

INSTRUCTOR'S SOLUTIONS MANUAL  
TO ACCOMPANY

# **FUNDAMENTALS OF MECHATRONICS**

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## Chapter 1 – Introduction to Mechatronics

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### Questions

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#### 1.1 What is mechatronics?

Mechatronics is the field of study concerned with the design, selection, analysis and control of systems that combine mechanical elements with electronic components as well as computers and/or microcontrollers. Mechatronics topics involve elements from mechanical engineering, electrical engineering, and computer science, and the subject matter is directly related to advancements in computer technology.

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#### 1.2 What are the elements of a mechatronic system?

The elements include mechanical system, sensors, actuators, controller, drive circuits, and signal conditioning devices, but not all of these elements need to be present.

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#### 1.3 How are mechatronic systems implemented?

They are implemented using a PC or a microcontroller as the control element.

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### Problems

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#### P1.1

##### a. Air bag

Most air bag safety systems use two sensors. A “crash” sensor that is located in the crush zone of the vehicle to detect the collision, and a “safety” or “arming” sensor that is located in the passenger compartment area to prevent false deployment of the air bag. The “crash sensor” could be a ball and tube design where a small metallic ball is held by a magnet at one end of a small tube. Under the force of the crash, the ball moves from its location and touch a switch at the other end of the tube. The “crash” sensor could also be a piezoceramic or an integrated circuit accelerometer. The “arming” sensor is similar to the “crash” sensor but it is designed to trigger at lower threshold levels.

##### b. Door locks

A powered door lock has electronic circuits to process the lock/unlock signals from keys and an electric actuator to move the lock. The actuator consists of a small DC motor connected through a system of gears to a rack that converts the rotational motion of the motor into a linear motion of the rack to move the lock up and down.

c. Powered side mirrors

A powered side mirror has two actuators to rotate the mirror about two axes. It has also sensors to detect the position of the mirror. Some mirrors are also equipped with a heating element to remove snow and ice from mirror.

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**P1.2**

a. Modern washing machine

Electronic control circuit, control switches and knobs, a 110 or 220 volts electric motor with transmission elements to rotate the drum, solenoids to control the flow of water, an electric pump to empty the water from the drum, a door closure sensor, water level and temperature sensors, a balance detection sensor for the drum, a sensor for soiled water (in some models), a timer, and a heater (in some models) to heat the water. Some newer models have sensors that measure the weight of the clothes.

b. Servo-driven industrial robot

Brushless DC motors, incremental or absolute encoders, proximity limit switches, control circuit, teach pendant, servo amplifiers, controller, and digital I/O modules. Many robots are also equipped with additional application-specific sensors such as vision and force sensors.

c. Automated entry door

Non-contact traffic flow sensors, drive motor with transmission elements, control and motor drive circuits, end of travel limit sensors, and in-door obstacle detection sensors.

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## Chapter 2 – Analog Circuits and Components

### Questions

**2.1** Define what is meant by an analog circuit.

An analog circuit is one in which the voltage is continuous and can have any value over a specified range.

**2.2** Name the two laws that are used to analyze electrical circuits.

Kirchhoff's Voltage Law (KVL) and Kirchhoff's Current Law (KCL).

**2.3** List the different types of toggle switches.

Single pole, single throw (SPST); single pole, double throw (SPDT); double pole, single throw (DPST); and double pole, double throw (DPDT).

**2.4** Define impedance.

Impedance is a generalization of the concept of resistance, and for a two-terminal element is defined as the ratio of the voltage to the current in that element.

**2.5** What impedance characteristic is desirable in measuring devices and why?

Should have high input impedance to minimize loading effects.

**2.6** What device has very large impedance at low frequencies?

A capacitor has very high impedance at low frequencies since its impedance is proportional to the inverse of its capacitance.

**2.7** What characteristic of an op-amp makes it useful to use it as an interface?

Its high input impedance and low output impedance make it useful to use as an interface.

**2.8** List the two rules that are used to analyze ideal op-amp circuits.

The assumption that  $V_+ = V_-$  along with the assumption that no current flows into the input terminals are the two basic rules that are used to analyze ideal op-amp circuits.

**2.9** List different types of op-amp circuits.

Op-amps circuits include those used for comparison, amplification, inversion, summation, integration, differentiation, or filtering.

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**2.10** What type of op-amp circuit is used in the implementation of an analog proportional control feedback loop?

A differential op-amp circuit to compute the error signal and an inverting op-amp circuit to implement the proportional gain.

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**2.11** Can the output voltage of an op-amp circuit exceed the supply voltage?

No the output cannot exceed the supply voltage.

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**2.12** List an advantage of AC signals.

Can be transmitted over long distances with small resistance losses.

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**2.13** Name one way to avoid a ground loop.

To connect all return paths in a circuit to a common ground point.

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**2.14** Define real power of an AC circuit.

It is the power absorbed by the load in the circuit and is equal to the product of RMS current, the RMS voltage, and the power factor.

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**2.15** List several applications of solenoids.

Solenoids are commonly used for on-off applications such as locking or triggering. Such applications include switching of electromechanical relays, door locks, ratcheting devices, and gate diverters.

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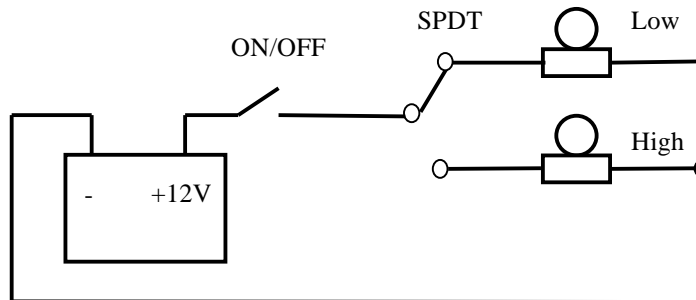
**2.16** What is a relay?

A relay is an electrically actuated switch that uses a solenoid to make or break the mechanical contact between electrical leads.

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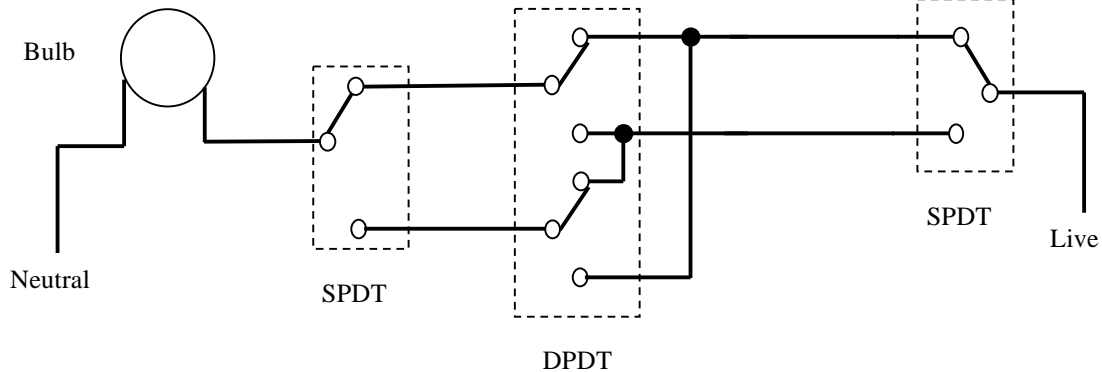
## Problems

### P2.1

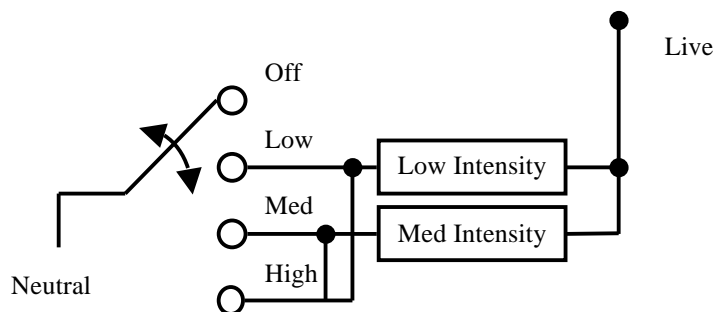


- P2.2** *Door bell switch: NO* (the door bell is activated when the switch is pressed down)  
*Refrigerator door light switch: NC* (the switch opens when the refrigerator door is closed)  
*Computer keyboard switch: NO* (the switch is activated when it is pressed down)

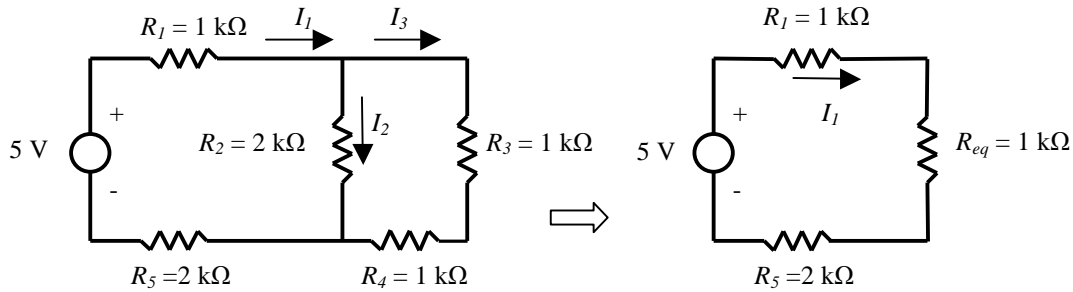
### P2.3



**P2.4** The switching circuit is shown below:



**P2.5** The given circuit can be simplified as shown below:



Note that  $R_3$  and  $R_4$  are resistors in series and their equivalent resistance  $R_{34}$  is  $2\text{ k}\Omega$ . The resistor  $R_2$  and resistance  $R_{34}$  are resistors in parallel and their equivalent resistance  $R_{eq}$  is equal  $1\text{ k}\Omega$ . The current  $I_1$  is then given as:

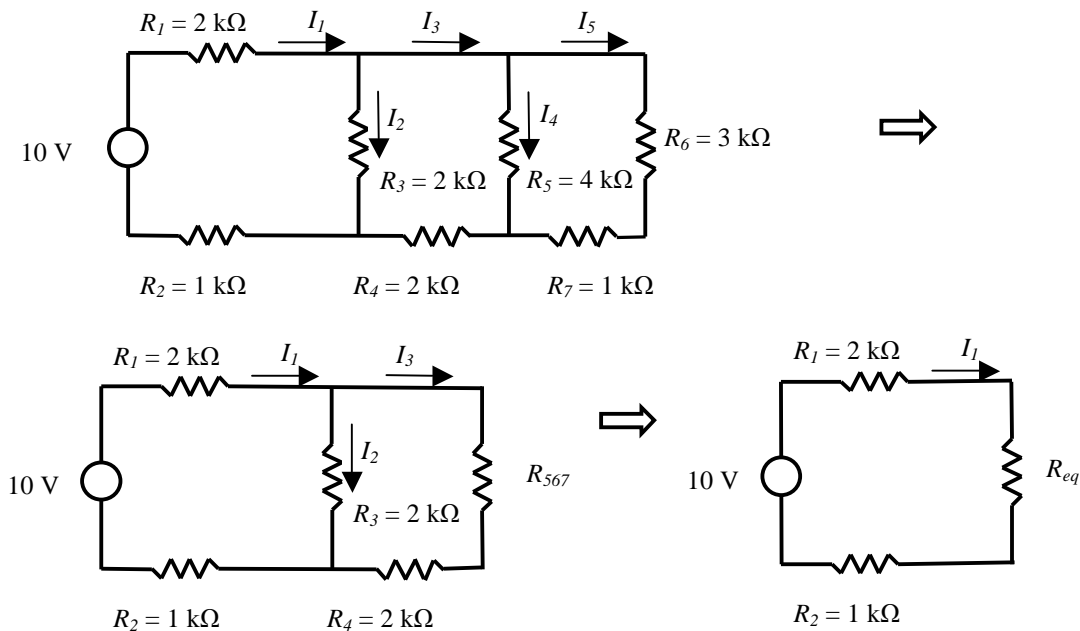
$$I_1 = \frac{5\text{ V}}{R_{Total}} = \frac{5}{1+1+2} = \boxed{1.25\text{ mA}}$$

The voltage drop across  $R_{eq}$  is given by:

$$\frac{5}{4} \cdot 1 = 1.25\text{ V}$$

Thus  $I_2$  is given as  $1.25\text{V}/2\text{ k}\Omega = \boxed{0.625\text{ mA}}$ . From KCL,  $I_3 = I_1 - I_2 = \boxed{0.625\text{ mA}}$ .

**P2.6** The given circuit can be simplified as shown below:



Note that  $R_6$  and  $R_7$  are resistors in series and their equivalent resistance  $R_{67}$  is  $4\text{ k}\Omega$ . The resistor  $R_5$  and resistance  $R_{67}$  are resistors in parallel and their equivalent resistance  $R_{567}$  is



equal 2 kΩ. Similarly,  $R_4$  and  $R_{567}$  are resistors in series and their equivalent resistance  $R_{4567}$  is 4 kΩ. The resistor  $R_3$  and resistance  $R_{4567}$  are resistors in parallel and their equivalent resistance  $R_{eq}$  is equal 4/3 kΩ. Thus, the current  $I_1$  is then given as:

$$I_1 = \frac{10\text{ V}}{R_{Total}} = \frac{10}{2+4/3+1} = \boxed{2.31\text{ mA}}$$

The voltage drop across  $R_{eq}$  is given by:

$$\frac{4/3}{13/3} 10 = \boxed{3.08\text{ V}}$$

Thus  $I_2$  is given as  $3.08\text{V}/2\text{ k}\Omega = \boxed{1.54\text{ mA}}$ . From KCL,  $I_3 = I_1 - I_2 = \boxed{0.77\text{ mA}}$ . Since  $R_5 = R_6 + R_7$ , then  $I_4 = I_5 = 0.77/2 = \boxed{0.385\text{ mA}}$ .

### P2.7

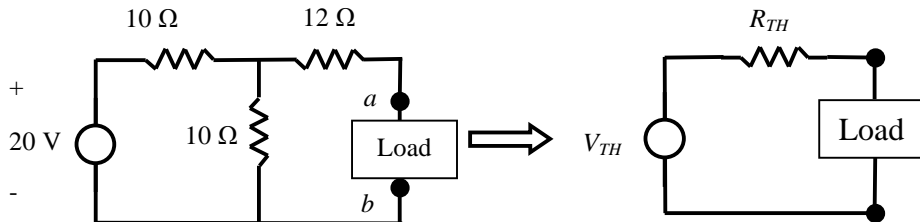
The voltage across the load resistor is given by:

$$\frac{100}{100 + R_S} 24 = 23$$

Solving for  $R_S$  gives  $\boxed{R_S = 4.34\ \Omega}$

### P2.8

a.



We start by determining the open circuit voltage at the terminals  $a$  and  $b$  when the load is removed. This is the same as the voltage drop across the  $10\ \Omega$  resistor opposite to the terminals  $a$  and  $b$ , thus  $\boxed{V_{TH} = 10\text{ V}}$ . To determine  $R_{TH}$ , we find the total resistance of this circuit at the terminals  $a$  and  $b$  when  $V_S$  is short circuited. In this case, the two  $10\ \Omega$  resistors act as two resistors in parallel with an effective resistance of  $5\ \Omega$ . This  $5\ \Omega$  resistor is in series with the  $12\ \Omega$  resistor. Thus  $\boxed{R_{TH} \text{ is } 17\ \Omega}$  ( $5+12$ ). The Thevenin equivalent circuit is shown above.

b.

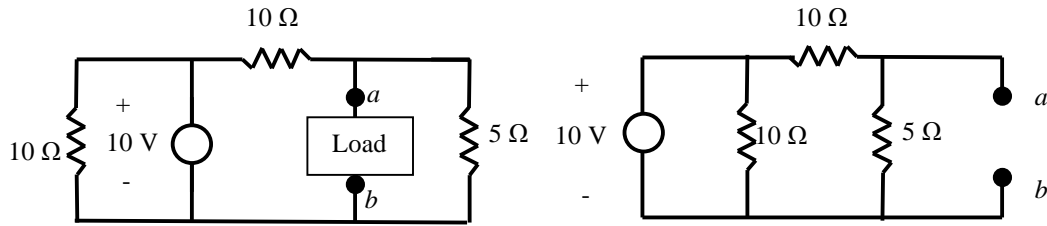


Fig. A

Fig. B

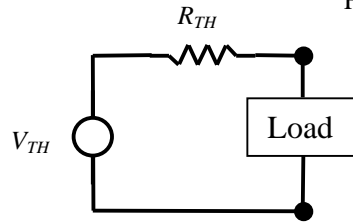


Fig. C

We start by determining the open circuit voltage at the terminals  $a$  and  $b$  when the load is removed. This is the same as the voltage drop across the  $5\ \Omega$  resistor as seen in Figure B above. This is equal to  $\boxed{10/3\ \text{V}}$ . To determine  $R_{TH}$ , we find the total resistance of this circuit at the terminals  $a$  and  $b$  when  $V_S$  is short circuited. When  $V_S$  is short circuited, the vertical  $10\ \Omega$  resistor does not come to play, and the circuit simply consists of the  $5\ \Omega$  resistor and the  $10\ \Omega$  horizontal connected as two resistors in parallel. Their effective resistance is  $10/3\ \Omega$ . Thus  $\boxed{R_{TH}\ \text{is}\ 10/3\ \Omega}$ . The Thevenin equivalent circuit is shown in Figure C.

**P2.9**  $\omega = 2\pi f = 2\pi(60) = 120\pi\ \text{rad/s}$

a) For a resistor,  $Z_R = R = 1000\ \Omega$

b) For an inductor,  $Z_L = j\omega L = 0.5 \times 120\pi j = 188.5\ \Omega j$

c) For a capacitor,  $Z_C = \frac{-1}{\omega C} j = \frac{-1}{120\pi(1 \times 10^{-6})} j = -2653\ \Omega j$

Total impedance =  $Z_R + Z_L + Z_C = \boxed{(1000 - 2464 j)\ \Omega}$

**P2.10** The angle  $\theta$  is given as  $\tan^{-1}(-2464/1000) = -67.91^\circ$

Power factor =  $\cos(\theta) = \cos(-67.91^\circ) = \boxed{0.376}$

**P2.11** The current through the load is given as:

$$I = V/Z = 110/Z = 0.2 \rightarrow Z = 550\ \Omega$$

The power factor =  $\cos \theta = X/R = 0.8$ , we get  $X = 0.8R$

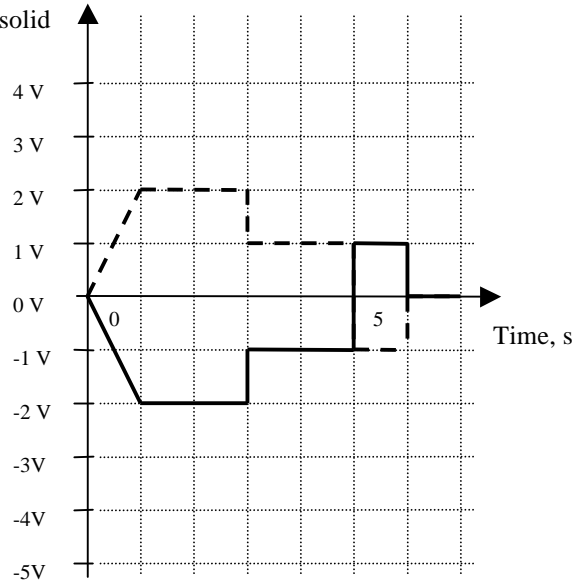
$$\text{Since } Z = R - Xj, \text{ we get } 550 = \sqrt{R^2 + (0.8R)^2}$$

Solving, we get  $\boxed{R = 429\ \Omega}$  and  $\boxed{X = 343\ \Omega}$

**P2.12**

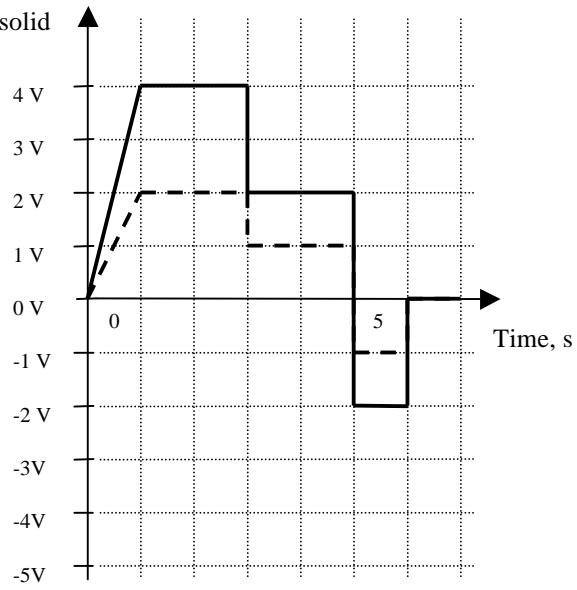
b.  $V_{out} = -R_2/R_1 V_{in} = -V_{in}$

Input ( $V_{in}$ ) - dashed  
Output ( $V_{out}$ ) - solid

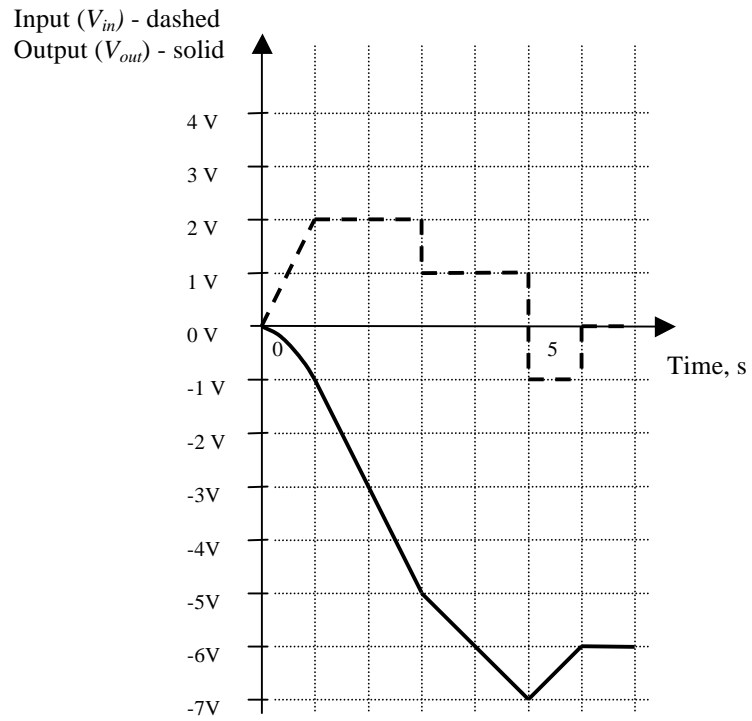


c.  $V_{out} = \left(1 + \frac{R_2}{R_1}\right) V_{in} = 2 V_{in}$

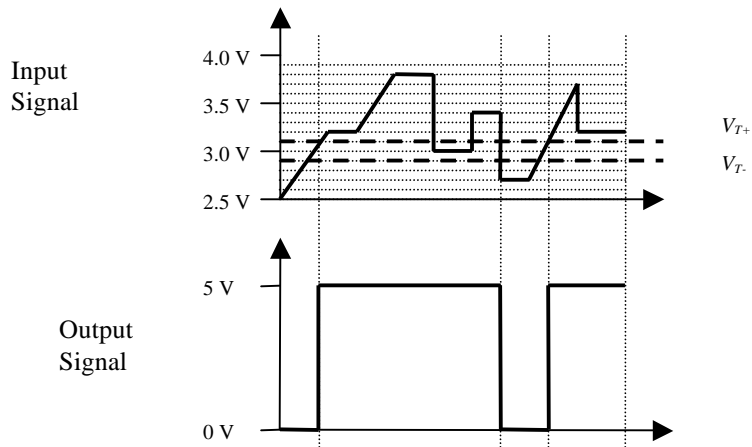
Input ( $V_{in}$ ) - dashed  
Output ( $V_{out}$ ) - solid



$$d. V_{out} = -\frac{1}{R_1 C} \int V_{in} dt = -\int V_{in} dt$$



### P2.13



**P2.14**

In the proposed circuit,  $R_1$  and  $R_2$  act as a voltage dividing circuit between  $V_{Tach}$  and  $V_O$ . The voltage output at the inverting input is then given by:

$$V_- = V_{Tach} - \left( \frac{V_{Tach} - V_O}{R_1 + R_2} \right) R_1 \quad (1)$$

where  $V_O$  is the voltage supplied to the motor. Noting that  $V_- = V_d$ , where  $V_d$  is the desired motor speed (in voltage units), and solving Equation (1) for  $V_O$ , we get:

$$V_O = V_d + (V_d - V_{Tach}) \frac{R_2}{R_1} \quad (2)$$

The expression for  $V_O$  in Equation (2) is not in the form of a closed-loop proportional controller due to the presence of the term  $V_d$ , and thus the proposed circuit will not operate as proposed. Note the expression for  $V_O$  can also be obtained from Equation (2.47) if we let  $V_1 = V_{Tach}$ ,  $V_2 = V_d$ ,  $R_3 = 0$ , and  $R_4 = \infty$ .

**P2.15**

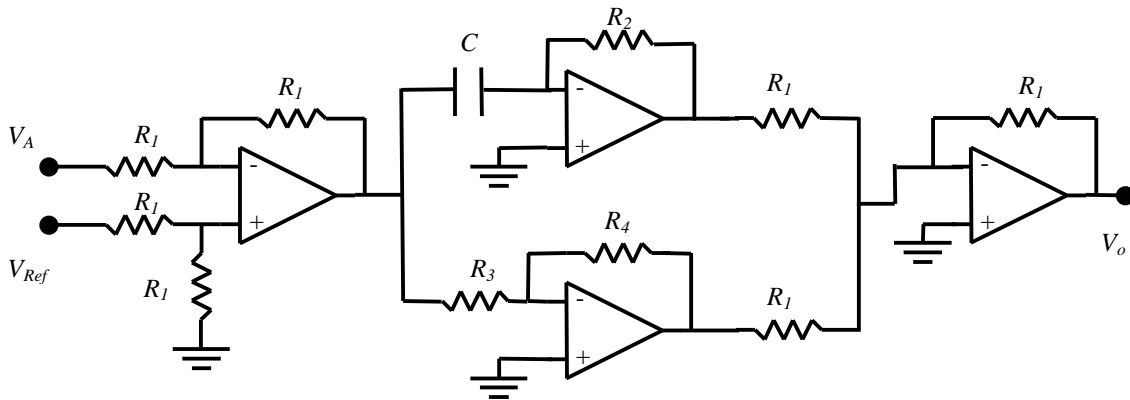
A PD controller has the following relationship between the control output  $V_o(t)$  and the error signal  $e(t)$ :

$$V_o(t) = K_P e(t) + K_D \frac{de(t)}{dt} \quad (1)$$

Where the error signal is defined as:

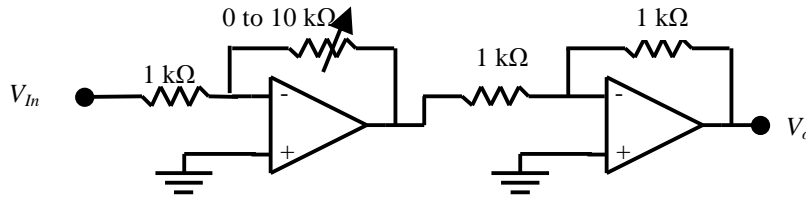
$$e(t) = V_{Ref}(t) - V_A(t) \quad (2)$$

and  $V_{Ref}(t)$  is the reference or desired value, and  $V_A(t)$  is the actual or measured value. The PD controller can be implemented as the cascade of three op-amps circuits. The first circuit is a differential op-amp circuit to compute the error signal. The second circuit, which actually consists of two op-amps, implements the P and D actions. The last stage sums and inverts the outputs from the P and D action circuits. The circuit is shown below. Note that the  $K_P$  gain is the ratio of  $R_4$  to  $R_3$  and the  $K_D$  gain is equal to  $R_2C$ . For a  $K_P$  gain of 5,  $R_3$  is 1.5 k $\Omega$  and  $R_4$  is 7.5 k $\Omega$  (both are standard resistance values). For a  $K_D$  gain of 0.1,  $C$  is 0.1  $\mu$ F and  $R_2$  is 1 M $\Omega$ . To allow for variable gains, a potentiometer can be used to replace the  $R_2$  and  $R_4$  resistors.



**P2.16**

The circuit is shown below. It consists of two cascaded op-amp circuits, the first circuit is to amplify the input voltage and the second circuit is to invert the output from the first circuit. To provide for variable gain, the feedback resistor in the first circuit should be a 0 to 10 kΩ potentiometer. With +/- 15 volts supply for the LM741, the maximum output of this amplifier is about 13 volts. For linear operation, the maximum input is then about 1.3 volts when the gain is 10. The maximum output current is 25 mA, which is the current output limit of the LM741.

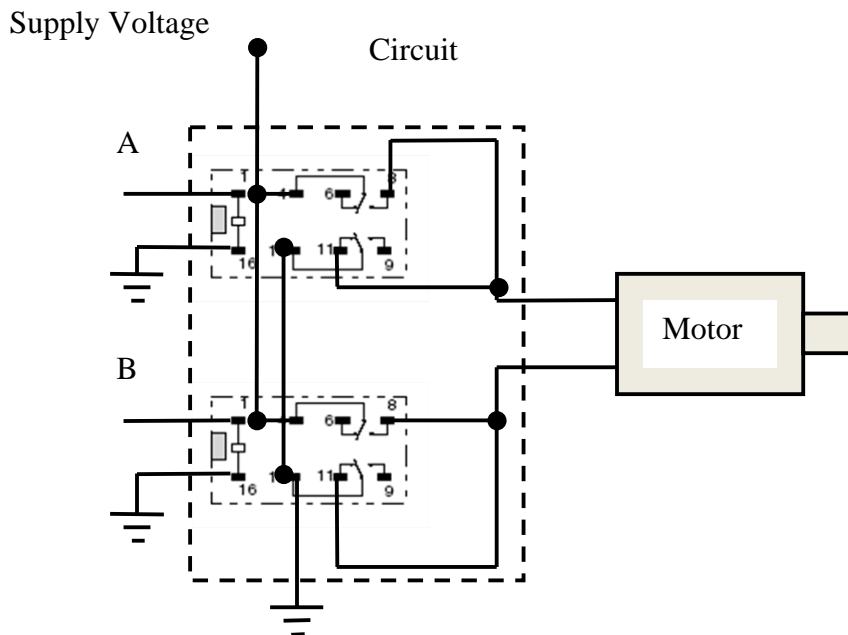


**P2.17**

Applications of solenoids include:

- The starter solenoid (linear type) in vehicles that is activated by the ignition switch and whose job is to close a circuit so that the starter motor runs.
- Pneumatic solenoids valves (linear type) which are used as switches for routing compressed air to positioning slides or grippers in many industrial applications.
- Rotary solenoids which are used to open the bolt in prison doors locks. Also, solenoids are used in card-operated smart locks in hotels doors to open the bolt.

**P2.18**



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**Laboratory/Programming Exercises**

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**L/P2.1**

This exercise is just implementation of the circuit in Figure P2.5. You need a breadboard, seven 1 k $\Omega$  resistors, a 5 VDC power supply, wires, and a multimeter to do this exercise.

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**L/P2.2**

See solution to Problem P2.18 for the circuit to be built. If a 5 VDC motor was used, then the same power supply can be used to power the motor and to supply the A and B signals to the circuit.

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