Course Name: Design of Electric Motors

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Title: Electric and Thermal Circuits Interface

Greetings to all of you. In this lecture, we will discuss the analogy between the electrical and thermal domains by utilizing the energy conservation principles. Let us consider the electromagnetic system, where we are transferring the power or energy from electrical domain to magnetic domain and then, magnetic domain to either mechanical or electrical domain. Electrical domain means with respect to the transformers and inductors, etcetera. Mechanical domain means for motors. Across these three domains, the energy or power is flowing in both directions.

Energy or power is flowing both directions from one domain to other domain and we have discussed the power invariance or power in across the different domains like electrical to magnetic domains. We have discussed in the initial lectures of this course and in this lecture, we will see the electrical and thermal. With respect to the losses, there is another domain like in a practical system. We will see the losses like core losses and copper losses and mechanical losses.

These losses are dissipated in the form of heat and this heat with respect to the thermal domain. There is a fourth domain involved in the electromagnetic system with respect to the loss that is thermal domain. In thermal domain, the energy flow or power flow is unidirectional, electrical to thermal and there is no loss in the thermal domain until unless it reach to the equilibrium state, the heat will flow from hotter object to the cooler object or hotter high temperature region to low temperature region. Let us say this is a temperature T 1 and this is a temperature T 2 and the heat will flow or heat will exchange till it reaches to the equilibrium state where the both temperatures of these two bodies are same and the heat will flow from high temperature object to the low temperature object. We will see the effort variables and flow variables across these two domains and in order to transfer power or energy from one domain to other domain, whether it may be electrical or magnetic or mechanical or it may be thermal domain.

In order to transfer power, we require effort and flow variables. Effort let us say x and flow variable is represented with y, then power is equals to x into y across all domains as per the energy conservation principle. It should match always. Effort variable is nothing but which creates the flow or rate of change. For example, voltage in a electrical domain flow variable is nothing but rate of change, like current is equals to rate of change of charge with respect to the time.

We will identify the effort variable and flow variables in electrical as well as thermal domain and we will see the power analogy. This is the electrical domain and this is the thermal domain and losses are dissipated in the form of heat and that heat dissipation we are considering as a thermal domain. In thermal domain, the points what we have to keep it in mind are there is no change in domain, like thermal to there is no other domain energy transfer only electrical domain to thermal domain. The energy or power will flow and there is no backward direction. The thermal domain is the lost, which is a storing domain or there is no energy or power lost and there is no loss component.

Till we reach the equilibrium state, the heat will flow from high temperature region to low temperature region until unless we are reaching the equilibrium state. Once the equilibrium state is reached, then these two temperatures will be same. For example, the hot object it is radiating the heat to the surroundings until unless these two objects temperature is same, then the equilibrium state will reach. Now, in electrical domain, the effort variable is potential difference that is voltage. In thermal domain, the temperature difference that is delta T as a effort variable and units are degree Celsius or Kelvin.

Here, units are volt and flow variable in electrical domain is I current that is rate of change of charge with respect to the time and the units are ampere. The flow variable in thermal domain is change or moment of entropy that is dS by dt. Here, entropy is nothing but measure of thermal energy S is equals to thermal energy per unit temperature. Entropy is a measure of thermal energy or heat per unit temperature. The units are Q is nothing but joules and temperature is nothing but Kelvin or degree Celsius.

The entropy units are joules per Kelvin and flow variable units are dS by dt is equals to watt per Kelvin or watt per degree Celsius. These are the units for change in entropy with respect to the time. Now, we will discuss the power equation across the electrical domain and thermal domain. Power in electrical domain is equals to effort variable into flow variable that is V into I. The units for voltage are volt and for current it is ampere.

It will give watt. So, watt represents the power and in thermal domain effort variable into flow variable that will give the power and effort variable is change in temperature and flow variable is dS by dt change in entropy with respect to the time. So, effort variable units are per degree Celsius or Kelvin and entropy change with respect to the time units are watt per degree Celsius. It will give again watt. Watt represents the power.

So, in both domain, the power is matched. Energy principle of energy conservation is matching. In the conventional representation, the flow variable with respect to the thermal is considered as heat flow rate that is phi which is that units are watts. If I will consider the flow variable as a heat flow rate in a conventional representation in most of the literatures, heat flow rate I am considering as a phi and the units are watt. The power is equals to delta T into phi here per degree Celsius or Kelvin into watt.

So, these units watt per degree Celsius or watt into Kelvin may not be is equals to power. So, here with respect to the conventional notation, power is not matching with respect to the flow variable. We should not use the heat flow rate as a flow variable. We have to use the entropy change with respect to the time as a flow variable in thermal domain in order to match the principle of energy conservation. Next we will discuss the thermal resistance and thermal capacitance.

Let us consider the thermal domain. In thermal domain, the heat will flow from higher temperature body to the lower temperature body until the thermal equilibrium happens. The entropy S is equals to thermal energy per unit temperature or change in entropy delta S is equals to delta Q by T. We can represent as per the thermodynamics second law. The change in entropy always should be greater than or equals to 0 and flow variable in the thermal domain is nothing but d S by d t that is nothing but d by d t of Q by T which will give the joule per degree Celsius into seconds joules per second.

We can consider as watt per degree Celsius. So, these are the units per entropy. Now, we will see the thermal resistance. The thermal resistance with respect to the empirical relations that is R theta is equals to temperature difference divided by power loss. If we will see the temperature difference T 1 at one point and T 2 at the second point, then the thermal resistance of the material is defined as R theta.

It is not a dissipating element. The thermal resistance will not dissipate any energy and the power loss is considered as a source here and the thermal resistance is nothing but temperature difference divided by power loss. This equation is derived with respect to the empirical approach that is delta T by P and here we will see the degree Celsius per watt units. Thermal resistance is nothing but the impedance which opposes the flow of heat that is nothing but R theta and the units are degree Celsius per watt or Kelvin per watt. The actual thermal impedance with respect to the energy conservation principle that is Z theta is equals to effort variable divided by flow variable.

Effort variable is nothing but change in temperature that is delta T and flow variable is nothing but rate of change of entropy that is d S by d T. This is nothing but the actual thermal impedance that is equals to delta T divided by T by d T of Q by T. So, it will give delta T by 1 by T into d Q by d T. So, this 1 by T I am bringing T above numerator side delta T divided by d Q by d T. So, this is nothing but the conventional d Q by d T is nothing but power right.

The energy with respect to the time is nothing but power. So, T into R theta. So, the effective thermal impedance is nothing but Z theta is equals to T into R theta. This equation represents that the thermal resistance for a given temperature T or at particular reference temperature what is the thermal resistance R theta. So, the thermal impedance with respect to the entropy or law of energy conservation principle Z theta will come T into R theta.

Next, thermal capacitance. Similar to the electrical capacitance, the thermal capacitance is nothing but the storing element which stores the entropy or heat energy. Let us consider the different temperature points T 1 and a iron piece at one plate side we have T 1 temperature and other end we have T 2 temperature. And in between these two ends how much heat energy or entropy is stored with respect to the thermal domain that is nothing but C t h or C theta thermal capacitance. So, with respect to the energy conservation principles or electrical domain charge is equals to C V right. In thermal domain entropy that is S is equals to Cth into change in temperature.

So, C t h theta I am representing as a new variable C t h theta is equals to S divided by delta T. S is nothing but entropy and delta T is nothing but change in temperature. S is nothing but Q by T into delta T. So, units are Q units energy units are joules divided by temperature to temperature into delta T again it will give the Kelvin into Kelvin that is joules per Kelvin square or joules per degree Celsius square anything we can utilize as a units. So, the actual thermal capacitance with respect to the empirical relations we can make it Q by delta T that is C t h.

ere C t h is the thermal capacitance with respect to the empirical relations. In the most of the literatures we can see C t h is equals to thermal capacitance Q by delta T the thermal energy with respect to the change in temperature. So, the thermal energy Q is equals to C t h into T in terms of if we will represent the thermal capacitance in terms of mass of the body as well as specific heat capacity then it will be small c mass into C p it is small letter into temperature it will give the thermal energy. Here m is nothing but mass of the body in the k g and specific heat capacity that is units are joules per k g per Kelvin. Here C t h is nothing but thermal capacitance with respect to the empirical formulas only and C t h theta is nothing but with respect to the energy conservation principle that is 1 by T into C t h.

So, the thermal capacitance with respect to per unit temperature will give the actual thermal capacitance with respect to the energy conservation principles. So, we can see here the with respect to the energy conservation principle the thermal capacitance C t h theta is nothing but this one. In general with the empirical formula C t h is equals to this one. Next we will discuss the analogy summary with respect to the electric domain and thermal domain. In electric domain the effort variable is voltage and flow variable is current I is equals to d Q by d t and electric resistance is r and this is r theta and power loss we can represent as the p current source thing this is the power loss and temperature difference is T 1 and T 2.

This is the conventional circuit representation, but for analogy purpose we can represent the source is here change in temperature and the thermal resistance is nothing but z theta and flow variable is d S by d t this is I theta thermal d S by d t. So, the effort variable is voltage in electric domain and here change in temperature and flow variable is nothing but current I is equals to d Q by d t here thermal current I theta is equals to d S by d t here units are d S by d t units watt per degree Celsius and temperature units are degree Celsius here volt and amperes for current. And next charge q here that is equals to integral I d t here charge q is equals to in the thermal domain charge is nothing but entropy that is s is equals to integral I theta d t s is equals to q by t we can represent the entropy in this form also joules per degree Celsius. Next the electrical resistance R is equals to effort variable divided by flow variable that is V by I R power divided by I square the units are ohms whereas, the thermal impedance z theta is nothing but effort variable delta t divided by flow variable d S by d t here the units are degree Celsius square divided by watt or Kelvin square by watt anything we can utilize. So, with respect to the empirical relation thermal resistance R theta is nothing but change in temperature divided by power loss that is delta T by P degree Celsius per watt or Kelvin per watt the units.

So, the actual thermal impedance is equals to t into R theta the thermal resistance this is thermal impedance R thermal resistance with respect to the entropy this equation is derived from the principles of energy conservation. And the thermal impedance is equals to the thermal resistance at a given temperature or the thermal resistance at a reference temperature t.

Next power is equals to V into I here units are watt with respect to the electric domain in thermal domain power is equals to delta T into d S by d t effort variable into flow variable and units are watt here also and electrical conductivity sigma is equals to 1 by rho units are rho is the resistivity of a material the units is equals to 1 by ohm meter and thermal conductivity lambda is equals to thermal conductivity is represented with lambda and units are watt per meter Kelvin or watt per meter into degree Celsius.

Next we will see the capacitance effect capacitance in electrical domain Q is equals to C into V right. So, c is equals to Q by V and units are coulomb per volt are farad in thermal domain the capacitance with respect to the energy conservation is C t h theta thermal capacitance only C t h theta means with respect to the energy conservation principles that is S divided by change in temperature S is nothing, but Q by T into delta T the units are joules per degree Celsius square or joules per Kelvin square the actual thermal capacitance with respect to the empirical relation that is C t h C t h is nothing, but Q by delta t that is joules per degree Celsius the thermal capacity capacitance Q is equals to C t h into T

with this I am concluding this lecture in this lecture we have discussed the electrical and thermal domain analogy with respect to the thermal resistance and thermal capacitance and flow variables and power equivalence. Thank you.