Electromagnetism
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Lecture – 79
Electromagnetic induction

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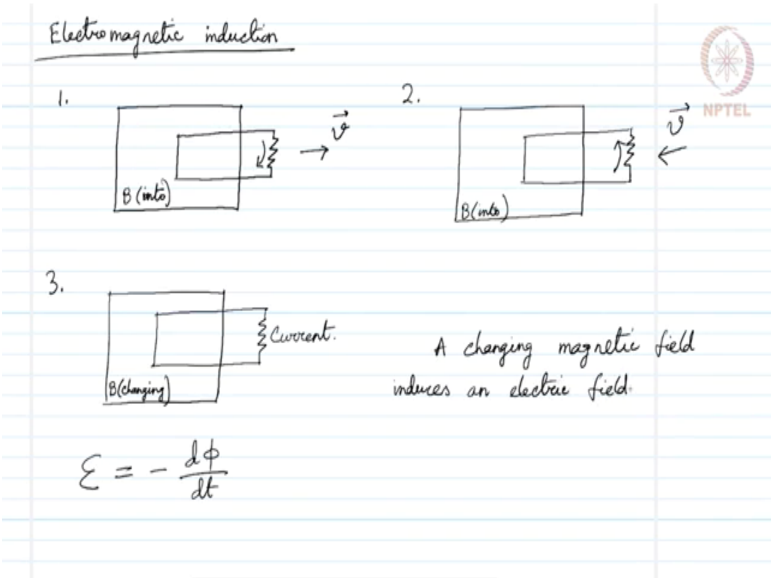

Let us move on to Electromagnetic induction. Let us consider 3 situations. In situation 1 we have this kind of a rectangle, this kind of a region where there is a magnetic field. And here is a current carrying loop with resistance at one end like this and the velocity this loop is pulled out of this magnetic field region with velocity V, this is the situation.

Now, if we have the magnetic field pointing into the screen, then if we pull out this loop as we have discussed earlier, we will have a current along this direction and Faraday, Michael

Faraday performed an experiment and saw exactly the same the current was along this direction.

Then he performed another experiment where, there was similar kind of a region with magnetic field. The magnetic field points into the screen again this time and there is a loop like this with some resistance at the end here. And now he made this loop move into the opposite direction towards the left and when he did that, he found there was also a current flowing, but the current direction reversed.

So, the current would this time flow earlier, let us see in which direction the current should have flown. So, we have considered earlier this case and the this was the direction of the current the way we have drawn it, then the current in this case would be in the opposite direction. And in the third experiment what he did was, he had a magnetic field here in this region and the magnetic field was changing with time. It was not constant over time rather it was changing with time.

And the loop was fixed, the loop was not being pulled out or pulled in to the magnetic field. Even then because the magnetic field was changing, the area was fixed still the magnetic flux was changing, and that gave rise to a current in this loop, that is pretty interesting. So, the flux is what we need? Not the motion the change in flux is what we need to induce a current in this kind of where this kind of a loop. Its not the motion of the loop itself, that is clearly proved from this experiment.

And the electro motive force as we have written it earlier as minus d phi dt, that would give the amount of the current provided we know the resistance in the circuit. Now, if we have a change in magnetic field. So, what we learned from this experiment? was changing a change in magnetic field induces an electric field otherwise there would be no current.

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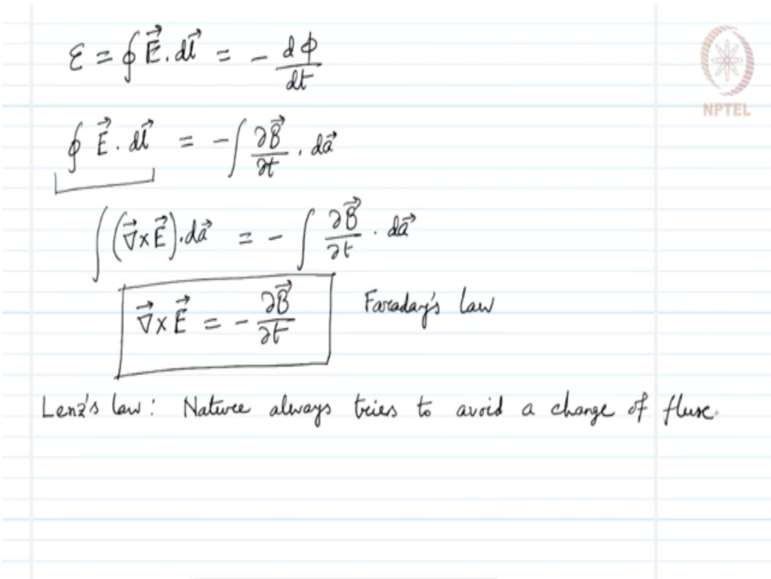

And how do we express this the electro motive force, as we have done it earlier a closed integral over E dot dl, that gives us minus d phi dt. And closed integral over E dot dl it could be written as. So, minus d phi dt if we have the magnetic field changing, then it will be minus integral of del B del t dotted with da.

So, this surface integral will give us E dot dl. And now we can convert this closed line integral using Stokes law, into curl of the electric field and the surface integral over that which is equal to minus integral of del B del t dot da and this expression to be true in general, for any electric and magnetic field we must have the curl of the electric field equal to minus del B del t.

This is very important, earlier we knew that the curl of electric field was always 0. Now, we have; so that was in the context of electrostatics. Now, in the context of time varying magnetic field, if there is time varying magnetic field present, we see that the curl of electric field is no longer 0. There is a finite curl of the electric field that is the negative of the rate of change of magnetic field with time. And this is known as the Faraday's law.

So, we can conclude that whenever for whatever reason the magnetic flux through a loop changes, we develop an emf and that emf will be developed in the loop. Now, we can write another law namely, Lenz Lenz's law that tells us nature always tries to avoid the avoid a change of flux.

So, that will tell us along what direction the induced current should flow, so that the change in flux is minimized. So, if the flux of magnetic field is changing due to a loop is being pulled out, then the current will be induced in such a direction. So, that the magnetic field is enhanced although the area is getting shortened and the other way around. If the magnetic field is changing in its magnitude, then a current will be induced in such a way that it tries to restore the original magnetic field. It will not be successful completely, but that is how nature will react to the situation.

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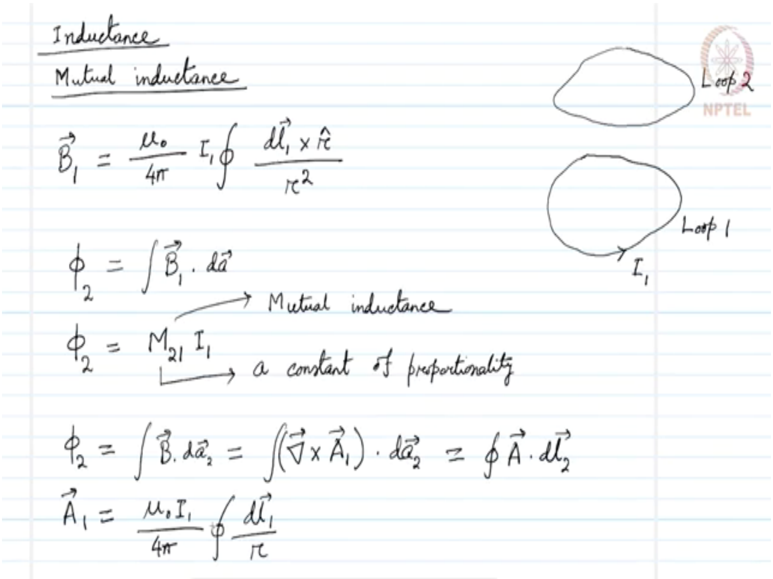

Let us develop the idea of inductance after this. And in the context of inductance, we will start with mutual inductance. What do we mean by mutual inductance? Let us consider that there is one current carrying loop here, that carries a current I 1, we call it loop 1. And there is another loop at the vicinity of loop 1, this is loop 2.

So, the magnetic field on loop 2 due to loop 1. So, the magnetic field due to loop 1, let us call it B 1 can be evaluated to B mu naught over 4 pi I 1 is a constant closed integral dl 1 cross r cap over r squared closed because we have a closed loop here in this picture. And if we now try to find the flux due to this magnetic field on the second loop. So, we call it phi 2 flux at the second Loop the magnetic flux due to this current, that will be B 1 dot da.

So, if we now for simplicity write down that phi 2 equals M 2 1 times the current which we can do because everything else is a constant of the geometry. M 2 1 is a constant of the geometry, only I the current is something that we can change in loop 1 and that leads to a flux magnetic flux in loop 2 everything else, that we have in this integral here, or the integral over the area element all these things are constants of geometry.

So, M 2 1 can be given as a constant of proportionality. And the flux in the loop 2 depends on its proportional to the current in loop 1 which means, we can write phi 2 as integration over B 1 dot d a 2 that is equals to integration over curl of A 1 dot d a 2 is nothing but closed line integral of the vector potential dot dl 2.

So, this M 2 1 is called the mutual inductance and we have this phi 2 the flux expressed in terms of the vector potential a closed integral over the vector potential. How do we express the vector potential ordinarily? A 1 can be expressed as mu naught I 1 over 4 pi, integration dl 1 over r and this is the expression for the vector potential.

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$$\phi_2 = \frac{\mu_0 I_1}{4\pi} \oint \left(\oint \frac{d\vec{l}_1}{r} \right) \cdot d\vec{l}_2$$

$$M_{21} = \frac{\mu_0}{4\pi} \oint \oint \frac{d\vec{l}_1 \cdot d\vec{l}_2}{r}$$

M_{21} depends only on geometry

$$M_{21} = M_{12}$$

$$\mathcal{E}_2 = -\frac{d\phi_2}{dt} = -M \frac{dI_1}{dt}$$

And if this is the expression for the vector potential, then phi 2 can be expressed as following what we have developed so far, mu naught times I 1 over 4 pi closed integral ok. Here we will have closed integral because we have a closed loop carrying I 1 current.

So, closed integral of a closed integral over d l 1 over r dot dl 2. So, the mutual inductance M 2 1 can be expressed as mu naught over 4 pi, double closed integral dl 1 dot dl 2 over r. So, we can see that M 2 1 depends completely on geometry and nothing else. And because there is a dot product involved and dot product is commutative M 2 1 would be equal to M 1 2.

It does not matter, whether we have dl 1 first or dl 2 first as long as we are evaluating the same integral. After establishing this let us write down the emf on the second loop that would be the rate of change of flux through the second loop in time, that is minus d phi 2 dt which is minus M d I 1 dt if we induce this change of flux due to change of current in the first loop, then this way we can write it. And this is the idea of mutual inductance, there is also an idea of self-inductance.

That means, due to the flow of a current in one loop and the change of the magnitude of the current there is a change in flux in the same loop itself. And that will also create an electromotive force. So, that kind of a phenomenon is called self-inductance.

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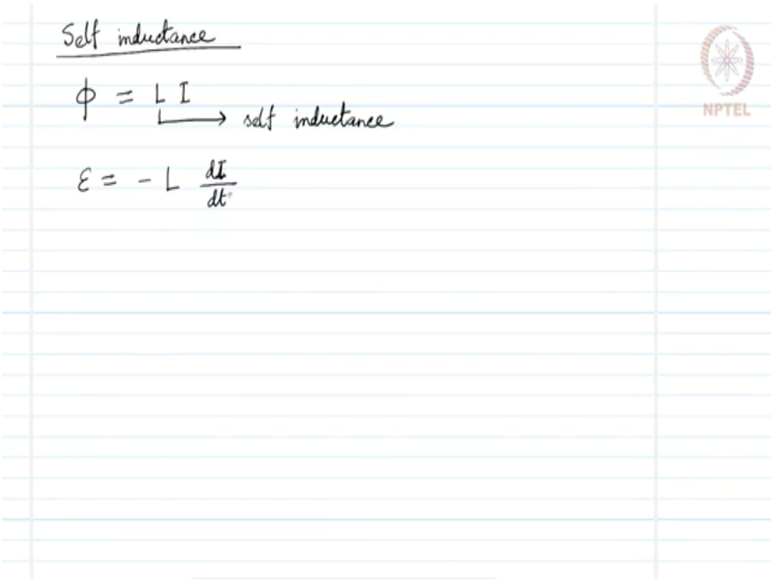

So, if we have phi flux, then this can be written as L times I in the context of self induction where, L is the constant due to the geometry which is called the self-inductance, and the emf epsilon can be expressed as minus L d I dt.