

   V_{U1C} = 2 [(Vproc var – Vtemp adj) + Voffset adj]

   V_{U1C} = 2 [(Vproc var – 6V) + 1.5 V] (Eq. 1)

5. As Temp ↑ ⇒ Vproc var ↑ ⇒ V_{U1C} ↑

6. The heater will be ON continuously until V_{U1C} = 0 V. This will happen when:

   V_{U1C} = 2 [(Vproc var – 6V) + 1.5 V] = 0 ⇒ Vproc var = 4.5 V

   From Figure 5 ⇒ Temp ≈ 270°C

7. When Temp = 300°C ⇒ V_{U1C} = + 1.0 V

   Therefore, solid-state relay will not be ON until $V_{\wedge\wedge}$ > + 1 V

8. When Temp = 350°C ⇒ V_{U1C} = + 2.8 V

9. When Verror = 0 (Vproc var = Vtemp adj), V_{U1C} = + 3 V (From Equation 1).

Thus, 350°C corresponds to zero error. This is the theoretical temperature setting of the controller.

10. It is difficult to predict whether a 50% duty cycle will cause the chamber temperature to rise, to fall, or to stay the same.

    It can be predicted, however:

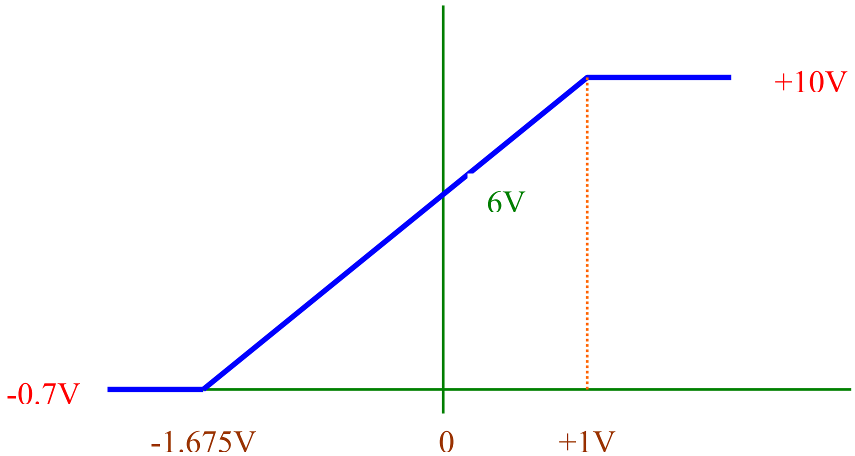
    a) If Temp ↑ ⇒ Duty cycle ↓
    b) If Temp ↓ ⇒ Duty cycle ↑

11. The controller will vary the duty cycle proportionally over a temperature range of approximately 250°C - 450°C. The actual chamber temperature will not vary nearly this much. It will vary slightly around the set point.

12. If Gain ↑ (R13) ⇒ Duty cycle will change more drastically for smaller temperatures (sensitivity ↑).

13. If Vtemp adj ↑ ⇒ chamber will reach a higher temperature before duty cycle decreases enough to reduce power to heater.

Problem: If R_{13} is adjusted to 40 kΩ draw the transfer curve.



Gain = 4

Since Voffset = 1.5 V, then Vo = 4 (1.5V) = 6 V (When error = 0)

Error min = Vout,min/Av – Voffset = (-0.7V/4) – 1.5 = - 1.675 V

Error max = Vout,max/Av – Voffset = (10V/4) – 1.5 = 1 V

Proportional band = (Vout,max - Vout,min)/Av = [10 – (- 0.7)]/4 = 2.675 V

Problem: If R_{13} is adjusted to 60 kΩ draw the transfer curve.

Problem: If the oscillator frequency is adjusted to 1 kHz, would the controller operate properly? Explain.

Solution: No, heater will not have continuous power.

Problem: If a random-trigger solid-state relay were substituted for the ZVS relay, would the controller operate properly? Explain.

Solution

No, heater may be damaged because hen heater is OFF, resistance is about 0 ohms. If solid-state relay is ON and VAC is at its peak, too much current will be developed.

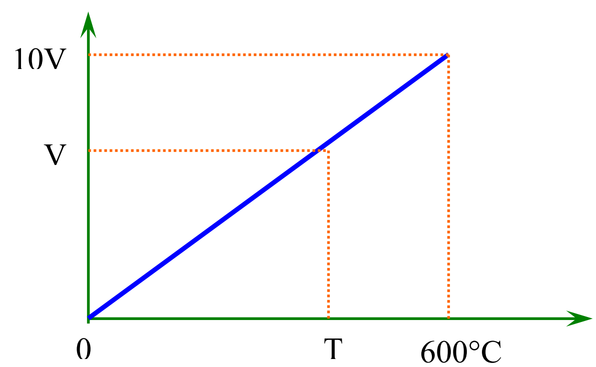
Problem: Is it possible to eliminate U_{1C}? Explain.

Solution

Not in this circuit because we need a noninverting output at U_{1C}.

Assume that R_{13} = 25k, Temp adjust = 3.965V and Offset adjust = 1.25 V.

Problem: When the error is zero, calculate the *exact* chamber temperature.



600°C/10 V = T/V

600°C/10 V = T/3.965V

T = [(600°C) (3.965V)]/10V = 237.9°C

Problem: If resistor R_{13} shorts, what would happen with the operation of the circuit?

Solution

If R_{13} shorts then the gain of the non-inverting summing amplifier is zero. Thus, the voltage at pin 13 of U_{1D} = 0 and since the voltage at pin 12 of U_{1D} > 0, the output of U_{1D} = + Vsat. This makes the heater ON fully.

Problem: If capacitor C were reduced by half, what would happen with the operation of the circuit?

Solution

If capacitor C were reduced by half, then the frequency of the triangle wave doubles. It will go from 6 Hz to 12 Hz. Period will be 1/12 = 83 ms, and a 10% duty cycle will be 8.3 ms. Since the line frequency is 60 Hz, the period is 16.6 ms, and at 10% duty cycle only half of a sine wave will feed the heater. In this case, some adjustments need to be made to keep the chamber temperature within the desired temperature within a narrow range.

Problem: If capacitor C were reduced by fourth, what would happen with the operation of the circuit?

Problem: Assume that R_{13} = 25k, Temp adjust = 5V and Offset adjust = 1.4 V. If the output from the thermocouple is 3.5 V, calculate the voltages at the following points:

Pin 2 (U_{1A}); Pin 3 (U_{1A}); Pin 6 (U_{1B}); Pin 5 (U_{1B}); Pin 9 (U_{1C}); Pin 10 (U_{1C})

Solution

The voltage at pin 3 of U_{1A} is equal to V_{R3}.

$V_{R3} = [R_3/(R_3 + R_7)]$ (Vthermocouple) = [10k/(10k + 10k)](3.5 V) = 1.75 V.

Since the voltage between pins 2 and 3 of U_{1A} = 0 (ed = 0), voltage at pin 2 of U_{1A} = 1.75 V.

Thus,

Pin 2 (U_{1A}): 1.75 V	Pin 3 (U_{1A}): 1.75 V	Pin 6 (U_{1B}): 0
Pin 5 (U_{1B}): 0	Pin 9 (U_{1C}): 0	Pin 10 (U_{1C}): 0

Problem: Assume that R_{13} = 25k, Temp adjust = 5V and Offset adjust = 1.4 V. If the output from the thermocouple is 4.5 V, calculate the voltages at the following points:

Pin 2 (U_{1A}); Pin 3 (U_{1A}); Pin 6 (U_{1B}); Pin 5 (U_{1B}); Pin 9 (U_{1C}); Pin 10 (U_{1C})

Problem: When the temperature reaches 250°C, indicate the voltages and/or waveforms that appear at the following test points. (Assume that the heater has been OFF for a long time). $U_{1A;}$ Pin 1; U_{1B}: Pin 7; U_{1C}: Pin 8

Solution

According to the condition of the circuit, Vtemp adj = 6 V.

At 250°C, Vprocess var = 4 V

U_{1A}: Pin 1 = Vprocess var – Vtemp adj = 4 – 6 = **- 2 V**

In addition, R_{13} has been adjusted to 20k and Voffset adj = 1.5 V.

U_{1B}: Pin 7 = Av U_{1B} (U_{1A},out + Voffset adj) = - 2 (- 2 + 1.5) = **+ 1 V**

U_{1C}: Pin 8 = **- 1 V** (Inverting amplifier)

Problem: When the temperature reaches 350°C, indicate the voltages and/or waveforms that appear at the following test points. (Assume that the heater has been OFF for a long time). U_{1A}: Pin 1; U_{1B}: Pin 7; U_{1C}: Pin 8

Problem: If R_{14} shorts then the voltage at pin 7 of U_{1B} is:

Solution
If R_{14} shorts practically nothing will change.

Problem: Assume that R_{13} has been adjusted to 15k and we need to maintain the temperature at around 400°C. Indicate all the change(s) that you would do.

Solution

1) Adjust R_5 until Vtemp adj ≈ 6 V (see figure 5)
2) Adjust R_{10} until Voffset = 4.4 V/1.5 = 2.9 V.

This is because at 400°C the U_{1C} output = + 4.4 V. In addition, the gain of the noninverting summing amp is R_{13}/R_{11} = 15k/10k = 1.5.

Problem: Assume that R_{13} has been adjusted to 25k and we need to maintain the temperature at around 300°C. Indicate all the change(s) that you would do.

Problem: When the chamber temperature reaches 410°C, indicate the voltage(s) at pin 8 of U_{1C}.

Solution

From Figure 5.

400°C – 6 V

410°C – X

X = [(410°C)(6 V)]/400°C = 6.15 V.

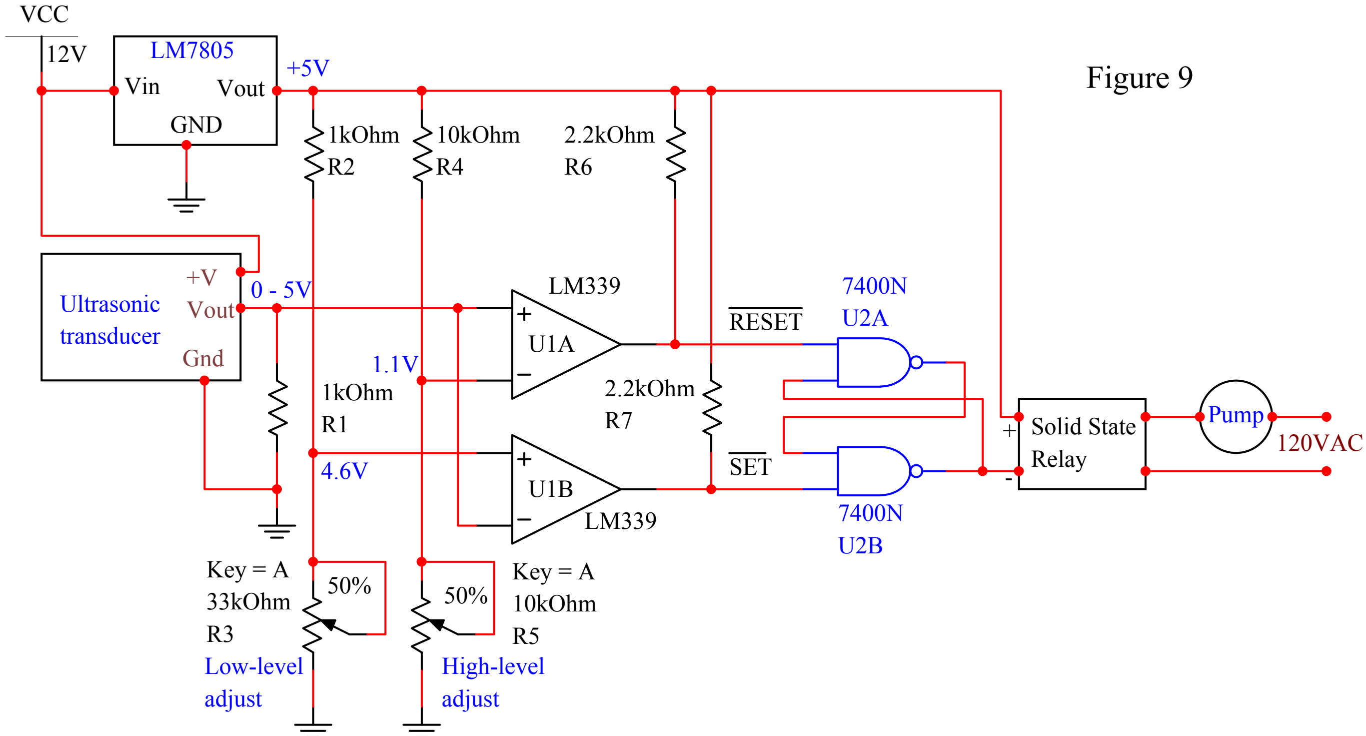
V_{U1A}, pin 1 = 6.15 – 6 = 0.15 V

V_{U1B}, pin 7 = - 1.5 (0.15 + 2.9) = - 4.58 V

V_{U1C}, pin 8 = + 4.58 V

Problem: When the chamber temperature reaches 330°C, indicate the voltage(s) at pin 8 of U_{1C}.

See Figure 9 below.



Set	Reset	Pump Control	Condition
L	L	---------------	This condition will never occur
L	H	H (pump OFF)	Water level has fallen below low threshold
H	L	L(Pump ON)	Water level has risen above high threshold
H	H	Unchanged	Water level is between two thresholds

Analyze the circuit.

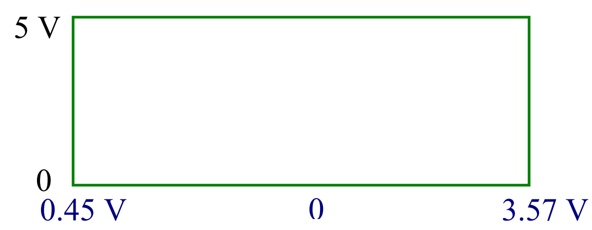
At least do this on your own.

Problem: If $R_3 = 2.5$ kΩ and $R_5 = 1$ kΩ draw the transfer curve.

Solution

$V_{R3} = [R_3/(R_2 + R_3)]\ (V_{CC}) = [2.5/(2.5 + 1)](5\ V) = 3.57\ V$

$V_{R5} = [R_5/(R_4 + R_5)]\ (V_{CC}) = [1/(10 + 1)](5\ V) = 0.45\ V$



Problem: If $R_3 = 1.5$ kΩ and $R_5 = 2$ kΩ draw the transfer curve.

Problem: If the voltage across R_5 were higher than the voltage across R_3, would the controller operate properly? Explain.

Solution

With the values shown in Figure 9, the pump will be ON when the water reaches the level of 10 inches from the sensor. The pump will be OFF when the level of the water drops to 28 inches from the sensor.

According to Figure 10, when the distance from the sensor is 10 inches, the output voltage from the sensor is 1.1 V. Likewise, the output voltage is 4.6 V when the distance reaches 28 inches.

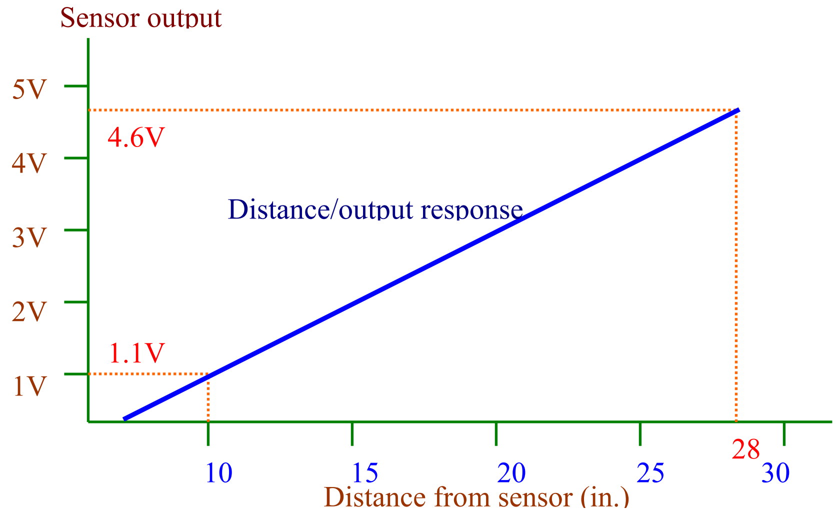


Figure 10

Now, assume that the voltage across R_5 were 3 V (High-level adj) and the voltage across R_3 were 2 V (Low-level adj). When the sensor output is 2.9 V, the voltage at pin 4 of U_{1A} (inverting input) is higher than the voltage at pin 5 of U_{1A} (non-inverting input). This makes the output of U_{1A} (pin 2) = 0. Thus, $\overline{RESET} = 0$. By the same token, the voltage at pin 6 of U_{1B} (inverting input) is higher than the voltage at pin 7 of U_{1B} (non-inverting input). This produces a zero output at pin 1 of U_{1B}. Therefore, $\overline{SET} = 0$.

We then have the condition that $\overline{SET}$ and $\overline{RESET}$ are both active. This is unacceptable in a RS-latch. In conclusion, the circuit won't operate properly.

Problem: What would happen if $\overline{SET}$ and $\overline{RESET}$ become LOW? Explain.

The output is unpredictable. In a RS-latch, $\overline{SET}$ and $\overline{RESET}$ cannot be active simultaneously.

The pump will be ON when the output of U_{2A} is____________________ (HIGH/LOW), and the output of U_{2B} is_________________________(HIGH/LOW).

Problem: Resistors R_6 and R_7 are needed because…..

Solution
the LM 339 IC has open-collector outputs.

Problem: When the output of the ultrasonic transducer is 1.09 V, the output of U_{2A} is__________ (HIGH/LOW), and the output of U_{2B} is____________________________(HIGH/LOW).

Problem: If R_3 and R_5 are adjusted to 50% respect to ground, calculating the values of $V_{LOW\ LEVEL}$ and $V_{HIGH\ LEVEL}$

Solution

V_{LOW} = [16.5/(1 + 16.5)] (5 V) = 4.7 V

V_{HIGH} = [5/(10 + 5)] (5 V) = 1.67 V

Problem: If R_3 and R_5 are adjusted to 70% respect to ground, calculating the values of $V_{LOW\ LEVEL}$ and $V_{HIGH\ LEVEL}$