Introduction to Electromagnetism
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Lecture - 49
Demonstrations on Faraday's law, Lenz's Law and Nonconservative Nature of Induced Electric Field

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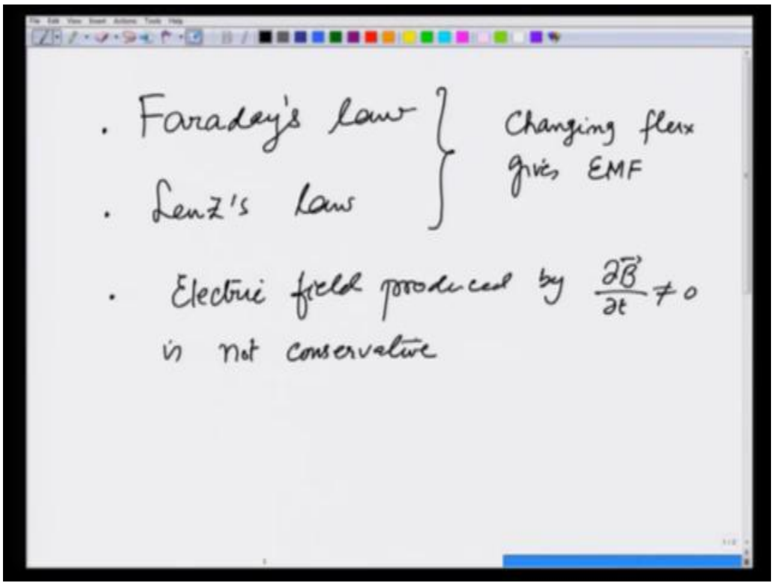

In the past week, we have been talking about Faraday's law, and the connected law which is Lenz's law. And what these laws said is that, a changing flux gives rise to an EMF – gives EMF. And the EMF is such that it opposes the change. Third point we made was that the electric field produced by changing magnetic field – that means dB dt not equal to 0, is not conservative. In today's lecture, I am going to show you some demonstrations, whereby I will show you Faraday's law – how an induced EMF lights a bulb. I will show you demonstration of Lenz's law, and I will also show you the nonconservative nature of electric field produced by a changing magnetic field.

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To demonstrate Faraday's law, what we have here is inside this box, we have a large number of turns of a current-carrying wire, which is connected here. And we have a lot of iron filled here. They are bicycle spokes that make the magnetic field concentrated here. When I turn this switch on the AC supply comes here; when the AC supply comes here; it produces a magnetic field, which is changing in time. And that magnetic field produced, that is, changing in time in turn produces an electric field, which is also changing in time. That electric field therefore, gives rise to a current if I put a wire here. And I should see the effect of that current. For example, here you see this bulb, which is connected to a lot of wires going around. So, if there is an electric field produced or there is an EMF produced due to changing magnetic field, it should produce a current here and this bulb should light up when I turn the AC on. So, let us have a look at that.

You see as soon as I turned the current on by this switch, you see that, the bulb lights up. In a similar manner, I have here a lot of LED’s connected. This is just to show you a colorful demonstration – lot of LED’s connected to the same set of wires; and as soon as I turned it on, you will see that, the LED’s will light up with different colors. So, you see that a changing magnetic field in this core gives rise to an EMF around it, because of the changing flux or and an electric field that is going around. To show Lenz’s law in this setup, last time, what I showed you in a small coil, I will show you this big coil. As soon as I turned it on, you will see that, this disc will move up.

To demonstrate Lenz’s law, what I have here are two tubes, which have this hole in them. This tube is made of aluminum and this tube is made of copper, so that I have these tubes made of material of different conductivity. Remember what is Lenz's law. Lenz’s law says that, any changing magnetic field produces currents in such a manner that, it opposes that change. And we will show you that, by putting a magnet inside, if the magnet is falling down, the magnetic field everywhere is changing and that produces a current in this tube; and the direction of current should be such that it opposes the coming down of the magnet; and therefore, magnet slows down what is known as magnetic braking. So, to show that, that really happens.

Let me first show you that, if I take this piece of chalk, which is nonmagnetic and put it through this, you will see it comes down immediately. Best way to see that is I will start counting and you will see how many counts it takes down. 1, 2 – 2 counts it came down; see it again – 1, 2. Same thing with the copper tube; if I take the copper tube here; I will put it through here – 1, 2; 1 – it immediately comes down. Let us now see what happens if I put a magnet through this. For this, I will use two different magnets to show you dependence: one is a small magnet here; you can focus here; this is a small magnet; and one is a large magnet; one has a very large magnetic moment; one has a small magnetic moment. So, let us put them here.

Let us take this magnet with a small magnetic moment and put it through this tube. Copper – remember is a very high conductivity material. So, let us put it and see what happens – 1, 2, 3; it took little longer. Again, let us do it – 1, 2, 3; if I take a magnet with larger magnetic moment; and let us see what happens. 1, 2, 3, 4, 5; you see it takes much longer. What happens if I put it in a material of smaller conductivity or larger distance. Let us see that – 1, 2, 3; it comes down in 3. So, smaller the conductivity, faster it goes. If it was a wooden tube, it would not really make any difference; it will come down in a time it was coming as a nonmagnetic material. So, here what I have shown you is that, let us do it in with the aluminum once more and you see it takes much longer. So, what I have shown you is as the magnet is put it in the tube – a conducting tube it starts generating current that opposes its coming down.

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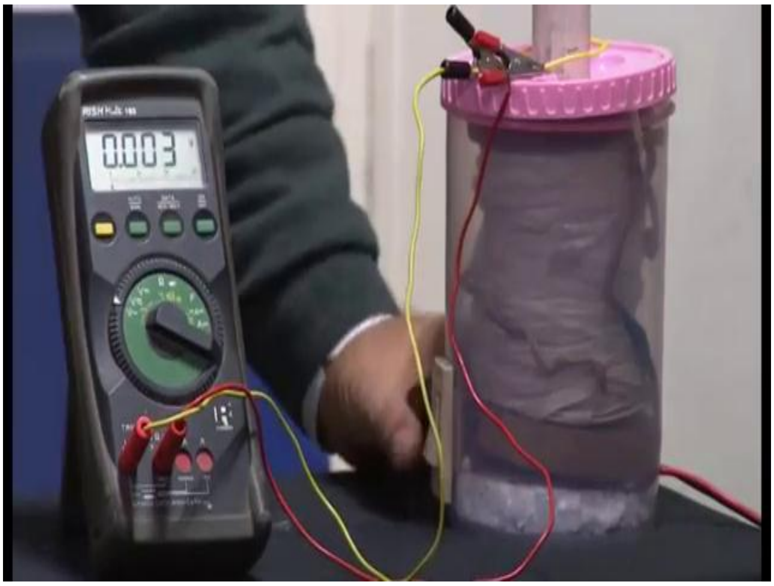

In this third demonstration, I am going to show you that, the electric field that is produced by changing magnetic field is nonconservative. Let us understand the meaning of nonconservative. By non-conservative field, what we mean is that, the potential between two given points is not well-defined and it depends on the path. So, what I have here is again the same coil that produces a changing magnetic field, because this is connected here to the AC and it produces this electric field, which is going around. And I have here a coil, which is a regular conducting wire with a resistance connected here. I will put this here, so that there is a current produced in this wire. When I take voltage difference between these two points; depending on how I connect them, you will see that the voltage comes out to be different.

To measure the voltage, we use this multimeter here; put it on AC because this is connected to an AC source. So, there is an alternating current that produces an alternating EMF here. And see now, if I connect this wire directly to the end of this resistance here, you will see that, I will see one particular reading when I turn the AC on. So, let us turn this on what the reading is. And you will see that, the reading is about 0.226. This is on this path. Now, let us change the path with the same two points. I will take this off and take it from behind and see what the reading would be. The same two points I am now taking it from behind. And let us see what the reading is. If I turn it on, you see reading is very very small for the same two points. Just to show you that, we did not really cheat… Some of you may wonder maybe I am doing some magic or some cheating. Let us do it again from the same side. If I do it from the same side and you will see again that, the reading is back to 0.225. I connect it here and again let us turn it on. And you see again it is back to 0.23 volts. So, you see depending on which path I am making by connecting these two points, the voltage is different. And that is the definition of non-conservative field. And what we have shown here than therefore, this changing magnetic field produces an electric field that is nonconservative.

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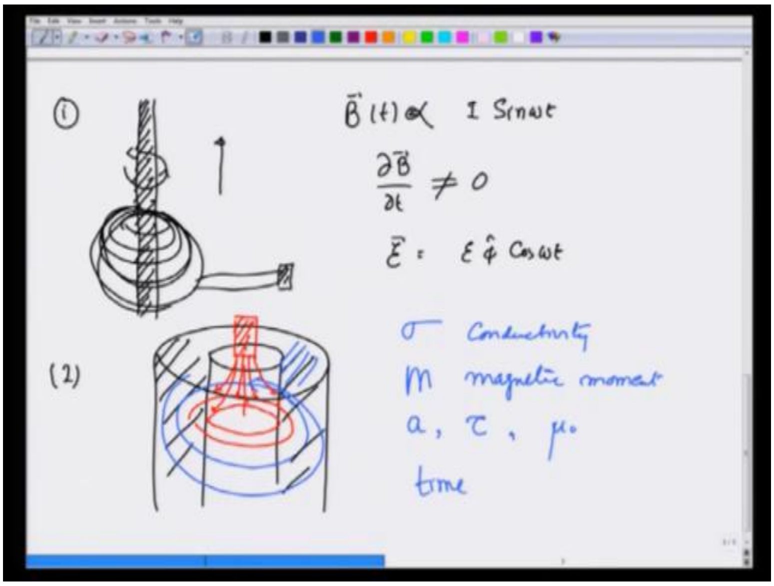

So, let us understand what we have done in these demonstrations. In the first demonstration, I had this long pipe, which was filled with metallic magnetic bicycle spokes; and all around it were these wires carrying AC. And this was connected to the mains. As soon as we turn the current on, there was a magnetic field, which was produced, which is time-dependent, which is proportional to the current, which is also time-dependent. And therefore, dB dt is not equal to 0; and dB dt – since B is in this direction, dB dt is also in this direction. And therefore, it produces an electric field, which is going around. That electric field produced is equal to E in that phi direction cosine of omega t. And that is what you observe. That was demonstration 1. You observe this electric field because the bulb lights up.

Demonstration number 2 – we had a pipe; this is solid. And we put a magnet inside it. This magnet has magnetic field lines going like this. As the magnet comes down at each point here or if I take a section here, the magnetic flux changes. As the magnetic flux changes, it produces an electric field going around. Let us make it with blue. It produces an electric field going around and that produces a current in the shell. And that current is such that it opposes the movement of the magnet. Now, higher the conductivity, higher the magnetic moment, higher the radius and thickness of the shell; depending on that, the current or the slowing down of magnet will change. One more quantity that will be there is mu 0. That is the permeability of the space. Combining all these through a dimensional analysis, I can create a formula for time that it will take to come down. I will give that as an assignment problem.

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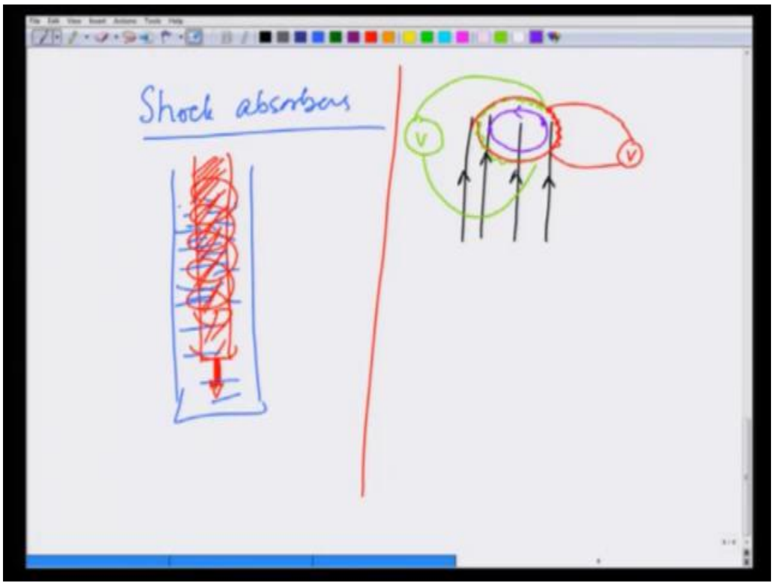

This technique of magnet slowing down is also used in making shock absorbers, whereby you put a ferrofluid, which carries ferromagnetic particles in a tube. And in this, you put the rod, above which there is whatever platform or car, which you want to slow down if it moves up and down; and through this, you let a current flow. As soon as the current flows, there is a magnetic field established. If this red object goes down or up, it produces an electric field. And therefore, that electric field when this red rod starts moving up and down, because of the magnetic field in this, produces an electric field and it produces a current in this ferrofluid, which in turn is such that it opposes the change. And therefore, the motion slows down or gets damped down.

Third – I showed you the nonconservative nature of the electric field produced. And I can model it like this that, in this field, I had ring going around. There was some resistance on this side and some other resistance on the other side. When I took the wires from this red side, I connected this to a voltmeter; I got one reading. On the other hand, when I connected the wires on the other side, I got a different reading. One can analyze this and check what these readings should be. And we indeed saw in the demonstration that, they are different. And therefore, the nature of field is nonconservative; and that is because the electric field lines close on themselves. Therefore, I cannot really define potential between two points. If I go twice, the potential will be larger. I will again give you an assignment problem in this to calculate the potential difference when the voltmeter is on the two different sides.