AC Circuits: Crash Course Physics #36

Crash Course: Physics
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===== Introduction (0:03) =====

We couldn't keep the lights on without alternating currents.

We've talked about how they change voltage, which helps transmit electricity over long distances, but there's so much more to the physics of AC circuitry. For example, how are alternating currents affected when you add resistors? Or capacitors? Or an inductor?

These three pieces of the electricity puzzle are used everywhere, and today we're going to put them together.

===== Main Episode (0:42) =====

When you talk about direct current circuits describing voltage and current in a given situation, it's pretty straightforward. Typically the voltage source in a DC circuit is unchanging, so the current will be constant too, but in an AC circuit, both the voltage and the current are constantly changing directions (from positive to negative, and back again).

So how do you describe values when they're constantly changing? Well, when a current alternates quickly, it's changing back and forth between maximum and minimum values (known as "peak current"), and "peak" here means "either maximum or minimum," "positive or negative," since the flow of current has the same magnitude.

Mathematically the current is equal to the peak current times the sine function related to the system's frequency (typically 60 hertz). And the same is true for the voltage in an AC circuit. It changes between a maximum and minimum peak voltage in order to generate the alternating current.

Now let's say you're calculating the average power consumed by an AC circuit. You can use the handy power expression for DC circuits which we've already derived in order to find the consumed energy over time in terms of current and resistance.

Then you can replace the current with our new equation for alternating current. Then since you want to find the average power, just take the average of the power expression. The sine squared function always reduces to one half when averaged.

This leaves you with an average power of peak current squared, times resistance, divided by two. But you can only take this equation for DC circuits so far before you have to start making some serious changes for it to help you figure out AC circuits.

Why? Because of "I": the value for current itself.

Think of driving a car in stop-and-go traffic. You speed up at times, you slow down at others, but if you average it out over the whole trip, you've got an effective speed somewhere in the middle.

That's what current is like in AC calculations. So in order to express current in this equation, we need a new variable that represents this effective value. And that variable is the root-mean-squared (or RMS) value of current.

It's really just the value you would get if you squared the current, took the average, and then square-rooted it again. Hence the name: "root-mean-squared."

Now this same derivation works for alternating voltage as well with the RMS value of voltage being equal to the peak voltage divided by the square-root of two.

With these two RMS values at your disposal, you can then use them in place of current and voltage in DC equations with power equalling RMS current times RMS voltage.

So now that we have RMS values to better describe current and voltage in AC circuits, let's think about how we can use the unique nature of AC circuits to our advantage.

For example: with coils of wire, we know that when the current is changing, a magnetic flux is induced in the coil, and that flux seeks to oppose the current with an electromotive force (or EMF) in the opposite direction. And this is the rule that we know as Lenz's Law.

And this relationship works the opposite way as well, with a changing magnetic flux inducing an EMF that opposes the flux.

Now in an AC circuit what you end up with is a changing current that induces an opposing magnetic flux, which in turn induces an EMF in the opposite direction of the current. This induction of an EMF that opposes the main current is called "self inductance."

And to calculate an induced EMF, you just take the change in current over time and multiply it by negative L. "L" is a constant known as the "inductance," signifying how well that specific coil induces an opposing current depending on its shape and size.

And it's negative because the induced EMF is in the opposite direction of the main current.

Inductance, by the way, is expressed in units called "Henries."

Induction of an force is so useful that engineers make coils that are designed to maximize their self-inductance. These coils that are designed for self-inductance are called "inductors." In a circuit diagram, they look like small coils, 'cause that's pretty much what they are.

So to get a handle on how inductors work let's first consider one in a DC circuit. Let's say the circuit has an inductor connected in series with a battery that has a constant voltage "V-naught." Since most inductors have a natural resistance, we'll say there's also a small resistor in series with the inductor and battery.

And because we have an inductance "L" and a resistance "R," we call this configuration an "LR circuit." If we set up this circuit and then insert the battery, the voltage will immediately be V-naught, but the current won't reach it's maximum value.

That's because the inductor opposes the sudden change in current that was caused by the sudden voltage change. So the current will increase gradually until it eventually reaches maximum current, which is the battery's voltage divided by the resistance.

The current in this case is kind of like a car that's accelerating from a dead stop. Even if you stomp down on the gas pedal, you won't immediately start going at top speed; you're going to have to build up to it over time. So you're going to have to consider time when you're dealing with inductors.

Mathematically, the current in the circuit with an inductor is expressed as the maximum current times one minus e to the negative t over tau. The maximum current is the voltage divided by the resistance, and tau is the time constant equal to the inductance divided by the resistance.

This time constant has all kinds of mathematical meaning which we can't get into right now, but you can see that as time goes to infinity, you get closer to the maximum current value.

Put in terms of our current energy, the maximum current is like the fastest that your car will go, and the time constant lets you know how long you need to press down on the accelerator to get there.

A small time constant means less time is needed to reach maximum speed, and also less time to slow down to a stop. A large time constant means the opposite: that a lot of time is necessary to speed up and slow down.

Now let's say the circuit has reached "steady state" with the current at that maximum value. There's no longer a change in current, so the inductor acts just like a piece of wire.

If the battery is suddenly removed, the current won't drop to zero immediately, because, remember, the inductor opposes the change in current with its own changing magnetic flux.

So after the battery's removed, the inductor generates its own current. This is like driving a car, then taking your foot off the accelerator: you stop the car from going faster, but you won't stop immediately. Instead you'll slow down over time before you stop entirely.

So you can write this as the decreasing version of the earlier current equation, with current equalling the maximum possible current times e to the negative t over tau. I-max is the same, and tau is the same, and once enough time is past, then current is equal to zero.

So inductors oppose a change in current, whether it's an increase or a decrease. When you switch a device on or off and you notice a delay, that's probably because an inductor is in the system. By flipping the switch you've either started or ended a voltage supply, but an inductor in the system delays the current from starting or stopping immediately.

Okay, so that's Inductors 101. Now let's go back to AC circuits and combine an inductor, a resistor, and a capacitor all in one circuit. Each component will behave differently when connected to the source of alternating voltage.

So before we combine everything, let's look at each component as if it alone were in series with the source.

Let's start with a resistor. When the voltage is at peak voltage, the current through the resistor will also be at peak current. Since the voltage and current peaks occur at the same time, the two are said to be "in phase."

For inductors and capacitors, however, the story's a little different. As the alternating voltage is applied across the inductor, the opposing EMF that's induced equals the amount of voltage that drops across the device. The inductor has an insignificant amount of resistance, so when it's the only device in the circuit, all the voltage must be opposed by the opposing EMF.

In this equation, the voltage is at maximum when the current is changing the fastest, and the voltage is zero when the current isn't changing at all. This means that when the current is zero, there's peak voltage, and when current is at its peak, and unchanging, the voltage is zero.

When you express this graphically, it means that the current lags behind voltage by ninety degrees or a quarter cycle. So in AC circuit inductors, we say that the current and voltage are "out of phase," which means they don't peak at the same time.

Capacitors in AC circuits are also out of phase, but for a different reason. Let's look at a circuit with only an alternating voltage source and a capacitor.

When the current flows in one direction, charge momentarily builds up on one of the plates. So when the voltage changes from positive to negative, the capacitor acts as a smaller voltage source that still pushes the current along. In this case, current leads voltage by ninety degrees, changing the direction ahead of the voltage source.

So let's sum up. Current in inductors lags voltage, current in resistors is in phase with voltage, and current in capacitors leads voltage.

Another thing that sets inductors and capacitors apart from resistors is that they don't release a lot of heat. The only part of an AC circuit that dissipates power is thermal energy is the resistance.

Inductors and capacitors both have negligible resistance, and they don't dissipate heat, but they do have voltage drops across each component. So their voltage drops will still affect how much voltage the circuit can supply to other components that do need to dissipate power.

So when you have an AC circuit with a resistor, inductor, and capacitor in series, you can calculate the voltage supplied versus the voltage applied across each component by adding all of the component voltage drops together. Every voltage drop peaks at a different time, but the sum will always equal that of the source. What goes in must go out!

This wraps up our last look at electricity. But you can't forget everything you've learned about electromagnetism yet, because it's coming back in a shiny, new form known as light.

===== Summary (9:16) =====

Today we learned about currents and voltages in AC circuits. We also learned about inductors, and we combined our knowledge of AC circuits with inductors, capacitors, and resistors in order to analyze how voltage and current interact with an alternating voltage source.

===== Credits (9:29) =====

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