Course Name: Design of Electric Motors

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Title: Electric and Magnetic Circuits Interface

Greetings to all, in this lecture we will discuss the interface with respect to the electric circuits and magnetic circuits, because all electromagnetic circuits consist of electrical domain as well as magnetic domain, right. And the outcome of this electromagnetic system we are utilizing to get the electrical energy or mechanical energy. With respect to the machines, we are taking the mechanical energy output, with respect to the inductors and generators and other things, we are taking it as a electrical energy. Let us consider a system, where electrical energy is the input and medium is magnetic circuit and output side we are taking the electrical energy or magnetic energy. In order to transfer the or transmit the power from one domain to other domain, we require the two variables, one is effort, other is flow variable, effort variable which is creating the flow in a medium. For example, voltage in a electric circuit, flow is nothing but rate of change.

Example, I can say rate of change of charge is nothing but current, right. So, I am representing in a generalized manner effort is as a x and it is a potential variable, flow variable I am representing with y and it is a kinetic variable. If you want to represent the power x into y is nothing but the power in all domains. If we will multiply the effort variable and flow variable and we will get the power.

Here energy or power is flowing in both directions. Now we will see the conventional representation of effort variable and flow variable across these domains, whether the conventional way of representation is right or not with respect to the energy conservation principle, we will discuss now. As per the energy conservation principle, the energy or power from one domain to other domain should match, we cannot create or we cannot destroy. Consider the same system, we have the electrical domain and magnetic domain and at the output side mechanical domain is there. The conventional way of representation with respect to the effort and flow variable, we will see whether power will match or not.

Effort variable in electric domain is voltage, flow variable is current, it is rate of change of charge, right dq by dt. Electric domain MMF is a flow variable, sorry MMF is a effort variable and flow variable we are considering the flux. These two are the invisible things, but voltage and current at the electrical side we can measure it and at the mechanical side we have the effort variable force and flow variable is velocity, force or torque anything is and velocity or speed. Now, as per the energy conservation principle, power across all domains is matching or not, we will derive it now. The conventional way of representation with respect to the flow variable in a magnetic domain that is flux is wrong, if the power will not match in all domain, we will prove that thing how and why it is not matching.

Power is nothing but x into y, right flow variable and into effort variable, voltage into current, voltage units are volt, current is ampere, then the product will be vat in electric domain, vat is representing the power only. In magnetic domain power is equals to MMF into flux as per the conventional representation in majority of the literatures. MMF is nothing but n into I and flux we have to derive from the Faraday's law, E equals to n d phi by dt. From here we can derive the flux is equals to 1 by n into induced EMF into time. If we will substitute that thing here, n into I in place of flux 1 by n into E into t, E is nothing but induced EMF and time t, n and n will be cancelled.

The final equation we can see I into E into t time, I is nothing but what ampere induced EMF in volt time in seconds. So, if we will do the product, it is Watt second, Watt second is what energy, power equals to energy is it correct, the answer is no, power is not equals to energy. So, from electrical domain to magnetic domain the representation of flux is wrong, we should not use flux as a flow variable. Similarly, at the mechanical domain side power is equals to force into velocity, force is in terms of Newton meter, sorry Newton only, torque is in Newton meter and velocity is in meter per second. So, Newton meter per second is a unit of Watt only.

So, power is matched in mechanical domain also. Similarly with respect to the magnetic domain, power is not matching by considering the flux as a flow variable. This is the conclusion 1, why we should not consider the flow variable as a flux in a magnetic circuit. Next if we will consider the simple electric circuit with a single voltage source and a simple resistance, the effort variable is voltage and flow variable is current and load side resistance we have. Now the power is equals to V into I, which is dissipating across the resistor, right in this circuit.

Here power is dissipating across the resistor or Pr is equals to I square R. The magnetic circuit is a circuit with a single voltage source and a single resistance. This is reluctance here MMF N into I and this is flux. In most of the literatures, we will see in this fashion, right, flow variable we have considered as a flux, but it is wrong. We have seen the conclusion 1, power is not matching and second conclusion if we will see here reluctance is not a dissipative element, whereas in electric domain resistance is a dissipative element.

But in magnetic domain, we are utilizing the core along with the air gaps to store the energy. The resistance or reluctance representation is wrong. We have to represent similar to the some stored element. Here power is equals to what MMF into flux that already we have derived. It is nothing but energy.

In terms of flow variable, if we will represent phi square R, it is wrong and dissipation should not happen. This is conclusion number 2. Because of these two conclusions, the flow variable has to be rate of change. Here flux is not a rate of change variable. We have to consider some rate of change variable and we have to make the electrical to magnetic domain analogy.

For that, we will utilize the gyrator capacitor models. These two circuits are not equal. To make the power equivalence in both domains, we have to use the gyrator capacitance model or resistance capacitance model. To overcome those two conclusions, first conclusion I will take. We have to match the power in electric domain as well as magnetic domain.

For that, we will utilize the gyrator capacitance model principles. The gyrator is nothing but a two port network that reflects the impedance in one side to other side impedance as a reciprocal manner. For example, simple transformer we can consider one side variables if will represent in other side the reciprocal term will come impedance matching. We can see here transformer for an example of gyrator number of turns n and effort variable at the primary side V1 and flow variable is I1, flow variable at the secondary side is I2 and effort variable is V2. V1 I1 is equals to V2 I2 power is matched at the both sides and V1 is equals to n into V2 and I1 is equals to I2 by n.

Here n is a gyrator constant. In order to make the variables or power equivalence, we have to follow with respect to the gyrator principle. Let us consider the magnetic circuit in order to make the equivalence between the efforts and flow variable. Here current flowing through the coil is I and number of turns V and effort variable at the electric side is voltage V. With respect to the gyrator capacitance model, we can represent this circuit as a two port network.

Here gyrator constant is n and flow variable at the primary side is current. Current is equals to rate of change of charge dq by dt and effort variable is voltage and effort variable at the secondary side or magnetic side will be mmf and flow variable is d phi by dt. We can represent this variable as Im. Im is equals to d phi by dt not the flux. So, both side flow variables and effort variables are defined with respect to the gyrator model.

Now, we will see the power equation. With respect to the electrical side, it is V into I. It is in a watts only. With respect to the magnetic domain, power is equals to effort variable mmf into flow variable d phi by dt. mmf is nothing but n into I.

d phi by dt we have to derive from the Faraday's law that is equals to E by n induced emf by n is nothing but d phi by dt. n will be cancelled E into I induced emf in terms of volt. Current is in terms of ampere units. So, we will see the watt only right here also. Earlier we have seen here watt second by considering flow variable as a flux that is wrong.

We have to consider flow means rate of change that is d phi by dt. So, we have matched the conclusion 1. Power is matching in both domains. Next how to satisfy the conclusion 2? Power should not dissipate in a magnetic circuit with our representation as a resistance. For that we have to utilize some storing element.

I will copy this the same magnetic circuit. This magnetic circuit we have to represent in a electrical circuit with respect to the flow variable and effort variable n into I. Here Im is equals to d phi by dt and storing element we should model the core as a capacitance that is Cm. Magnetic capacitance is equals to 1 by reluctance or it is equals to permeance. So, capacitor will store the energy with respect to the charge flow.

Here d phi by dt flux is flowing in a magnetic circuit. Now, we will see what is the value of capacitance or reluctance with respect to the magnetic circuit. Let us consider the magnetic material of length l. The cross sectional area of this core is AC and permeability is mu that is equals to mu naught mu r. Mu is the permeability of free space and mu r is the permeability of the material and B fields are flowing in this direction.

We have to represent as a d phi by dt as a flow variable. Now, we have to represent this thing as a equivalent of capacitance, magnetic capacitance Cm. In an electrical circuit, the capacitance Ce is equals to what in terms of permittivity and area of the plate and distance between the two plates epsilon into A by d. Here epsilon is the permittivity of the material and A is the area of plates and d is the distance between the two plates of the capacitor. Same way, we can analyze the magnetic capacitance instead of epsilon in the electric capacitance permeability will come that is mu into area of cross section of the core divided by length of the material or length of the material with respect to the both ends.

mu is the equals to mu naught mu r into area of cross section divided by length of the material. So, this is equivalent of magnetic capacitance. It is represented as Henry units Cm is equals to 1 by reluctance. This value is equals to mu A by L. From here reluctance, we can showcase as a L by mu A.

It is not equivalent of resistive model. It is the reciprocal with respect to the magnetic capacitance. So, if you will apply KVL in this equation, the voltage with respect to the source should be equals to the voltage with respect to the capacitor as per the electrical circuits analogy KVL should match. So, Vmmf or source n into I should be equals to the capacitor voltage Vcm ni is equals to 1 by C integral IDT. Capacitor voltage is nothing but 1 by C integral IDT q equals to Cv.

From there, we will get this equation. Here I is nothing but what flow variable 1 by Cm into integral of d phi by dt into dt. So, Mmf is equals to 1 by Cm integral of d phi results in flux divided by magnetic capacitance. This is the final equation with respect to the capacitor voltage. If you will represent in terms of reluctance, Mmf is equals to flux into reluctance, which is inversely proportional or reciprocal of magnetic capacitance. It should not call it as a magnetic Ohm's law that is V equals to IR form.

We should not represent this thing. This is the equation with respect to the capacitor. In a practical magnetic circuits, there will be a loss, right? Hysteresis losses, core losses will be there, right? The hysteresis loss we have to represent as a ESR of the capacitor and this is the actual magnetic capacitance and source will be Mmf or effort. IEM is equals to this one. So, the equivalent circuit for a magnetic circuit without air gap with a single coil should be in this manner. Now, we will see the actual analogy with respect to the both circuits.

This is with respect to the magnetic circuit and electric circuit with respect to the resistive manner. We will see the analogy. Electric this side magnetic. So, let us consider the simple circuit with a resistor. Flow variable is I is equals to dQ by dt and voltage V and resistance R, magnetic circuit side we have magnetic capacitance Cm with respect to this magnetic circuit.

I am neglecting the ESR Mmf. This is d phi by dt. IEM is equals to here effort variable is what? voltage this side Mmf or we can call it as a E mf at the electrical side similar to Mmf at the magnetic side and flow variable is flow of charge that is dQ by dt. I is equals to dQ by dt. Here flow variable is I m is equals to d phi by dt rate of change of flux. Here rate of change of current in electrical side.

Power is equals to V into I. Here power is equals to Vm into I m that is Mmf into d phi by dt. The resistance if we will represent at the electrical side that is V by I as per the Ohm's law or power divided by I square. Anything we can utilize it. So with respect to the power divided by I square is equation 1 by T integral of V into I dt divided by I square. This is the power equation in terms of power the resistance equation or units will be Ohm this side and resistance at the magnetic domain R am is equals to Mmf divided by d phi by dt we can represent or with respect to the power equation P divided by I square.

Here P is nothing but 1 by T integral of Mmf into flow variable d phi by dt into dt divided by flow variable square that is d phi by dt square. This is nothing but magnetic resistance. The charge at the electric side Q is equals to integral of I dt. Here flux is equals to integral of I m into dt. I m is nothing but flow variable d phi by dt into dt we can represent.

The charge at the electrical side will be this one the flux at the magnetic side. Then capacitance effect capacitor voltage equation will be V equals to 1 by C integral of I dt, q equals to Cv. Same equation at the magnetic domain side V m or Mmf is equals to 1 by C m integral of I m dt. So, 1 by C m integral of d phi by dt into dt this will give flux divided by C m magnetic capacitance. So, final equation with respect to the capacitance effect will be this thing and in terms of reluctance we can write it as a Mmf equals to flux into reluctance.

This is the actual analogy with respect to the electric domain and magnetic domain. So, while representing in a magnetic circuits or while analyzing the magnetic circuits we have to keep it in mind always the flow variable will be d phi by dt only. For representation with respect to the current and number of turns n and voltage will be V the flux in the core or B fields in the core we can represent with flux or d phi by dt both are correct this is only for representation of flux lines, but flow variable is always d phi by dt. With this I am concluding this lecture. In this lecture we have discussed the electric and magnetic circuits interface.

So, what are the flow variable and effort variable with respect to these two domains and respective analogy we have discussed in detail. Thank you.