Chapter 10: Air Breakdown

10.1 How is a silicon controlled rectifier (SCR) similar to the breakdown of a gas?

10.2S By comparing to an actual Paschen curve for air at atmospheric conditions, verify that a first-order approximation for this nonlinear curve is

$$V_B = 320 + 7\times 10^6 d \quad \text{V}$$

10.3 Does corona occur before or after a glow or arc discharge? Explain.

10.4 For a 30 V dc circuit, how can multiple switches be used to reduce the probability of an arc?

10.5 For high-voltage transmission systems, conductors of similar voltage and phase are bundled together (spacing around 1.5 ft). Why does bundling reduce corona? Will corona affect the dielectric conductance, typically modeled as *G*, of a transmission line?

10.6S A 100 kV, dc, high-voltage cable is required for a paint spraying system. Unfortunately, it must be placed in a plastic tube with a diameter of 0.25". This tube makes contact with grounded objects. What flexible insulation around the high-voltage conductor should be used to prevent breakdown? Propose a wire gauge for the conductor. Estimate the maximum electric field inside the insulation.

10.7 The spacing between contacts for a 600 V ac system is 1/16". Is this a suitable distance to prevent breakdown?

10.8S A source indicated that "an inherent protection system" is built into 60 Hz indoor power wiring with a sparkover level of 6 kV. Determine whether this number is reasonable. [Harris, '99]

10.9. For the general expression given in the chapter for the voltage across a switch (for $t \geq 0$) that is in series with a series *RC* load,

$$v_{cs} = A\cos(\omega t) - \frac{A}{\sqrt{(\omega RC)^2 + 1}}\cos\left[\omega t + \tan^{-1}\left(\frac{1}{\omega RC}\right) - 90^\circ\right]$$

simplify, reduce, or rewrite this expression to show clearly the amplitude of this voltage relative to the source voltage's <u>amplitude</u> for any time *t*. Do not use specific numerical cases to show this relationship. Check the result if the switch is opened during a zero-current crossing. The source voltage is sinusoidal.

10.10 Determine the expression for the voltage across a switch (for $t \geq 0$) in series with a parallel *RL* load if the switch is opened at a zero-current crossing at $t = 0$. Assume the source voltage is sinusoidal as in this chapter.

10.11 Determine the expression for the voltage across a switch (for $t \geq 0$) in series with a series *RL* circuit that is in parallel with a resistor R_x. Assume the switch is opened at a zero-current crossing at $t = 0$ and the source voltage is sinusoidal as in this chapter.

10.12 Determine the expression for the voltage across a switch (for $t \geq 0$) in series with a parallel RC load if the switch is opened at a zero-current crossing at $t = 0$. Assume the source voltage is sinusoidal as in this chapter.

10.13 Provide a practical example of a device (not discussed in this book) that could be modeled by a single resistor. Repeat for a single inductor and a single capacitor.

10.14E A switch is in parallel with a capacitor, C. This switch/capacitor combination is then in series with an inductor L and a sinusoidal voltage source. Determine the expression for the voltage across the switch for $t \geq 0$ if the switch opens at $t = 0$. This is not a sinusoidal steady-state problem. Laplace transforms should be used with initial conditions.

10.15 A switch is in series with a parallel LC load. This switch and load are in series with a sinusoidal voltage source. Repeat the entire analysis provided in this chapter to determine the voltage across the switch for $t \geq 0$ if the switch opens at $t = 0$.

10.16 A closing switch connects a 50 V dc voltage source to a 10 Ω load. Repeat the same analysis presented in this chapter given for a 450 V dc supply and 5 kΩ load.

10.17 What is the rate of change in the voltage across an opening switch for a circuit consisting of a dc supply in series with a resistor R in series with a parallel LC circuit? The switch is in series with R and the supply voltage V_s.

10.18 Verify that the maximum voltage across the capacitor of a series RLC circuit is

$$v_{c,max} = V_s\sqrt{1+\frac{L}{CR^2}} = \frac{V_s}{R}\sqrt{R^2+\frac{L}{C}}$$

by using the expression for the voltage across the capacitor for an underdamped circuit without losses:

$$v_C(t) = A\cos(\omega_o t) + B\sin(\omega_o t) \quad \text{where } \omega_o = \frac{1}{\sqrt{LC}}$$

The initial voltage across the capacitor is V_s and the initial current through the inductor is V_s/R. It will be necessary to determine the derivative of $v_C(t)$ to determine this maximum voltage.

10.19 It is stated that for an RC protection network the requirement for no oscillation

$$C_{cs} > \frac{4L}{R_{tot}^2}$$

is usually not adhered to since the required capacitance is larger than that required by the no-breakdown requirements:

$$\frac{L}{R^2\left(\frac{V_B}{V_s}-1-\frac{R_{cs}}{R}\right)^2} < C_{cs} \quad \text{and} \quad \frac{V_s}{RE_A s+\frac{V_s R_{cs}^2}{L}} < C_{cs}$$

Determine whether this is true. State all assumptions.

10.20 How should the series *RC* protection network be modified if it is only necessary to prevent breakdown during the opening of the switch? (Assume that the protection network is in parallel with the switch.)

10.21 Show that the *RC* protection network can be used for ac circuits.

10.22C A 50 V dc supply is connected via a switch to an inductive load, R = 400 Ω in series with L = 10 mH. The parasitic capacitance across the load is 100 pF. Will the switch breakdown? If the switch will breakdown, determine the values for a series *RC* protection network to be placed across the switch to prevent this breakdown. How fast can the switch be opened and closed? What is the minimum value for the capacitance if the network is not to oscillate? If the maximum voltage across the switch should be much less than 100 V, what can be done?

10.23C Repeat Problem 10.22 but assume a 100 V dc supply and 100 mH inductor.

10.24C Repeat Problem 10.22 but assume a 500 V dc supply.

10.25C Repeat Problem 10.22 but assume a 100 V dc supply and a 150 Ω resistor.

10.26C For the *RC* protected circuit discussed in the switch network discussion in this chapter, which is similar to that given in Problem 10.22, use SPICE (or other circuit simulation package) to determine the true maximum voltage across and current through the switch. Compare these results with the various approximations provided in this chapter. Increase the capacitance by a factor of 10 and 100 and repeat the analysis.

10.27C Using SPICE (or other circuit simulation package), determine the relative difference in drop-out time for an *RL* load for two different protection networks. The first network is a single resistor, R_x, in parallel with the *RL* load. The second network is this same resistor in series with a real diode, which are in parallel with the *RL* load. Assume R = 200 Ω, L = 10 mH, and V_s = 75 V. Is either of these specific networks very effective in reducing the voltage across the switch? Use three different reasonable value for R_x that only lightly load the supply.

10.28C Using SPICE (or other circuit simulation package), determine the drop-out time for an *RL* load that is in parallel with a protection network consisting of a single diode in series with a zener diode. Compare this drop-out time to a protection network consisting of a single diode. Assume R = 200 Ω, L = 10 mH, and V_s = 75 V. Use various reasonable values for the breakdown voltage of the zener that are less than and greater than the supply voltage. Clearly show on the plots when the voltage across the zener is less than (in magnitude) than its reverse breakdown voltage. Plot the power dissipated in the various components. Determine, or estimate, the total power dissipated in each of the components after the switch is opened. Is most of the power dissipated in the zener diode?

10.29C Using SPICE (or other circuit simulation package), determine the drop-out time for an *RL* load that is in parallel with a protection network consisting of a single capacitor, C_x, in series with a diode. Then, repeat the analysis for a protection network consisting of a single diode and compare the results. Assume $R = 200$ Ω, $L = 10$ mH, and $V_s = 75$ V. Use three different reasonable values for C_x. A real model for the capacitor should be used. Why is this important?

10.30 Show that the time constant for the overdamped, nonoscillatory circuit consisting of a capacitor, C_x, in parallel with an *RL* load is

$$\tau = \begin{cases} \dfrac{2L}{R} & \text{if } C_x = \dfrac{4L}{R^2} \\ \dfrac{L}{R} & \text{if } C_x >> \dfrac{4L}{R^2} \end{cases}$$

Are there any additional restrictions not specifically stated?

10.31 For an *RL* load, a single resistor R_x is placed across a switch connecting the load to a dc supply V_s. Compare this protection network to a single resistor across the load. Why does a resistor across the switch allow for less actual current through the switch during arcing then a resistor across the load? [Holm]

10.32EC A proposed method of reducing the "kickback" voltage of an inductive load when the current through it suddenly changes to zero is to placed an additional bifilar winding across the inductor and to short circuit this secondary winding. The bifilar winding is a tightly coupled secondary winding of equal inductance. It was stated that this provides a strong damping effect on the rate of change in the flux. Perform the necessary analysis and simulation to determine the effectiveness of this proposal. [National]

10.33C Using SPICE (or other circuit simulation package), determine the drop-out time for an *RL* load that is in parallel with a protection network consisting of a capacitor, C_x, in series with a resistor, R_x, in series with two parallel diodes, as shown in Figure 1. Assume $R = R_x = 200$ Ω, $L = 10$ mH, and $V_s = 75\cos(377t)$ V. Allow $Q = 0.25$, 0.5, and 1. Which value of Q has the smallest drop-out time? Explain why this is reasonable.

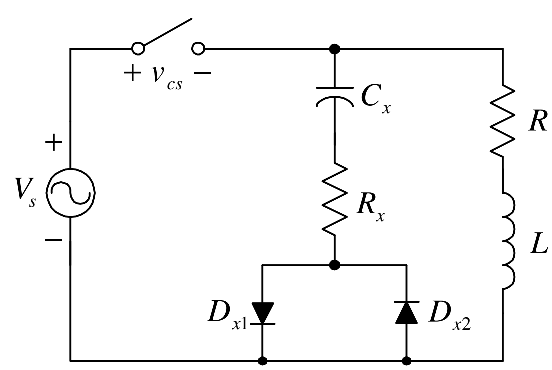

Figure 1

10.34C Discuss the operation of the protection network given in Figure 2. Then, assume $R = 200\ \Omega$, $L = 10$ mH, and $V_s = 75\cos(377t)$ V. Using SPICE (or other circuit simulation package), plot the voltage across each of the diodes, each of the capacitors, and the *RL* load. First, assume that $C_x = C_y$ for $Q = 0.25$, 0.5, and 1. Then, using these same values for C_y, let $C_x = 10C_y$ and repeat the SPICE analysis. Are there any advantages of this circuit over the one discussed in this chapter involving a single capacitor?

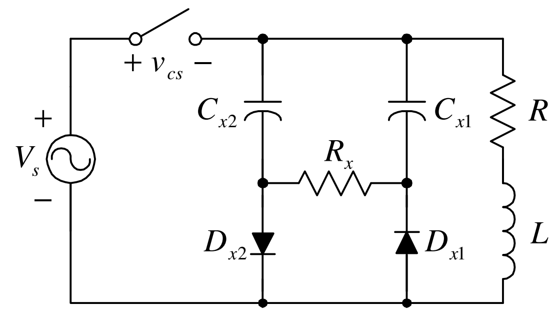

Figure 2

10.35 Starting with Laplace's equation, derive the expression *X* given in the chapter table for the maximum electric field between the two electrodes (*X* will be provide by your instructor). As stated in this section, assume there is no line, surface, or volume charge between the electrodes.

10.36 Starting with Poisson's equation, derive the expression *X* given in the chapter table for the potential between the two electrodes for the given volume charge density (*X* will be happily provided by your instructor). From this potential, determine the electric field between the electrodes.

10.37 For the two specific regions $(\rho_\#, \phi_\#, z_\#)$ and $(r_\#, \theta_\#, \phi_\#)$ provided by your instructor and given in Table 1 and Table 2, sketch each region on the same set of axes. Clearly state whether each region is a point, line, surface, or volume. Then, state whether their intersection is a point, line, surface, or volume. If they do not intersect, state "none."

Table 1

Cylindrical Coordinate Region (ρ, ϕ, z)			
#	$\rho_\#$	$\phi_\#$	$z_\#$
1	$\rho \le 1$	$0 \le \phi \le \frac{\pi}{4}$	$z = 1$
2	$0 \le \rho \le 1$	$\frac{\pi}{4} \le \phi \le \frac{\pi}{2}$	$0 \le z \le 1$

3	$1 \le \rho \le 2$	$\frac{\pi}{2} \le \phi \le \pi$	$z \ge 1$
4	$\rho = 1$	$\phi = \frac{\pi}{2}$	$z = -1$
5	$\rho \ge 1$	$\phi = \pi$	$-1 \le z \le 0$
6	$\rho = 2$	$\phi = \frac{3\pi}{2}$	$z = 0$
7	$0 \le \rho < \infty$	$0 \le \phi < 2\pi$	$-\infty < z < \infty$

Table 2

Spherical Coordinate Region (r, θ, ϕ)			
#	$r_{\#}$	$\theta_{\#}$	$\phi_{\#}$
1	$r \le 1$	$0 \le \theta \le \frac{\pi}{4}$	$0 \le \phi \le \frac{\pi}{4}$
2	$0 \le r \le 1$	$\frac{\pi}{4} \le \theta \le \frac{\pi}{2}$	$\frac{\pi}{4} \le \phi \le \frac{\pi}{2}$
3	$1 \le r \le 2$	$\frac{\pi}{2} \le \theta < \pi$	$0 \le \phi < 2\pi$
4	$r = 1$	$\theta = \frac{\pi}{4}$	$\phi = \frac{\pi}{4}$
5	$r \ge 1$	$\theta = \frac{\pi}{2}$	$\phi = \frac{\pi}{2}$
6	$r = 2$	$\phi = \frac{3\pi}{4}$	$\phi = \frac{3\pi}{2}$
7	$0 \le r < \infty$	$0 \le \theta \le \pi$	$0 \le \phi < 2\pi$

10.38 A crystal ball consists of an inner spherical conductor of radius 2 cm surrounded by a concentric outer transparent conductor of radius 10 cm. When the applied voltage, V (> 0), across the electrodes is large enough to break down the air *everywhere* between the inner and outer electrodes (the outer electrode is the reference), a brilliant blue haze emanates from the crystal ball. The volume charge density between the electrodes is then $10/r^2$ nC/m^3. Determine the solution for the potential and electric field between the electrodes. What is the minimum voltage necessary to "operate" this crystal ball (i.e., to produce the blue haze)? Assume the medium between the electrodes breaks down at 3 MV/m.

10.39 Fuel oil (with a dielectric constant of 3) is pumped through a grounded pipe (with an inner radius of 5 cm) to a commercial tanker. The fluid is just beginning to break down. The breakdown strength of the fuel oil is 6 MV/m. Assuming a uniform charge density in the pipe, determine the potential and electric field distributions inside the pipe. [Crowley, '86]

10.40 Determine the relative net bound charge along each of the given dielectric interfaces for the following set of concentric cylindrical regions:

$\rho = 2$ electrode at potential of -10 V
$2 < \rho < 3$ free space
$3 < \rho < 4$ ideal dielectric with $k = 4$
$4 < \rho < 5$ ideal dielectric with $k = 6$
$5 < \rho < 6$ ideal dielectric with $k = 2$
$\rho = 6$ electrode at potential of 0 V

Which interface has the greatest magnitude of bound surface charge? (The surface area of a cylindrical surface is proportion to its radius.)

10.41 Determine the relative net bound charge along each of the given dielectric interfaces for the following set of concentric spherical regions:

$r = 2$ electrode at potential of 0 V
$2 < r < 3$ ideal dielectric with $k = 2$
$3 < r < 4$ ideal dielectric with $k = 4$
$4 < r < 5$ ideal dielectric with $k = 3$
$5 < r < 6$ ideal dielectric with $k = 5$
$r = 6$ electrode at potential of 5 V

Which interface has the greatest magnitude of bound surface charge? (The surface area of a spherical surface is proportion to the square of its radius.)

10.42 A flat interface between two dielectrics exists in the *xz* plane. A surface charge of ρ_S exists along the interface. For $y > 0$ near the interface,

$$\vec{E}_3 = -4\hat{a}_x + 2\hat{a}_y + 3\hat{a}_z \quad y > 0 \quad \text{where } k = 3$$

Determine both $\vec{E}_2$ and $\vec{D}_2$ for $y < 0$ near the interface where $k = 2$.

10.43 A flat interface between two dielectrics exists in the *yz* plane. A surface charge of ρ_S exists along the interface. For $x < 0$ near the interface,

$$\vec{D}_4 = 4\hat{a}_x - 2\hat{a}_y + 3\hat{a}_z \quad x < 0 \quad \text{where } k = 4$$

Determine both $\vec{E}_5$ and $\vec{D}_5$ for $x > 0$ near the interface where $k = 5$.

10.44 A flat interface between two dielectrics is described by the surface $\phi = \pi/4$ in the cylindrical coordinate system. A surface charge of ρ_S exists along the interface. For $\phi > \pi/4$ near the interface,

$$\vec{D}_4 = -2\hat{a}_\rho + 4\hat{a}_\phi + 3\hat{a}_z \quad \phi > \frac{\pi}{4} \quad \text{where } k = 4$$

Determine both $\vec{E}_2$ and $\vec{D}_2$ for $\phi < \pi/4$ near the interface where $k = 2$.

10.45 A curved interface between two dielectrics is described by the surface $\rho = 2$ in the cylindrical coordinate system. A surface charge of ρ_S exists along the interface. For $\rho < 2$ near the interface,

$$\vec{D}_3 = 4\hat{a}_\rho - 2\hat{a}_\phi - 5\hat{a}_z \quad \rho < 2 \quad \text{where } k = 3$$

Determine both $\vec{E}_4$ and $\vec{D}_4$ for $\rho > 2$ near the interface where $k = 4$.

10.46 A curved interface between two dielectrics is described by the surface $r = 3$ in the spherical coordinate system. A surface charge of ρ_S exists along the interface. For $r > 3$ near the interface,

$$\vec{E}_2 = 4\hat{a}_r - 2\hat{a}_\theta - 5\hat{a}_\phi \quad r > 3 \quad \text{where } k = 2$$

Determine both $\vec{E}_4$ and $\vec{D}_4$ for $r < 3$ near the interface where $k = 4$.

10.47 A curved interface between two dielectrics is described by the surface $\theta = \pi/3$ in the spherical coordinate system. A surface charge of ρ_S exists along the interface. For $\theta < \pi/3$ near the interface,

$$\vec{E}_3 = -3\hat{a}_r + 4\hat{a}_\theta - 5\hat{a}_\phi \quad \theta < \frac{\pi}{3} \quad \text{where } k = 3$$

Determine both $\vec{E}_2$ and $\vec{D}_2$ for $\theta > \pi/3$ near the interface where $k = 2$.

10.48 A curved interface between two dielectrics exists in the xy plane described by the equation $y = x^2 + 3$. No surface charge exists along this curved interface. For $y > x^2 + 3$ near the interface,

$$\vec{E}_2 = -4\hat{a}_x + 2\hat{a}_y - 3\hat{a}_z \quad y > x^2 + 3 \quad \text{where } k = 2$$

Determine both $\vec{E}_5$ and $\vec{D}_5$ for $y < x^2 + 3$ near the interface where $k = 5$.

10.49 Two concentric long cylindrical conductors of radii $\rho = a$ and $\rho = b$ ($a < b$) are at ground potential. A uniform volume charge of ρ_V exists from $a < \rho < c$ where the dielectric constant is equal to k. Free space exists from $c < \rho < b$. A surface charge of ρ_S exists at $\rho = c$. Determine the expressions for the potential and electric field everywhere between the grounded conductors. Determine all constants of integration.

10.50 Two concentric spherical conductors of radii $r = a$ and $r = b$ ($a < b$) are at ground potential. A uniform volume charge of ρ_V exists from $a < r < c$ where the dielectric constant is equal to k. Free space exists from $c < r < b$. A surface charge of ρ_S exists at $r = c$. Determine the expressions for the potential and electric field everywhere between the grounded conductors. Determine all constants of integration.