My own basic theory by David Sphar

What causes phase shifting in an inductor…

?

It is common knowledge that inductors create a voltage to current phase shift up to 90 degrees. Here I will investigate a concept about why this happens. As the idea is faintly developed in my head I will use this presentation to both organize my thoughts and explore various practical applications of my understanding.

Disclaimer: I have not yet attended any university electrical theory classes and as such will probably use some funny terminology. Also, these ideas as simply my own understanding *to date*. This could cause some of these theories to disagree with current scientific understanding. As I learn, my theories will evolve, and may come to greater agree or disagree with current scientific beliefs. Also, I am not yet rehearsed in the history of electricity and electronics and may present ideas that others have already investigated. If you are familiar of any pre-existence of the practical applications that I present, please guide me to the originator so I can give them proper credit. Consider the following pages with a critical mind. Use your own experience and understanding to either verify or discredit the things presented here. All concepts and practical applications that I present are released freely as open source, unless they have *previously* been protected under patent law without my knowledge. Please use them freely, but as you use these concepts and illustrations I ask that you reference them appropriately. Thank you.

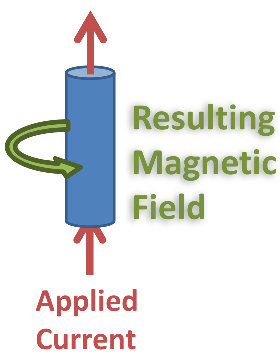
David Kirk Sphar

Concept One: Magnetic Flux ‘Interference’

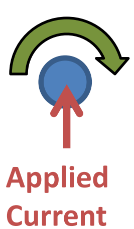
In studying, I found out that the term I am looking for is inductive reactance. However, I was not able to find a real explanation of what this is. Most texts simply write this off as Lenz Law manifesting itself in a coil of wire. But what is really going on? If we are to ever discover how to manipulate Lenz Law, we must understand thoroughly what is causing this inductive reactance.

Concept 1a: Electromagnetism

We know that as we apply an electric current through a wire it creates a magnetic field around that wire.

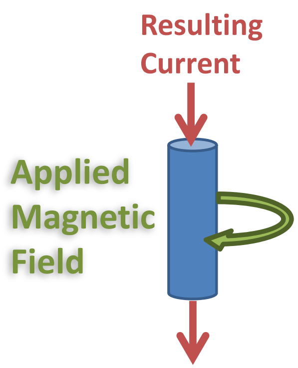


Applied Current = Resulting Magnetic Field

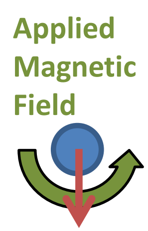


Concept 1b: Electricity Generation

We also know that as we apply a changing magnetic field to a wire, it will induce an electrical current through the wire. This only happens while the magnetic field is changing.

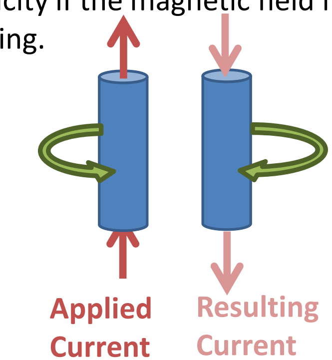


Applied Magnetic Field = Resulting Current

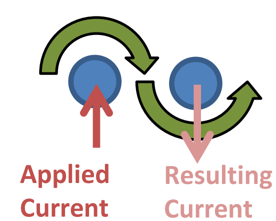


Concept 1c: Resulting Current (opposite direction)

If we combine concepts 1a and 1b by placing two wires next to each other, the current in the first wire creates a magnetic field that influences the second wire. Picture the magnetic fields connecting like gears and you will understand that the electric current in the second wire will travel opposite of the first. Again, the second wire will only have electricity if the magnetic field from the first is changing.



Applied Current = Resulting Magnetic Field = Resulting Current



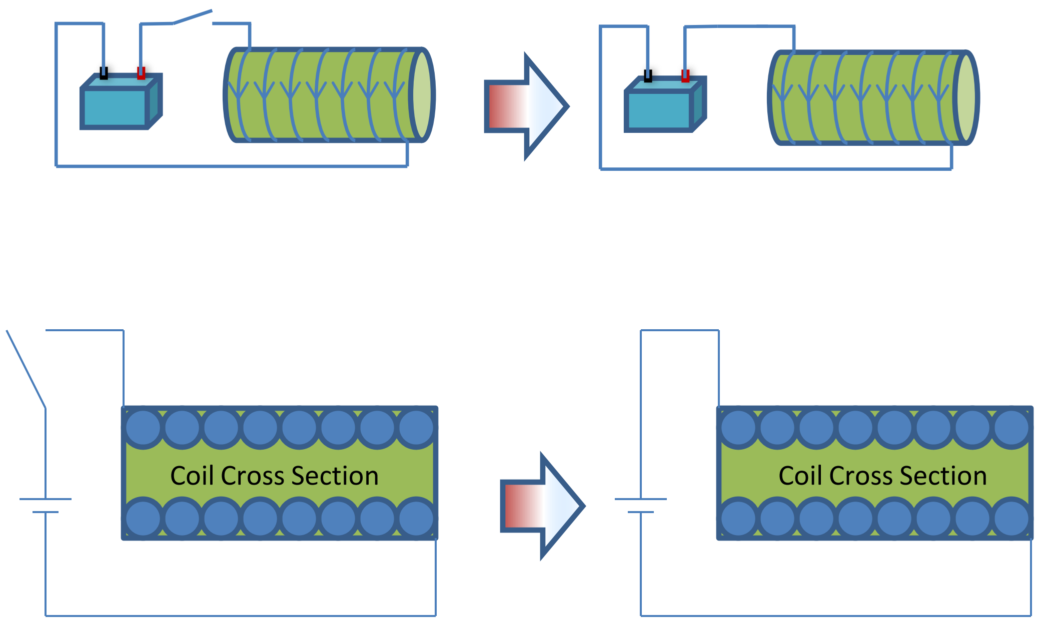
David Sphar

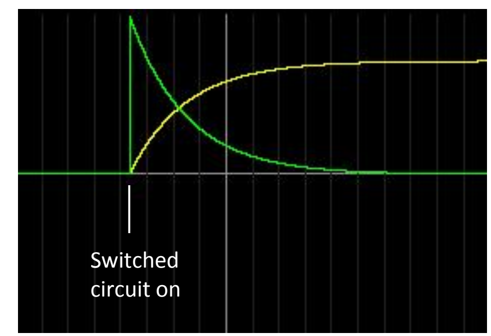
Concept One (cont.): Magnetic Flux ‘Interference’

Now we will introduce a simple circuit containing a steady DC source and a coil of wire, also called an inductor. We know that at the moment we close the circuit, no current flows through the inductor but voltage is at its peak. But why is that?

Basic inductor circuit

Notice DC power source





Voltage

Current

Basic inductor circuit with a DC power source. Switch is open.

Close switch to initiate an electrical current.

Observe: at the point we switch the inductor circuit on we get an immediate spike of voltage but no current. Then as time goes on our voltage decreases, while our current increases. Why does this happen?

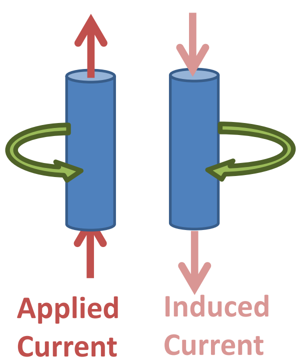
Concept One (cont.): Magnetic Flux ‘Interference’

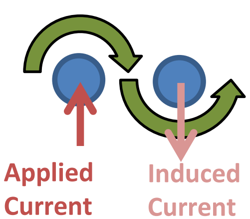
To investigate why voltage is maximum and current is zero when we switch the circuit on, we will consider the following relationships.

Concept 1a: applied current in a wire = resulting magnetic field around the wire
Concept 1b: changing the magnetic field around a wire = resulting current in the wire
Concept 1c: applied current in a wire = resulting current (opposite direction) in neighboring wire do to 1a + 1b

Remember Concept 1c

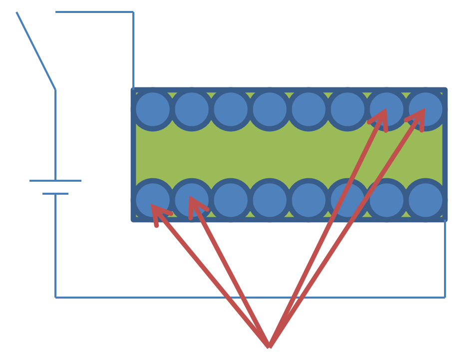
If we place two wires next to each other and apply a current in one, the growing magnetic field will create a current going the opposite direction in the second. In simple terms, when the current begins to flow in the first wire, it creates an opposing current in the second wire. Important: this induced current only happens when the magnetic field from the first wire is changing (ie when the current through the first wire changes.





What about a coil of wire?

When you wind a coil of wire, you are placing multiple sections of wire next to each other. See below. Because these sections of wire are all a part of the same wire, the applied current and resulting current will not act the same way as if they were separate wires.

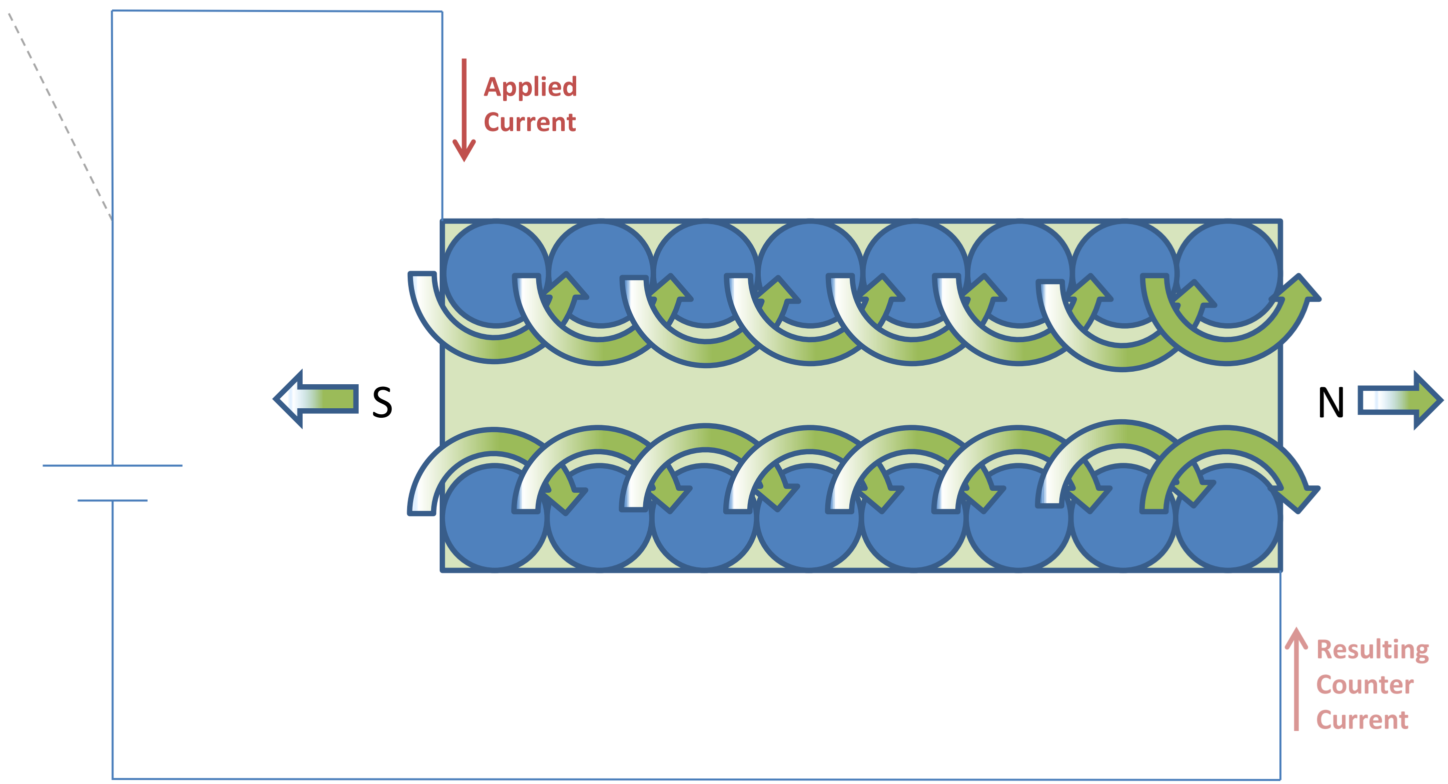


Notice that parts of the same wire form segments that are parallel with each other.

David Sphar

Concept One (cont.): Magnetic Flux 'Interference'

Again, as we apply an electric current in a coil of wire in one direction, the magnetic interaction between windings will create an electric current in the opposite direction. This is because concept 1c that we discussed earlier.



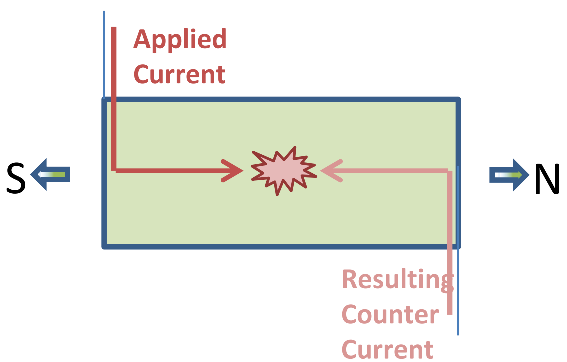
David Sphar

Concept One (cont.): Magnetic Flux 'Interference'

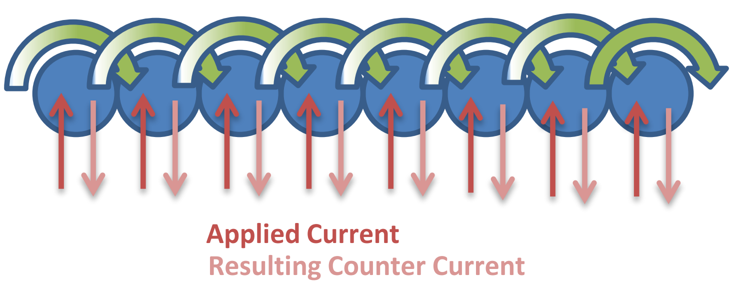
Now it is easy to understand why voltage is at a maximum and current is zero when we first close the switch. If we recall, voltage is the potential electrical difference. When an inductor circuit is first switched on we have a huge electrical potential from the source pushing in one direction, but do to the magnetic flux change in the coil, we have an electrical potential being pushed in the opposite direction. We can represent these as positive and negative electrical potentials respectively. The difference between these two is our total voltage within the coil itself…
positive V - negative V = large positive V

(+V) – (-V) = Total Voltage

Note: this total voltage represents the voltage within the wire that is actually part of the coil. If you are comparing the potential difference in the wire before it goes in to the coil (+V) to the potential difference in the wire after it comes out of the coil (0), you will get V – 0 = Vtotal, or in other words, your applied voltage only. This is the voltage that electricity theory commonly accepts in an inductor. Note to self: maybe?



OR



When you first power the circuit, the resulting counter current (Back EMF) is equal to the forward current and as such the voltage is high, but the current is zero. Current can't flow because it is being pushed backwards at equal force by the back current. Now we know the answer to our first question, but what happens as time goes on?

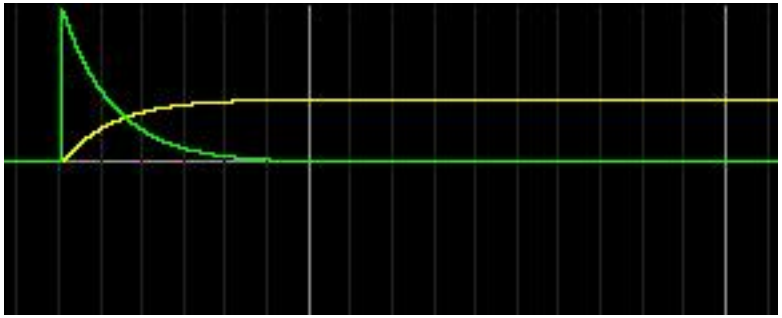
David Sphar

Concept Two: Why the Logarithmic Increase in Current?

Why the Logarithmic Increase in Current…

?

Now that we know what happens in an inductor the moment we apply a DC voltage source, we can investigate what happens to it as time continues. If we graph the current through an inductor as it charges, we see that it looks like it is increasing in a logarithmic fashion. Why?



David Sphar

Concept Two: Why the Logarithmic Increase in Current?

In order for us to understand why current increases in such a manner we must understand the inductor charging process. I have not been able to find a clear and thorough explanation and once again rely on my own understanding and theory. This may just be too basic to discuss, but I needed to make it clear in my head. Hence the following. Remember this theory currently makes sense to me but may change (or become stronger) as I gain more knowledge and experience. Please study these steps and the illustration together carefully so you can understand what is happening.

Concept 2a: The Inductor Charge Cycle (7 Steps)

Step 0: A positive voltage is applied to the inductor

Step 1: There is a positive change of current through the inductor

Step 2: This change in current creates a positive change of magnetic field around the inductor

Step 3: This change in the magnetic field creates a back flow of current equaling the positive current change seen in step one

Step 4: The new positive current (Step 1) and negative current (Step 3) oppose each other and stop the change in inductor current

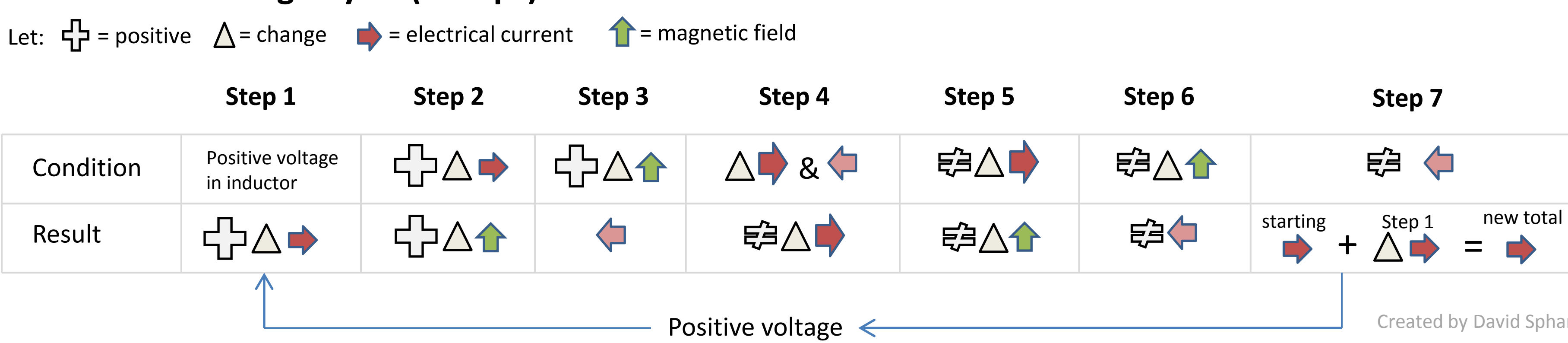
Step 5: Because there is no more change in inductor current, there is no more change of the magnetic field in the inductor

Step 6: Because there is no more change of magnetic field in the inductor, there is no more back EMF as found in Step 3

Step 7: With no back EMF, our new total current is equal to the starting current (before Step 1) plus the change in current found in Step 1.

(with no more back EMF limiting the forward current, it will start increasing again which loops back to step 1)

The Inductor Charge Cycle (7 steps) Fig. 2.1

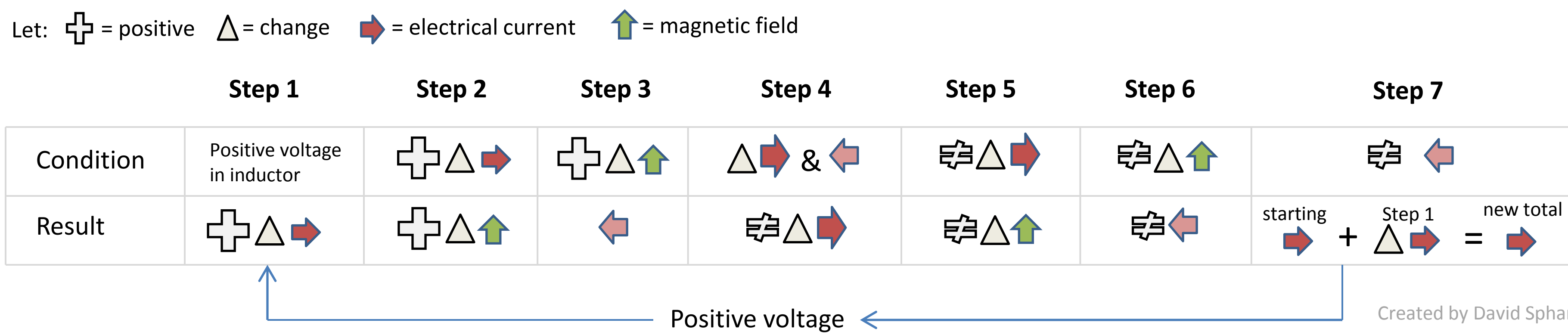


Created by David Sphar

Concept Two: Why the Logarithmic Increase in Current?

I will run you through a few cycles mathematically so you can see what is going on. In reality the change in time during the Inductor Charge Cycle is approaching 0. $\Delta(t) \rightarrow 0$ However, for demonstration purposes, let's assume that all changes are equal to 1.

The Inductor Charge Cycle (7 steps) Fig. 2.1



Example of the Inductor Charge Cycle Fig. 2.2

	Cycle One	Cycle Two	Cycle Three	Cycle Four	Cycle Five	Cycle Six	Cycle Seven
	Starting current (Si) = 0	(Si) = 1	(Si) = 2	(Si) = 3	(Si) = 4	(Si) = 5	(Si) = 6
Step 1	Δi = 1	Δi = 1	Δi = 1	Δi = 1	Δi = 1	Δi = 1	Δi = 1
Step 2	Δm = 1	Δm = 1	Δm = 1	Δm = 1	Δm = 1	Δm = 1	Δm = 1
Step 3	Δ(-i) = 1	Δ(-i) = 1	Δ(-i) = 1	Δ(-i) = 1	Δ(-i) = 1	Δ(-i) = 1	Δ(-i) = 1
Step 4	1 + (-1) = 0 Δi	1 + (-1) = 0 Δi	1 + (-1) = 0 Δi	1 + (-1) = 0 Δi	1 + (-1) = 0 Δi	1 + (-1) = 0 Δi	1 + (-1) = 0 Δi
Step 5	0Δi = 0Δm	0Δi = 0Δm	0Δi = 0Δm	0Δi = 0Δm	0Δi = 0Δm	0Δi = 0Δm	0Δi = 0Δm
Step 6	0Δm = 0bi	0Δm = 0bi	0Δm = 0bi	0Δm = 0bi	0Δm = 0bi	0Δm = 0bi	0Δm = 0bi
Step 7	**0Si + 1Δi = 1Ti**	**1Si + 1Δi = 2Ti**	**2Si + 1Δi = 3Ti**	**3Si + 1Δi = 4Ti**	**4Si + 1Δi = 5Ti**	**5Si + 1Δi = 6Ti**	**6Si + 1Δi = 7Ti**
Output	Total Current (Ti) = 1	Total Current (Ti) = 2	Total Current (Ti) = 3	Total Current (Ti) = 4	Total Current (Ti) = 5	Total Current (Ti) = 6	Total Current (Ti) = 7

David Sphar

Concept Two: Why the Logarithmic Increase in Current?

If you watch the Total Current as it increases in the previous table you will see that the current was increasing linearly (1 unit for every cycle). This would be true if there was absolutely no resistance in your circuit whatsoever. But, as we know there is resistance in every circuit.

Test this. Create a basic DC inductor circuit with zero resistance in a simulator like this one http://www.falstad.com/circuit/. You will see that the current increases in a straight line forever, as long as a voltage is applied. But, we don't live in simulators. This is the real world. And why do inductor currents grow in a logarithmic fashion in the real world? **The answer is simple,** especially if you consider the principles without confusing it with calculus and complex math formulas. It is easier to understand without considering things like the differential equation $V = L\ (di(t) / dt)$. Yes, get that fundamental inductor equation OUT of your head!

As the magnetic flux builds in the inductor, the back emf gets weaker and weaker. Because of this you would think that the change in current would increase due to less back EMF, but this is not so. Why? Well, the thing that drives current through the inductor is voltage. And as we will investigate, voltage will decrease in an inductor as current increases.

We already stated that voltage in an inductor is the potential energy in the inductor, or in other words, the potential difference in current. Hence if we take the actual current (i) and subtract it from the maximum current (Mi) we find the potential difference in the inductor, or a number which we can use to find the Voltage. It's that easy! Let me show you.

Concept 2c: Use maximum current (Mi) and instantaneous current (i) to find voltage in an inductor

Let's say we have a resistive inductor circuit (RL circuit) that has a 50 Ω resistance, an inductor with 3 Henrys, and a 100 volt power source. We know that the current on resistive circuits is limited by the formula of applied voltage / resistance. $i = v / R$

so

Our maximum current Mi =
$i = 100v / 50\Omega$
or $i =$ **2 amps**

For the ease of demonstration we will pick the first time constant in our inductor. We know that at this time constant (which is 60 milliseconds) our current is 63.21% of the maximum current. Hence at 60 milliseconds current is moving through the coil at 2 * .6321 = 1.2642 amps

so

Our actual current at 60 milliseconds
$i = 1.2642$ amps

David Sphar

Concept Two: Why the Logarithmic Increase in Current?

From the last page we know
- R = a 50Ω
- L = 3
- P = 100v
- Mi = 2 amps
- i @ 60 ms = 1.2642 amps

If we find the difference between the max i and the i @ 60ms we get the potential current difference (Pi) in the coil.
Mi – i = Pi so 2 – 1.2642 = .7358
Pi = .7358 amps

Now that we know the potential difference current in the inductor, we can convert it to volts by using the formula V = Pi*R
V = .7358 * 50 = 36.79 volts

Therefore with this calculation we find that the voltage in the inductor is 36.79 volts at 60 milliseconds.

Hence with this calculation we find that the voltage in the inductor is 36.79 volts at 60 milliseconds.

In other words, at 60 milliseconds, there is 36.79 volts of force to drive the next inductor charge cycle.

What about volts at 1 millisecond?
Let's do another voltage calculation for this inductor, but this time let's do it at 1 millisecond. At 1ms we find that we have a current i of .03298 amps. If we take the maximum amps Mi of 2 and subtract i we get 1.96702 potential change amps. We convert these to volts by multiplying by the resistance of 50Ω to get 98.351 volts driving the current increase at 1 millisecond.

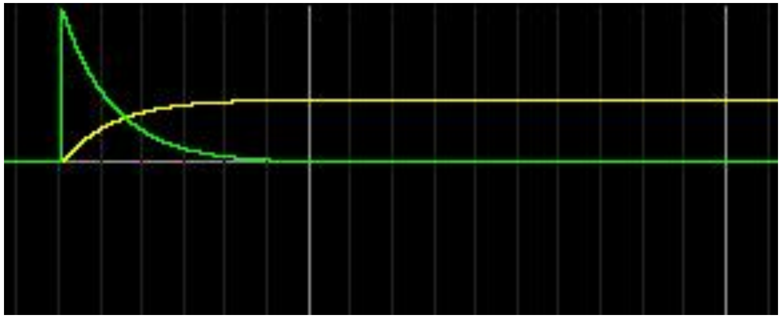
Or volts at 0 seconds? (when you close the switch)
When you close the switch your actual current is zero, and as such the potential difference current is 2 amps minus 0 amps = 2 amps of potential change. We convert these to volts by multiplying by the resistance of 50Ω to get 2a * 50Ω = 100 volts (our entire applied voltage) driving the coil at 0 seconds. Hence when we close the circuit the inductor has the full voltage driving current across it.

David Sphar

Concept Two: Why the Logarithmic Increase in Current?

Now we can see the pattern that causes the current to taper off the closer we get to or maximum voltage the way it does. On the previous page we learned that at 0 seconds there are 100 volts driving the current through the inductor, at 1 millisecond there are 98.351 volts driving the current across the coil, and at 60 milliseconds there are only 36.79 volts driving the current across the inductor. The voltage starts high and decreases with time. As voltage drops we have less propulsion power to accelerate the current. Because of this, as time goes one, current builds less and less slowly as time goes on.

If we were to calculate more points along the timeline the graph would look something like the one below. The green line represents voltage that accelerates current across the inductor. You will notice that as the current increases the voltage decreases. This is because the things we learned in our last exercise. The more current there is, the smaller the gap between max current and actual current. This decrease in the potential current represents a decrease in the driving voltage in the inductor. The decrease is do to resistance in the circuit.



In other words, as the current increases, the voltage decreases, and as the voltage decreases, our inductor looses the driving force that accelerates the current through the inductor. Eventually, voltage approximates zero and all that you have left is current. This current is equal to the maximum current of the inductor circuit as calculated by voltage and resistance. The reason you no longer see voltage in the inductor is because the magnetic field around the inductor has reached its maximum, and as such, does not change. Without it changing, you no longer get back EMF. Without back emf, the conductor simply transports the energy as free moving current.

Ok, so now that we know that, what about the original question?

Concept Three: AC inductor phase shifting

What causes phase shifting in an inductor…

?

Well we have come this far and it is now time to finish up. Using most of what we have learned we can figure out why the phase shift in an AC inductor will always be 90 degrees or less.

Concept Three: AC inductor phase shifting

So far we have figured out that the voltage in the inductor is greatest when the change in inductor current is the greatest. With DC, this happens when we first switch the circuit on. We also know that over time the current is greatest in a dc circuit and the voltage is the smallest. Can we use this relationship when thinking about AC current?

Sort of. With a smooth sinusoidal wave this will hold true. Consider some degree of phase shift a given because of the back EMF we find in a single wire inductor. If you add a second pickup wire this relationship will not work correctly. Also, if your AC input is not a smooth sine wave, the relationship will not work either.

For now, let's assume that we have the correct coil and waveform. If we consider that voltage is the force that increases current it is easy to realize that when voltage is at its peak, current will be increasing the most. (note: if current is at it's biggest negative peak, current will be decreasing its greatest amount). How does that look on a scope shot?

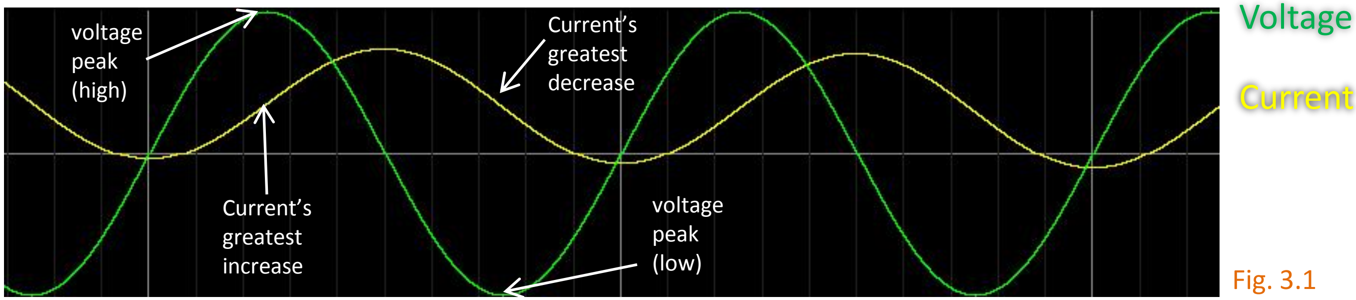


Fig. 3.1

Now to investigate why the phase shift will never be more than 90 degrees. In simple testing we learn that as our frequency increases our phase shift will increase (if it is less than 90 degrees), however, what happens if we increase our frequency past the point where we reach 90 degrees phase shift? Wont the pattern continue and allow us to create a phase shift more than 90 degrees? The answer: no.

The reason being, is that even if the RL circuit has not reached its maximum current point, when voltage is at zero, there will be no more voltage to drive your current up to it's maximum potential. Hence if your frequency his higher than the time it takes for your inductor to reach maximum current, the voltage will have already dropped and therefore it cannot drive your current up as high as it could be. In essence, at higher frequencies you are limiting current flow due to the voltage changing directions so fast that the inductor doesn't have enough time to let the full current through. In practical terms, increasing frequency past the 90 degree point will only serve to keep the current below its maximum value instead of increasing the phase shift greater than 90 degrees. It would also makes sense that you could use this principle to create a variable inductor "resistor" based on frequency. The higher the frequency, the greater the inductor resistor value. That's pretty cool! Ok, anyways, lets look at the example on the scope.

Concept Three: AC inductor phase shifting

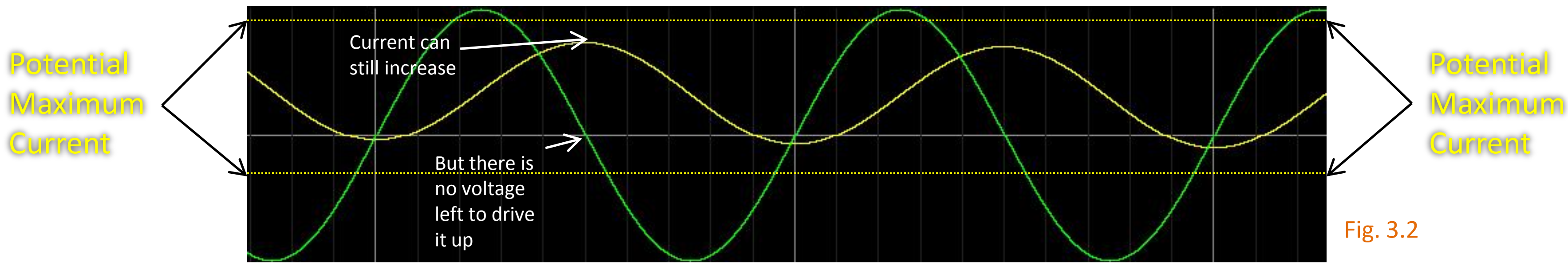


Fig. 3.2

The above happens when our frequency is far past the point that we reach a 90 degree phase shift. The higher we increase the frequency past the 90 degree mark, the less current will be allowed to flow through the inductor. Now we see that due to this relationship, the phase shift in an inductor will never be more than 90 degrees. But what determines if the phase shift is lower then 90 degrees and how can we calculate / manipulate this?

If we have an inductor that charges faster than the frequency cycle, it will allow more current through it because back EMF will either not be of equal strength or there will be moments every cycle where there is no back emf in the coil. Either way, current is allowed to keep somewhat of a pace with the frequency. Therefore you get a phase shift, but not as large as 90 degrees. That is why the higher resistance the higher the frequency needed to get a 90* phase shift. Resistance decreases the max current which allows the inductor to charge more quickly (the circuit reaches max current faster). So if you want to maintian a certain phase shift with a different load you either have to change the inductance of the coil, or you have to change the frequency to match the new inductor 5 time constant. Note to self: does the inductor 5 time constant hold true with AC power??)

I have more that I wanted to discuss here, but I need to get this posted. Sorry for any typos or weird terminology. This was simply a learning exercise for me and I realize I have much more to learn. Thanks for taking time to read this. ☺

David (Shades)