EM IV: Electromagnetic Induction, RLC & AC Circuits

FIZIKA SJPO Training

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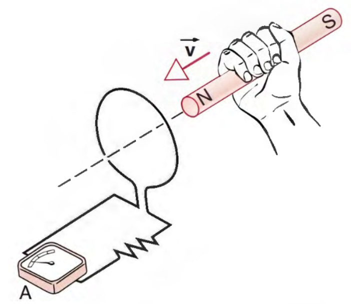
Contents

1 Electromagnetic Induction

1.1 Faraday's Law

In 1831, Michael Faraday carried out an experiment which discovered what is now known as electromagnetic induction. In the previous topic, we learnt how electric fields can create magnetic fields. What Faraday showed in his experiment is that the inverse is possible as well: that is, a (changing) magnetic field can create an electric field.

Let us look at this phenomenon in action with a simple experiment.



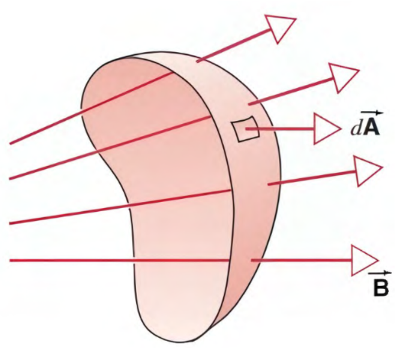
We set up a circuit as shown below. There should be no reading in the ammeter because there is no electromotive force (emf). In other words, there is no source driving current through the circuit. However, interestingly, when we move the permanent magnet through the loop, we observe a deflection in the ammeter.

This tells us that moving a magnet through the hoop creates an emf which drives current through the ammeter. We call this the *induced emf*, which drives an *induced current*.

However, when we hold the magnet still, we observe no deflection in the ammeter. This means that only a **changing** magnetic field create an induced emf.

Through his experiments, Faraday discovered that the magnitude of the induced emf in a circuit is equal to the rate at which the magnetic flux through the circuit is changing, which is known as Faraday's law. To understand this law, we need to first look at what is magnetic flux.

Magnetic flux is the same as electric flux, which we have covered in Gauss's law.



Magnetic flux Φ, is the product of the **area** and the **B field** that is perpendicular to the area, or

$$\Phi = B_\perp A \tag{1}$$

This equation assumes that the magnetic field is constant across the entire area. You can visualize the magnetic flux as the number of field lines passing through a certain area.

Now, we can now write down the equation for Faraday's law:

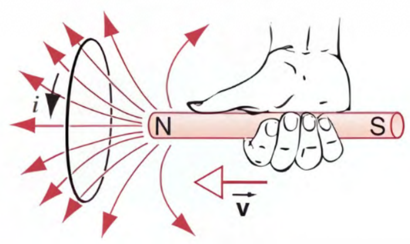
$$|\varepsilon| = \left|\frac{\mathrm{d}\Phi}{\mathrm{d}t}\right| \tag{2}$$

Hence, if you move a magnet through a coil, the induced emf, ε, is equal to the rate of change of magnetic flux through the coil. If there are N turns of tightly wounded coils, then the overall induced emf will be equal to the sum of the induced emf by each of the coils. This is the same as for example, batteries connected in series. So, with N coils,

$$|\varepsilon| = N\left|\frac{\mathrm{d}\Phi}{\mathrm{d}t}\right| \tag{3}$$

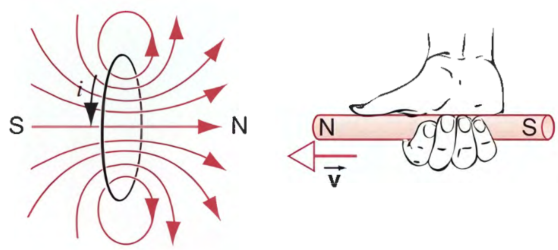
1.2 Lenz's Law

Now, let us discuss the direction of the induced current and emf. Let us look at a simple setup.



You are pushing a permanent magnet through a coil. Since the magnetic flux through the coil is changing, there must be an induced emf, and hence, an induced current through the coil. But the question is, what will be the direction of the induced current?

Since the coil is a circle, if there is a current through the circle, it would generate a magnetic field. Depending on the direction of the current, there would either be a north pole or a south pole facing the permanent magnet. Suppose a south pole is facing the permanent magnet, when you move the permanent magnet closer to the loop, the loop would essentially attract the permanent magnet, and accelerating it. Here, you have basically generated free energy, which is not possible. Hence, the only possible scenario is that it is a north pole facing the magnet, repelling the magnet and slowing it down.



So, electromagnetic induction basically acts like a frictional force that slows down objects. This idea is given more formally in Lenz's law, which states that the direction of the induced current will be such that it **opposes** the change that created the induced current.

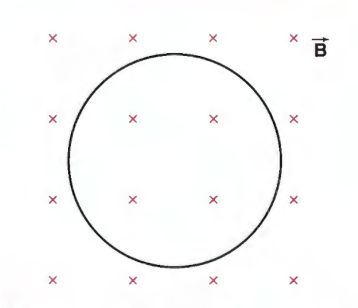
You can modify Faraday's law to show Lenz's law as

$$\varepsilon = -\frac{\mathrm{d}\Phi}{\mathrm{d}t} \tag{4}$$

The negative sign indicates the induced emf always opposes the change in magnetic flux.

With that, let us look at some examples.

Example 1.1. A circular loop of wire of radius $r = 0.32$ m and resistance $R = 2.5\ \Omega$ is placed in a uniform magnetic field that is perpendicular to the plane of the loop and initially directed into the page, as shown in the figure below. The field varies with time as $B = 2t$, and it is pointing into the page. Find the magnitude and direction of the current in the loop.



Solution. To get the magnitude of the induced current, we first calculate the magnitude of the induced emf with Faraday's law, then use Ohm's law to get the magnitude of the induced current. By Faraday's law

$$\varepsilon = \frac{\mathrm{d}\Phi}{\mathrm{d}t}$$

We got rid of the absolute sign for now because we are dealing with the magnitude only. Magnetic flux, Φ is simply the product of the area of the circle and the magnitude of the B field, so,

$$\varepsilon = \frac{\mathrm{d}(BA)}{\mathrm{d}t} = A\frac{\mathrm{d}B}{\mathrm{d}t}$$

This is because the area of the coil did not change, and only the magnetic field is changing. So, the rate of change of magnetic flux is just the area of the circle times the rate of change of the magnetic field.

We can see that the rate of change of the magnetic field is the gradient of the linear equation $B = 2t$, which is 2. The area is simply the area of the circle, so

$$\varepsilon = \pi r^2\frac{\mathrm{d}B}{\mathrm{d}t} = \pi(0.32)^2(2) = 0.6434 \text{ V}$$

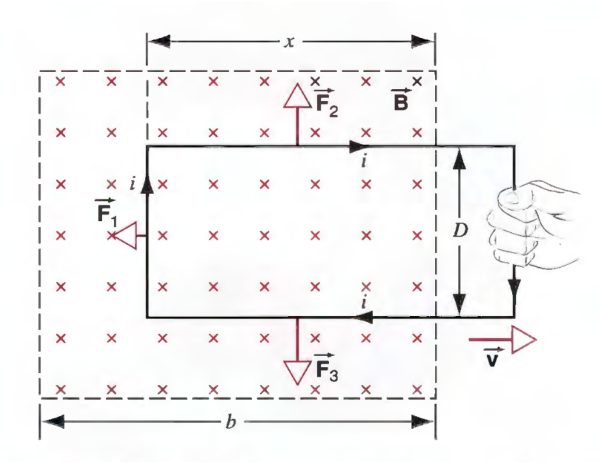
Now, we use Ohm's law to find the induced current.

$$I = \frac{\varepsilon}{R} = \frac{0.6434}{2.5} = 0.26 \text{ A}$$

Next, we find the direction of the induced current. The magnetic field is increasing into the page, so the induced current must generate a magnetic field out of the page to counteract the increasing field into the page. With the right hand rule, the induced current is anticlockwise.

1.3 Motional EMF

Suppose one end of a rectangular loop of wire is inside a magnetic field, and we pull the loop out of the magnetic field.



This case is similar to the previous case, except the magnetic field is constant, but the area of the loop in the magnetic field changes. Since $\Phi = BA$ and here A is changing, there is a change in the magnetic flux Φ through the loop.

Thus, here,

$$\varepsilon = \frac{\mathrm{d}\Phi}{\mathrm{d}t} = B\frac{\mathrm{d}A}{\mathrm{d}t}$$

Since the breadth is constant, the rate of change of area $\mathrm{d}A/\mathrm{d}t$ is the product of its breadth and the rate of change of its width (which is the velocity of the loop), so

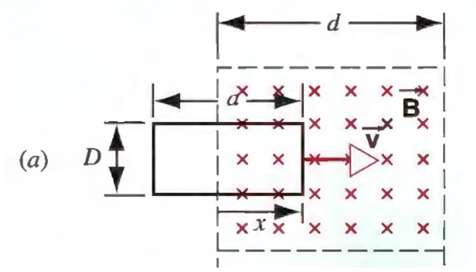
$$\varepsilon = \frac{\mathrm{d}\Phi}{\mathrm{d}t} = BvD \tag{5}$$

The direction of the induced current opposes the decrease in magnetic flux in the loop, so the induced current must increase the magnetic flux in the loop, thus by the right hand rule, it is clockwise.

In these cases, the exact same result can be obtained if you look at the magnetic force on the electrons in the wire of the circuit. When the circuit is pulled out, there is a current to the left since the electrons are moving to the right. Since there is a magnetic field into the page, by the left hand rule, the electrons experience a downward force. This essentially creates a current upwards, which is consistent with our result from Faraday's law.

With an upwards induced current, you can apply the left hand rule once again, and you will realise that there is a magnetic force to the left, resisting the motion. Thus, for these kind of problems, it can be useful to think about them in terms of magnetic forces, though Faraday's law will give you the same result.

Example 1.2. Figure below shows a rectangular loop of resistance R, width D, and length a being pulled at constant speed v through a region of thickness d in which a uniform magnetic field B is set up by a magnet. As functions of the position x of the right-hand edge of the loop, plot (a) the flux Φ through the loop, (b) the induced current i, and (c) the rate P of production of internal energy in the loop. Use $D = 4$ cm, $a = 10$ cm, $d = 15$ cm, $R = 16\ \Omega$, $B = 2.0$ T, and $v = 1.0\ \mathrm{m\ s^{-1}}$.



Solution. Outside the field, the magnetic flux is 0. When the loop is completely inside the field, the magnetic flux is simply BDa. In the intermediate regime, the area of the loop in the field increases linearly as its shape is a rectangle, so the rate of change of magnetic flux is constant.

Using Faraday's law,

$$\varepsilon = -B\frac{\mathrm{d}A}{\mathrm{d}t} = -BvD$$

And using Ohm's law,

$$i = \frac{\varepsilon}{R}$$

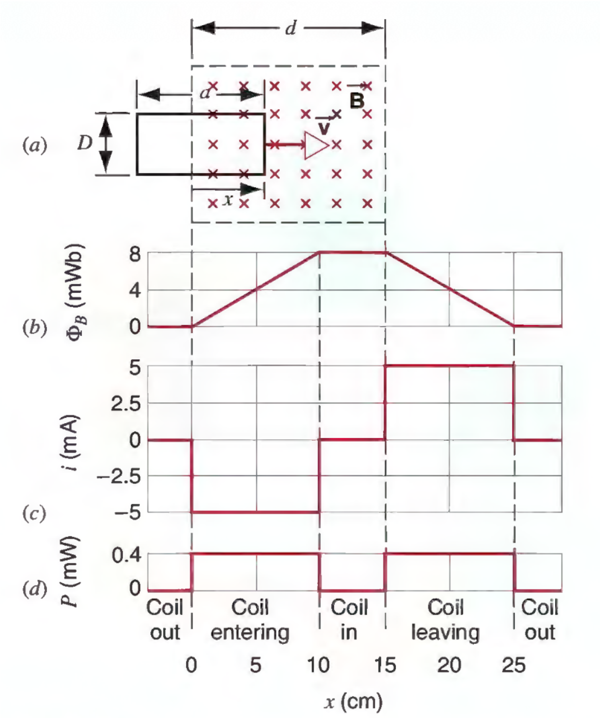
Plugging in the values, you should get -5 mA.

When the coil exits the field, the magnetic flux is *decreasing*, so you have to flip the sign.

This is only valid while the coil is entering or exiting the magnetic field. When the coil is completely inside the field or completely outside, there is no change in magnetic flux, thus no emf is induced.

Lastly, the power can be calculated with $P = i^2R$. This value is constant since the current i is constant.

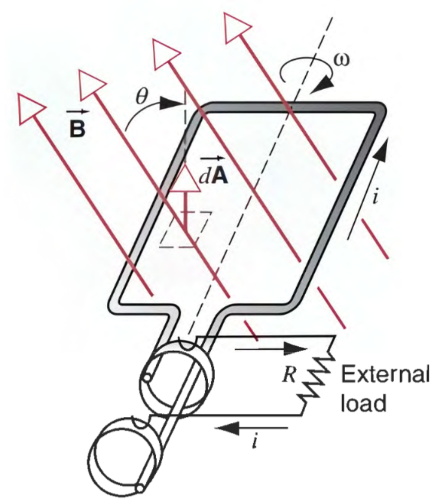
Plotting the graph, we get the following:



1.4 Generators

Have you ever wondered how electric generators work? Almost all of them work the same way: they use some sort of fuel to heat up water into steam, and uses the steam to drive a turbine. The turbine is a coil of wire inside a magnetic field. When the turbine turns, there is a change in magnetic flux in the coil, thus inducing an emf and creating electricity.

Let us look at a simple electric generator, with N loops of wires stacked on top of each other.



Let us suppose that the loop in the generator rotates with an angular velocity of ω, starting with the magnetic field passing perpendicularly through the loop. Recall that the magnetic flux is the product of the area and the component of the magnetic field *perpendicular* to that area, so the magnetic flux is

$$\Phi = NBA\cos\theta = NBA\cos\omega t \tag{6}$$

Here, Φ explicitly depends on time t. We can now use Faraday's law to find the rate of change of Φ with respect to time. The rate of change (i.e. the derivative with respect to time) of $\cos\omega t$ is $-\omega\sin\omega t$, so

$$\varepsilon = NBA\omega\sin\omega t \tag{7}$$

As you can see, the generated emf is a sinusoidal function of time. This is how AC (alternating current) voltages are generated.

Example 1.3. An electrical generator consists of 5 rectangular loops of dimensions 8.4 cm by 15.4 cm. It rotates in a uniform magnetic field of 0.126 T at a frequency of 60.0 Hz about an axis perpendicular to the field direction. What is the maximum emf that is generated by the loop?

Solution. We know that the emf is

$$\varepsilon = -\frac{\mathrm{d}\Phi}{\mathrm{d}t} = NBA\omega\sin\omega t$$

The maximum value is obtained when $\sin\omega t$ is 1. So, maximum emf is given by

$$\varepsilon = NBA\omega = (5)(0.126)(0.084)(0.154)(2\pi)(60) = 3.07\text{ V}$$

2 RLC Circuits

As a recap, we learnt previously that the potential difference across a resistor is

$$V = RI$$

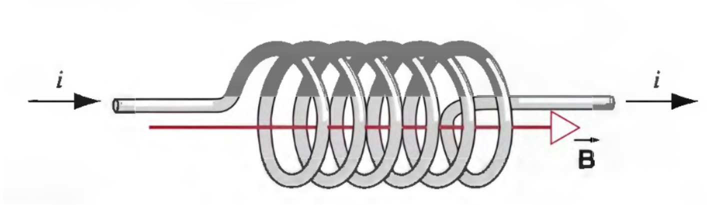
and for a capacitor, it is

$$V = \frac{Q}{C}$$

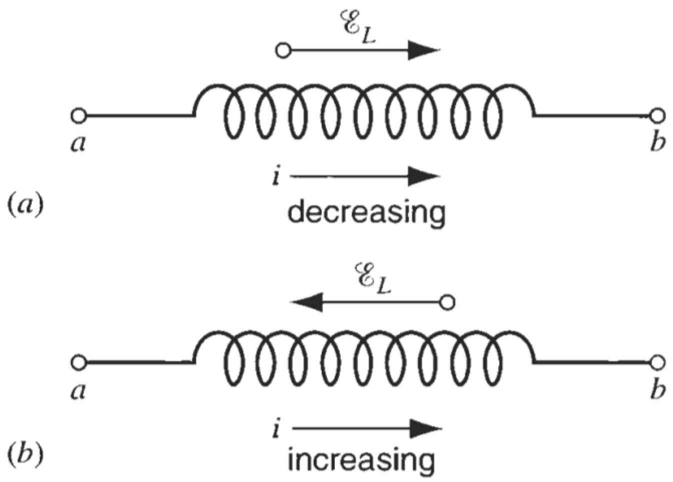
Now, we turn our focus onto the inductor, the last of the three electrical components that make up an *RLC circuit*.

2.1 Inductors

An inductor stores energy much like a capacitor. However, instead of an electric field, an inductor stores its energy with a magnetic field.



An example of an inductor is a solenoid. As current flows through the inductor, a magnetic field is generated in the inductor. When the current through the inductor changes, the magnetic flux in the inductor also changes. By Faraday's law, this creates an induced emf across the inductor.



For capacitors, we have the capacitance, which is a value that depends on the geometrical properties of the capacitor. For inductors, we have the inductance, which likewise only depends on the geometry. We define

$$\Phi = LI \tag{8}$$

where Φ is the magnetic flux through the inductor (for example, a loop of wire) and I is the current. L is known as the inductance, measured in Henries (H). By differentiating with respect to time and using Faraday's law, we get that the emf across an inductor is

$$\varepsilon = L\frac{\mathrm{d}I}{\mathrm{d}t} \tag{9}$$

The energy stored in an inductor is given by

$$E = \frac{1}{2}LI^2 \tag{10}$$

Example 2.1. A coil has an inductance of 53 mH and resistance of 0.35 Ω. (a) If a 12 V emf is applied, how much energy is stored in the magnetic field after the current has built up to its maximum value?

Solution. For the maximum current after a long time, the rate of change of current is 0, so the current is constant. Thus, the emf across the inductor is 0. Hence, we can use Ohm's law to find the maximum current,

$$I = \frac{V}{R} = \frac{12}{0.35} = 34.3 \text{ A}$$

The energy is then

$$E = \frac{1}{2}LI^2 = \frac{1}{2}(0.053)(34.3)^2 = 31 \text{ J}$$

2.2 Inductor Combinations

We can analyse the effective inductances of inductor combinations using similar concepts to that of resistor or capacitor combinations.

Suppose we have n inductors in series, with inductances $L_1, L_2, \ldots, L_n$. Hence, they share the same current I. The total potential difference across them is the sum of that across each inductor,

$$\varepsilon = \varepsilon_1 + \varepsilon_2 + \cdots + \varepsilon_n = L_1\frac{\mathrm{d}I}{\mathrm{d}t} + L_2\frac{\mathrm{d}I}{\mathrm{d}t} + \cdots + L_n\frac{\mathrm{d}I}{\mathrm{d}t} = (L_1 + L_2 + \cdots + L_n)\frac{\mathrm{d}I}{\mathrm{d}t}$$

Therefore, the effective inductance of the inductors in series is

$$L_{\text{eff}} = L_1 + L_2 + \cdots + L_n \tag{11}$$

Now, suppose we have n inductors in parallel with the inductances stated previously. Hence, they share the same potential difference ε. The total rate of change of current across them is the sum of that across each inductor,

$$\frac{\mathrm{d}I}{\mathrm{d}t} = \frac{\mathrm{d}I_1}{\mathrm{d}t} + \frac{\mathrm{d}I_2}{\mathrm{d}t} + \cdots + \frac{\mathrm{d}I_n}{\mathrm{d}t} = \frac{\varepsilon}{L_1} + \frac{\varepsilon}{L_2} + \cdots + \frac{\varepsilon}{L_n} = \varepsilon\left(\frac{1}{L_1} + \frac{1}{L_2} + \cdots + \frac{1}{L_n}\right)$$

Therefore, the effective inductance of the inductors in parallel is

$$\frac{1}{L_{\text{eff}}} = \frac{1}{L_1} + \frac{1}{L_2} + \cdots + \frac{1}{L_n} \tag{12}$$

Note the similarities to resistors – the inductances add in series, and the reciprocals of the inductances add in parallel.

2.3 Oscillations in LC Circuits

Let us examine a basic circuit with an inductor and a capacitor connected in series.

Since the components are connected in parallel,

$$\varepsilon_C + \varepsilon_L = 0$$

ε_C and ε_L are the emf from the capacitor and inductor respectively. So,

$$\frac{Q}{C} + L\frac{\mathrm{d}I}{\mathrm{d}t} = 0$$

Since current is the rate of change of charge ($I = \mathrm{d}Q/\mathrm{d}t$), the rate of change of current is $\mathrm{d}I/\mathrm{d}t = \mathrm{d}^2Q/\mathrm{d}t^2$.

Getting rid of all I and only using Q, we get

$$\frac{Q}{C} + L\frac{\mathrm{d}^2Q}{\mathrm{d}t^2} = 0$$

or

$$\frac{\mathrm{d}^2Q}{\mathrm{d}t^2} = -\frac{Q}{LC}$$

This looks awfully similar to the equation for simple harmonic motion! Recall that in simple harmonic motion,

$$\frac{\mathrm{d}^2x}{\mathrm{d}t^2} = -\omega^2 x$$

Here, our charge Q plays the role of the displacement x! Thus, charge and current in a LC circuit is analogous to the displacement and velocity in mechanical simple harmonic motion, with $\omega^2 = 1/LC$.

Thus, charge is analogous to displacement, and current is analogous to velocity. The capacitor acts like a spring with "spring constant" $1/C$, while the inductor acts like a block undergoing SHM with "mass" L.

Example 2.2. A 1.5 μF capacitor is charged to 57 V. The charging battery is then disconnected and a 12 mH coil is connected across the capacitor, so that LC oscillations occur. What is the maximum current in the coil? Assume that the circuit contains no resistance.

Solution. If you find this difficult, start thinking about these values using their mechanics analogues. We are given the spring constant (capacitance) and the mass (inductance). We are also given the initial conditions with the initial voltage. Thus, for a mechanics question, we can calculate the initial elastic spring energy, and equate it to the maximum kinetic energy to get the maximum velocity.

Returning to EM, we equate the maximum energy in the capacitor with the maximum energy in the inductor.

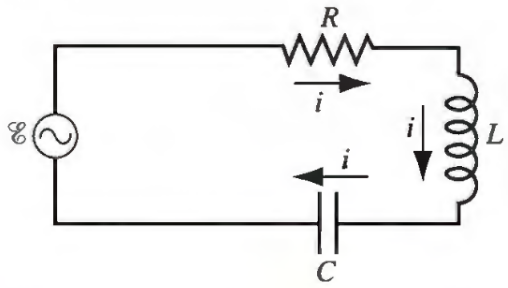
$$\frac{1}{2}CV^2 = \frac{1}{2}LI^2$$

$$I = V\sqrt{\frac{C}{L}} = 0.64 \text{ A}$$

3 AC Circuits

AC circuits, or alternating current circuits, are circuits driven by a sinusoidal source, such as a generator from the previous section. Analysing this kind of circuits is inherently different from a DC circuit because voltage and current now changes with time instead of being constant.

Here is an example of a circuit driven by an AC source.



In AC circuits, the emf of the source generally follows a sinusoidal wave. It can be described as such.

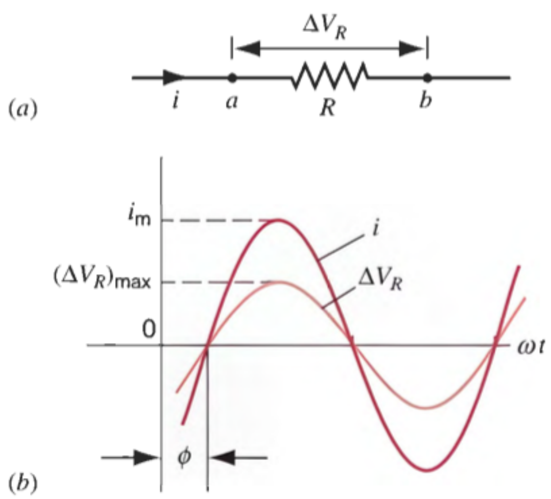
$$\varepsilon = \varepsilon_{\text{max}} \sin \omega t \tag{13}$$

ε_{max} is the maximum emf of the generator, or the peak voltage, and ω is the angular frequency.

After a while, the current in the circuit becomes a sinusoidal wave as well, which is what we call steady state. The current would then follow

$$I = I_{\text{max}} \sin(\omega t + \phi) \tag{14}$$

First, let us look at a simple AC circuit. Suppose a resistor is connected to an AC source. As expected, the current in the resistor follows a sinusoidal wave that follows the source voltage. This is because of Ohm's law $V = RI$ – since V is a sine wave, I must also be a sine wave.



We call these waves in phase, because both waves are at their maximum or minimum at the same location on the x-axis.

However, what is the power dissipated in the resistor? Turns out, we cannot really use the peak current I_{max} and peak voltage V_{max}, because most of the time, the current and voltage through the resistor is far lower than these maximum values! Instead we use something called the **root-mean-square** (rms) current and voltage.

$$P_{\text{ave}} = V_{\text{rms}} I_{\text{rms}} \tag{15}$$

P_{ave} is the *average* power through the resistor over many cycles. Of course, the instantaneous power is still $P = VI$, but since I and V are functions of time, P is also a function of time, so it may not be very useful. Instead, P_{ave} is a constant value that characterises the long-term behaviour of an AC circuit.

To convert from peak voltage and current to their rms values, you divide them by a factor of $\sqrt{2}$. That is,

$$V_{\text{rms}} = \frac{V_{\text{max}}}{\sqrt{2}} \tag{16}$$

$$I_{\text{rms}} = \frac{I_{\text{max}}}{\sqrt{2}} \tag{17}$$

3.1 Impedance

We know that resistors are characterised by their resistance. But what about capacitors and inductors? Turns out, there is a similar quantity for them, called the reactance. The reactance will create a lag, or a phase shift, between the current and voltage over a circuit component.

For an inductor, the reactance is

$$X_L = \omega L \tag{18}$$

And for a capacitor, it is

$$X_C = \frac{1}{\omega C} \tag{19}$$

To analyse an RLC circuit driven by an AC source, it is often useful to define a quantity called the impedance.

$$Z = \sqrt{R^2 + (X_L - X_C)^2} \tag{20}$$

The impedance, Z, is useful because it is basically the resistance, but for AC circuits. So, you can replace the R in Ohm's law with Z.

$$\varepsilon_{\text{peak}} = Z I_{\text{peak}} \tag{21}$$

Let us examine the peak current, I_{peak}.

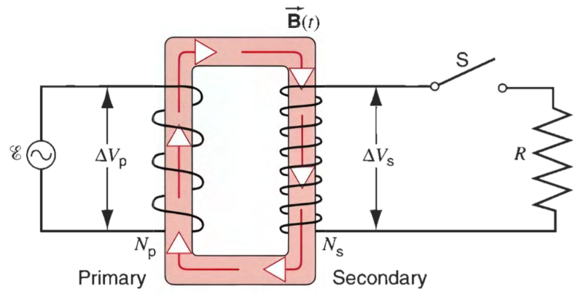
$$I_{\text{peak}} = \frac{\varepsilon_{\text{peak}}}{Z}$$

For I_{peak} to be maximum, Z has to be minimum. Thus, the reactance of the capacitor and the inductor must cancel out. This is called the resonance condition.

3.2 The Transformer

When we are using electrical appliances, it is often more useful if the voltage is not too high (on the order of 10^2 volts). Since our transmission lines are typically at very large voltages (on the order of 10^4 volts), it is both unsafe and inconvenient for us to transfer such voltages directly to our houses. However, for transmitting power through electricity, it is much better to use high voltages. This is because to minimise the power due to the resistance of the transmission line, $P_{\text{lost}} = I^2 R$, the current must be minimised. For a fixed amount of power transmitted $P_{\text{transmitted}} = VI$, the voltage V and current I are inversely proportional, so the current can be minimised by *maximising the voltage.*

As a result, people have invented devices to step up and step down AC voltages, called transformers. In the generators, the voltage is stepped up to a very large value, allowing it to be transmitted efficiently to a power station near your home. Near your home, another transformer steps down the voltage for household use. A diagram of a simple transformer is shown below.



A transformer is usually made out of 2 coils and an iron core that links them. Looking at the primary coil, the alternating current source there creates an oscillating magnetic field in the iron core. Since iron has high magnetic permeability (field lines travel inside easily), the secondary coil also feels a magnetic field inside, and hence, there is a magnetic flux felt by the secondary coil. Since the magnetic field is also oscillating, the magnetic flux of the secondary coil also changes, thus inducing an emf and a current in the secondary coil.

Let us look at this scenario with physics. We know that the magnetic field is changing at the same rate in the iron core and that the magnetic flux is equal in both coils, as the cross sectional area of the coils are the same. Hence, $\mathrm{d}\Phi/\mathrm{d}t$ is the same for both coils. Using Faraday's law,

$$V_\mathrm{p} = -N_\mathrm{p}\frac{\mathrm{d}\Phi}{\mathrm{d}t}$$
$$V_\mathrm{s} = -N_\mathrm{s}\frac{\mathrm{d}\Phi}{\mathrm{d}t}$$

V_p and V_s are the voltages of primary and secondary coils, and N_p and N_s are the number of turns in their respective coils. You will notice that while the magnetic flux is the same, the magnetic flux linkage, $N\,\mathrm{d}\Phi/\mathrm{d}t$, is different for both coils as they have different number of turns, which is what makes transformers work.

Taking the ratio of these 2 equations, we get

$$\frac{V_\mathrm{p}}{V_\mathrm{s}} = \frac{N_\mathrm{p}}{N_\mathrm{s}} \tag{22}$$

and equivalently,

$$I_\mathrm{p}N_\mathrm{p} = I_\mathrm{s}N_\mathrm{s} \tag{23}$$

These 2 equations are the most important equations for transformers, as the coil count and voltage/current are the important quantities you need to solve for in a typical transformer problem.

Example 3.1. A transformer on a utility pole operates at $V_\mathrm{p} = 8.5$ kV on the primary side and supplies electric energy to a number of nearby houses at $V_\mathrm{s} = 120$ V, both quantities being rms values. The rate of average energy consumption in the houses served by the transformer at a given time is 78 kW. (a) What is the turns ratio $N_\mathrm{p}/N_\mathrm{s}$ of this step-down transformer? (b) What are the rms currents in the primary and secondary windings of the transformer?

Solution. Using the formula,

$$\frac{N_\mathrm{p}}{N_\mathrm{s}} = \frac{V_\mathrm{p}}{V_\mathrm{s}} = 70.8$$

Using $P = VI$,

$$I_\mathrm{s} = \frac{78\times10^3}{120} = 650\text{ A}$$
$$I_\mathrm{p} = \frac{78\times10^3}{8.5\times10^3} = 9.18\text{ A}$$

4 Problems

Problem 4.1 (SJPO 2013)**.** Two identical bar magnets are dropped from equal heights. Magnet A is dropped from above bare earth, whereas magnet B is dropped from above a copper plate. Which magnet will strike the surface first?

(A) Magnet A

(B) Magnet B

(C) Both will strike at the same time.

(D) Whichever has the N pole toward the ground.

(E) Whichever has the S pole toward the ground.

Problem 4.2 (SJPO 2022)**.** You push a bar magnet with its north pole away from you toward a loop of conducting wire in front of you. The plane containing the loop is perpendicular to the magnet. As the north pole approaches the loop, the current in the loop is ________.

(A) clockwise then counterclockwise

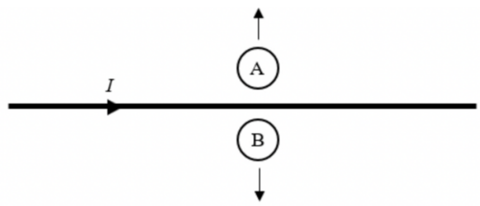
(B) counterclockwise then clockwise

(C) zero

(D) clockwise

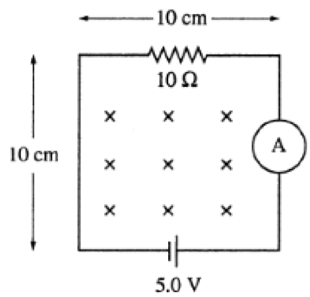
(E) counterclockwise

Problem 4.3 (SJPO 2023)**.** Two small loops of wires A and B are located close to a straight wire which carries a conventional current in the direction shown. Both loops are moved away from the straight wire. What are the orientations of the conventional current generated in each loop while this occurs?



	Loop A	Loop B
(A)	Clockwise	Anticlockwise
(B)	Anti-clockwise	clockwise
(C)	No current	No current
(D)	Anti-clockwise	Anti-clockwise

Problem 4.4 (SJPO 2011)**.** The circuit shown below is in a uniform magnetic field that is into the page and is decreasing in magnitude at the rate of 150 T/s. The current in the loop is:



(A) 0.35 A counter-clockwise

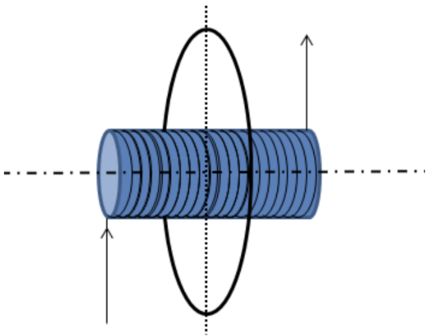
(B) 0.35 A clockwise

(C) 0.65 A counter-clockwise

(D) 0.65 A clockwise

(E) 0.85 A counter clockwise

Problem 4.5 (SJPO 2012)**.** The following shows a wire coiled around an insulating, non-magnetic pipe with a current running in it. A conducting ring is placed near the centre of the coil with their axes aligned (see figure below). As the electrical current is decreased, which of the following happens?



(A) The conducting ring experiences a force that tends to shrink the area of the circle.

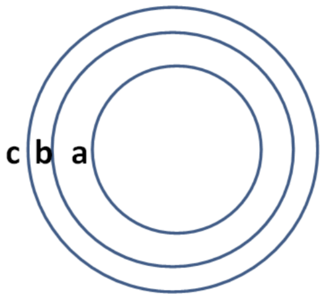
(B) The conducting ring experiences a force that tends to expand the area of the circle.

(C) The conducting ring experiences a force that tends to move it to the right.

(D) The conducting ring experiences a force that tends to move it to the left.

(E) The conducting ring does not experience any force at all.

Problem 4.6 (SJPO 2013)**.** As shown in the diagram, a, b, c are three concentric circular wire loops with radii $R_a < R_b < R_c$. The three loops have the same resistances. When a clockwise current through a is suddenly increased, the induced current in loops b and c is



(A) Clockwise, $i_b > i_c$

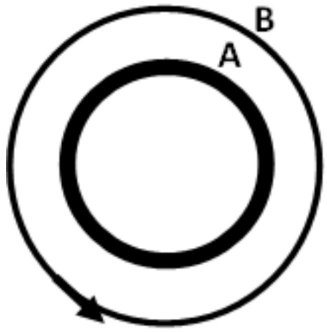
(B) Anti-clockwise, $i_b > i_c$

(C) Clockwise, $i_b < i_c$

(D) Anti-clockwise, $i_b < i_c$

(E) Zero

Problem 4.7 (SJPO 2015)**.** A plastic ring A is rubbed with rabbit fur and gains a negative charge. It is then placed inside a metal ring as shown in the diagram below. An electrical current can be induced in the metal ring B (anticlockwise as indicated in diagram) when A is



(A) turning clockwise with constant angular velocity.

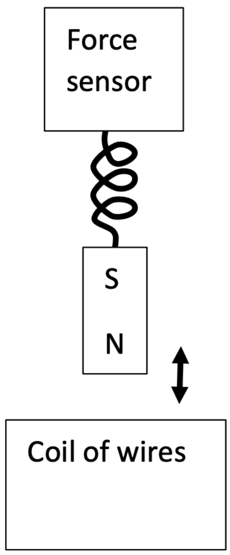
(B) turning anti-clockwise with constant angular velocity.

(C) turning clockwise with increasing angular velocity.

(D) turning anti-clockwise with increasing angular velocity.

(E) not turning.

Problem 4.8 (SJPO 2016)**.** A bar magnet attached to the end of a spring performs simple harmonic motion above a coil of wires as shown in the diagram. The other end of the spring is attached to a fixed force sensor which was zeroed when the magnet was at its equilibrium position. The EMF across the coil of wires and the force are plotted against time. Which of the following statement is true?



(A) The magnitude of the EMF is maximum when the force is zero.

(B) The magnitude of the EMF is maximum when the magnitude of the force is maximum.

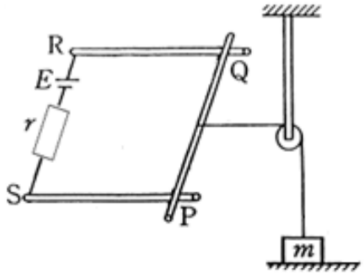
(C) The magnitude of the EMF is zero when the magnitude of the force is maximum.

(D) The magnitude of the EMF is zero when the force is zero.

(E) The EMF also has a perfectly sinusoidal waveform.

For the following 3 questions:

As shown in the figure, a metal rod is placed on two fixed conducting rails at points P and Q. R and S are the end points of the rails, so $PQRS$ is a square circuit of side l on a horizontal plane. Between RS is a battery of emf E, a resistance r and a switch (not shown). A mass m resting on the floor is connected to the rod at the mid-point of PQ by a horizontal string which passes through a pulley and runs parallel to the rails.



Neglect the resistances of the rails, the rod and the contacts as well as the internal resistance of the battery. Neglect also the mass of the rod and string, and the friction between parts in relative motion. Take $g = 10$ m/s^2, $m = 0.1$ kg, $l = 1.0$ m, $E = 20.0$ V, $r = 100$ Ω.

Now, we want to lift the mass by passing as small as possible a magnetic field B through the circuit.

Problem 4.9. In which direction should the magnetic field point?

(A) any direction will do

(B) horizontal leftward

(C) horizontal rightward

(D) vertically downward

(E) vertically upward

Problem 4.10. Let the magnetic field be increased from zero at a constant rate so that the mass m starts to move up at 1 second. The value of the magnetic field at this time is ________.

(A) 3 T

(B) 2 T

(C) 4 T

(D) 10 T

(E) 5 T

Problem 4.11. If the rate of increase of the magnetic field B approaches zero, the magnitude of the magnetic field required approaches ________.

(A) 3 T

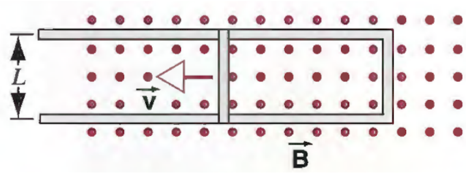
(B) 2 T

(C) 4 T

(D) 10 T

(E) 5 T

Problem 4.12. The figure below shows a conducting rod of length L being pulled along horizontal, frictionless, conducting rails at a constant velocity $\vec{v}$. A uniform vertical magnetic field $\vec{B}$ fills the region in which the rod moves. Assume that $L = 10.8$ cm, $v = 4.86$ m/s, and $B = 1.18$ T.



(a) Find the induced emf in the rod.

(b) Calculate the current in the conducting loop. Assume that the resistance of the rod is 415 mΩ and that the resistance of the rails is negligibly small.

(c) At what rate does the internal energy of the rod increase?

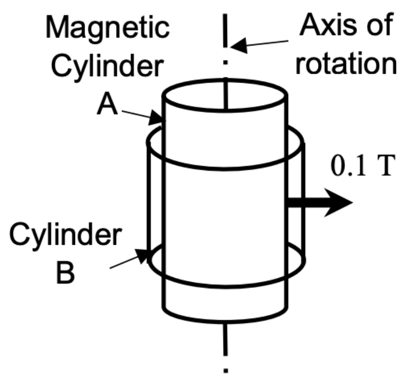
(d) Find the force that must be applied by an external agent to the rod to maintain its motion.

(e) At what rate does this force do work on the rod? Compare your answer to that in part (c).

Problem 4.13 (SJPO 2017)**.** Two coaxial cylinders, A and B may be rotated on the axis as shown in the figure. The inner non-conducting cylinder A is magnetized such that a 0.1 T magnetic field points uniformly outwards through the curved surface of conducting but non-magnetic cylinder B with radius 5 cm and length 4 cm. The potential difference between the top and bottom of cylinder B may be measured using a stationary voltmeter.

Consider the following cases:

I cylinder B rotates at 120 rpm, cylinder A is stationary,
II cylinder A and B rotate at 120 rpm together,
III cylinder B rotates at 120 rpm, cylinder A rotates at 120 rpm in the opposite way,
IV cylinder A rotates at 120 rpm, cylinder B is stationary.



Which is true?

(A) Case III produces the largest potential difference and all other cases produce lower potential differences.

(B) Cases I and II produce the same potential difference.

(C) Cases I and IV produce the same potential difference.

(D) Case II produces zero potential difference.

(E) Not (all or one) but (some or none) of the above is true.

Problem 4.14 (SJPO 2018)**.** Two identical LED light bulbs are rated as 12 W, 100–240 V. That is, the electronics within the bulb provides fixed 12 W of electrical power to the light emitting diodes in the bulb as long as the AC power supply can provide an RMS voltage anything between 100 V to 240 V. Assume the electronic circuit is 100% efficient. What is the current when the two bulbs are connected in series to 240 V?

(A) 0.012 A

(B) 0.025 A

(C) 0.050 A

(D) 0.10 A

(E) 0.20 A

Problem 4.15 (SJPO 2018)**.** When a capacitor C is connected directly to an ideal AC voltage source with an amplitude of 1.0 V, the AC current has an amplitude 1.0 A. When an inductor L is connected directly to the same source, the AC current has the same amplitude of 1.0 A. When a resistor R is connected directly to the same source, the AC current has the same amplitude. When all three components are connected in series with the ideal AC voltage source with an amplitude of 1.0 V, the AC currents amplitude is ________. Assume that the AC frequency is constant.

(A) 0.33 A

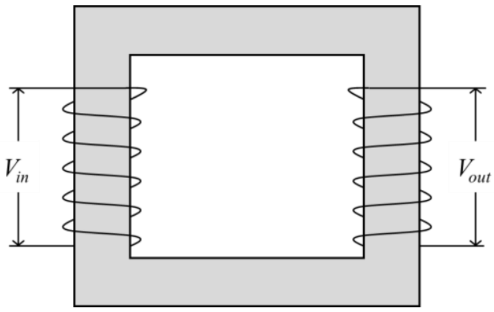
(B) 0.58 A

(C) 1.0 A

(D) 1.7 A

(E) 3.0 A

Problem 4.16 (SJPO 2017)**.** Consider the alternating-current transformer above. Which of the following statements gives the correct explanation and phase difference between V_{in} and V_{out}?



(A) By Faraday's Law, phase difference = 0 (i.e. V_{in} and V_{out} are in phase).

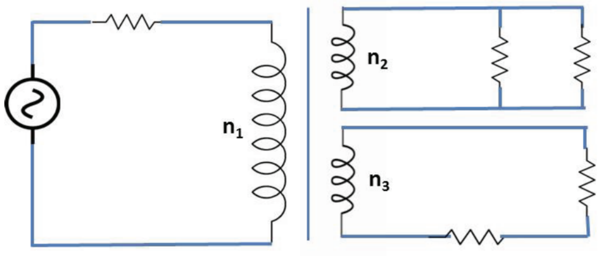
(B) By Faraday and Lenz's law, phase difference = 45°.

(C) By analogy to simple harmonic motion, phase difference = 90°.

(D) By Fleming's Left hand rule, phase difference = 135°.

(E) By Lenz's Law, phase difference = 180° (i.e. V_{in} and V_{out} are in anti-phase).

Problem 4.17 (SJPO 2014)**.** In the diagram as shown, the resistor loads have the same power rating. They are attached in the circuit as shown. The respective number of windings in the ratio $n_1 : n_2 : n_3$ is thus



(A) $1 : 2 : 1$

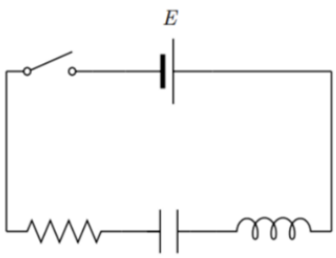
(B) $2 : 1 : 2$

(C) $4 : 2 : 1$

(D) $1 : 1 : 2$

(E) $4 : 1 : 2$

Problem 4.18 (SJPO 2025)**.** A resistor, an uncharged capacitor and an inductor are connected in series with a battery of e.m.f. E. The switch has initially been open for a long time. At time $t = 0$, the switch is closed. What is the voltage V_C across the capacitor and the voltage V_L across the inductor at times $t = 0$ and $t = \infty$?



(A) $V_C = 0,\ V_L = 0$ at $t = 0$; $V_C = 0,\ V_L = 0$ at $t = \infty$

(B) $V_C = 0,\ V_L = 0$ at $t = 0$; $V_C = E,\ V_L = 0$ at $t = \infty$

(C) $V_C = 0,\ V_L = E$ at $t = 0$; $V_C = 0,\ V_L = 0$ at $t = \infty$

(D) $V_C = 0,\ V_L = E$ at $t = 0$; $V_C = E,\ V_L = 0$ at $t = \infty$

(E) $V_C = E,\ V_L = 0$ at $t = 0$; $V_C = 0,\ V_L = E$ at $t = \infty$

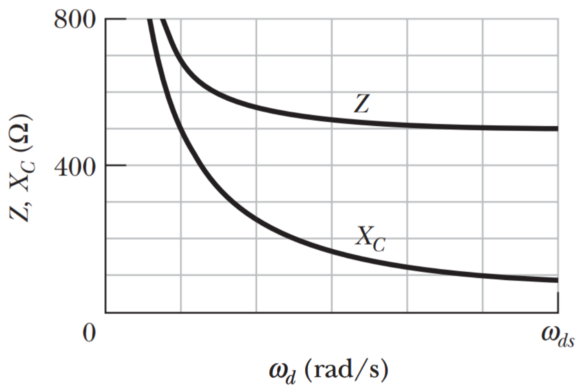
Problem 4.19 (HRK)**.** A circular coil has a 10.0 cm radius and consists of 30.0 closely wound turns of wire. An externally produced magnetic field of magnitude 2.60 mT is perpendicular to the coil. (a) If no current is in the coil, what magnetic flux links its turns? (b) When the current in the coil is 3.80 A in a certain direction, the net flux through the coil is found to vanish. What is the inductance of the coil?

Problem 4.20 (HRK)**.** An oscillating LC circuit consists of a 75.0 mH inductor and a 3.60 mF capacitor. If the maximum charge on the capacitor is 2.90 mC, what are (a) the total energy in the circuit and (b) the maximum current?

Problem 4.21 (HRK)**.** In an oscillating LC circuit, $L = 3.00$ mH and $C = 2.70$ mF. At $t = 0$ the charge on the capacitor is zero and the current is 2.00 A. (a) What is the maximum charge that will appear on the capacitor? (b) At what earliest time $t = 0$ is the rate at which energy is stored in the capacitor greatest, and (c) what is that greatest rate?

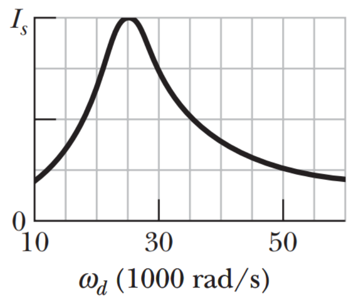
Problem 4.22 (HRK)**.** A series circuit containing inductance L_1 and capacitance C_1 oscillates at angular frequency ω. A second series circuit, containing inductance L_2 and capacitance C_2, oscillates at the same angular frequency. In terms of ω, what is the angular frequency of oscillation of a series circuit containing all four of these elements?

Problem 4.23 (HRK)**.** An alternating source with a variable frequency, a capacitor with capacitance C, and a resistor with resistance R are connected in series. The figure below gives the impedance Z of the circuit versus the driving angular frequency ω_d; the curve reaches an asymptote of 500 Ω, and the horizontal scale is set by $\omega_{ds} = 300$ rad/s. The figure also gives the reactance X_C for the capacitor versus ω_d. What are (a) R and (b) C?



Problem 4.24 (HRK)**.** An electric motor has an effective resistance of 32.0 Ω and an inductive reactance of 45.0 Ω when working under load. The voltage amplitude across the alternating source is 420 V. Calculate the current amplitude.

Problem 4.25 (HRK)**.** The current amplitude I versus driving angular frequency ω_d for a driven RLC circuit is given in the figure below, where the vertical axis scale is set by $I_s = 4.00$ A. The inductance is 200 mH, and the emf amplitude is 8.0 V. What are (a) C and (b) R?



Problem 4.26 (HRK)**.** An ac generator provides emf to a resistive load in a remote factory over a two-cable transmission line. At the factory a step-down transformer reduces the voltage from its (rms) transmission value V_t to a much lower value that is safe and convenient for use in the factory. The transmission line resistance is 0.30 Ω/cable, and the power of the generator is 250 kW. If $V_t = 80$ kV, what are (a) the voltage decrease ΔV along the transmission line and (b) the rate P_d at which energy is dissipated in the line as thermal energy? If $V_t = 8.0$ kV, what are (c) ΔV and (d) P_d? If $V_t = 0.80$ kV, what are (e) ΔV and (f) P_d?