Control Engineering

Prof. S. D. Agashe
Department of Electrical Engineering
Indian Institute of Technology, Bombay

Lecture – 06

After thinking about control systems in general in somewhat descriptive terms, we will turn our attention now to something more specific. We will soon start writing down equations and things like that. So I will start with an example, of course it will be a classroom example.

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So one may not expect to find the control system about which I will start talking in some place exactly the way I am telling you. But the purpose of the example is to convey some of the concepts and ideas that are involved in this study analysis and design of control systems. So keep that in mind also you will have to read up about some of the things that I have mentioned from a good textbook and assuming that most of you are familiar with electric motors of various kinds in particular we will take up a simple electric motor namely a DC motor.

Now a DC motor as you know has two windings, one winding is call the armature winding and the other is called field winding. The current in the field winding produces the magnetic field and the conductors which constitute the armature winding when they carry a current interact with the magnetic field producing a force or a torque and that is how the motor rotates. Of course as you know because I am talking about a DC motor what is called a commutator is required.

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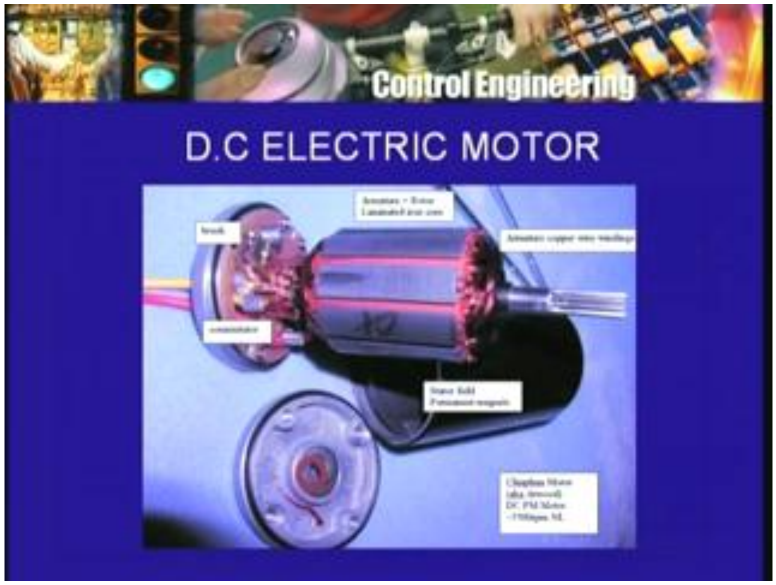

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Now the motor for our purposes we will start will drawing diagrams will be represented by a more or less a standard symbol, to recall the symbol for the motor armature. Well it is something quite simple and it suggests the shape of the armature as well as the fact that rotation is involved so here is the symbol for the motor armature and two little things are placed at two ends of a diameter and these are supposed to represent the brushes that press upon the commutator. So there are two wires that are connected to the brushes. So that armature current can be made to flow, remember this symbol of a motor armature with a pair of brushes. Since it is called an armature, we will denote the current in it at any moment of time by the standard symbol for current which is I with a subscript A to remind us of armature and because the current may be changing with time I am showing it as I_A as function of time.

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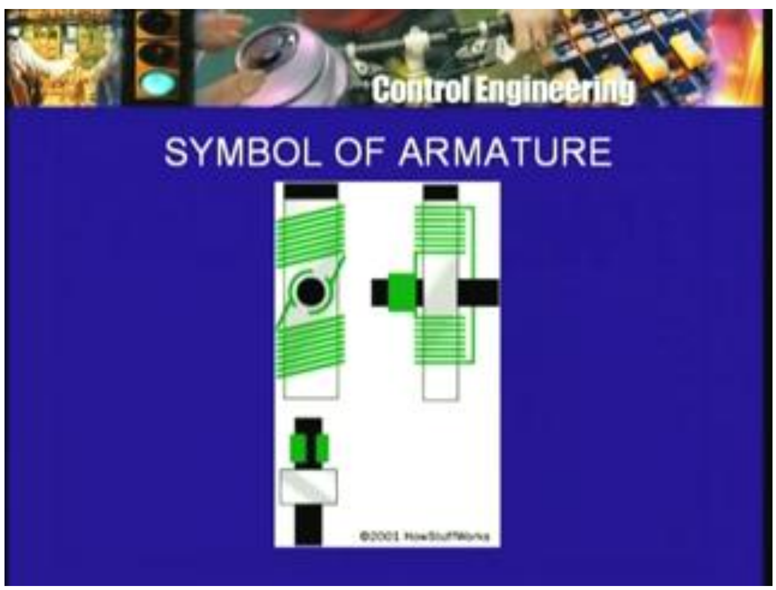

So far I only have the armature of the motor but as I mentioned earlier there is another winding which produces the magnetic field and this is shown by a symbol, this normally represents an inductor or a coil. So here is the symbol for the field winding, the coil is supposed to remind you of magnetic field and indeed, wire is wound around the pole area of the which results in the production of the magnetic field. This winding will also carry a current because it is the field winding the current flowing in it at any moment of time we will denote it by I again for current in general but F for field current and if it is varying with time then T, so I $_F$ of T will be the field current I $_A$ of T will be the armature current at any moment of time.

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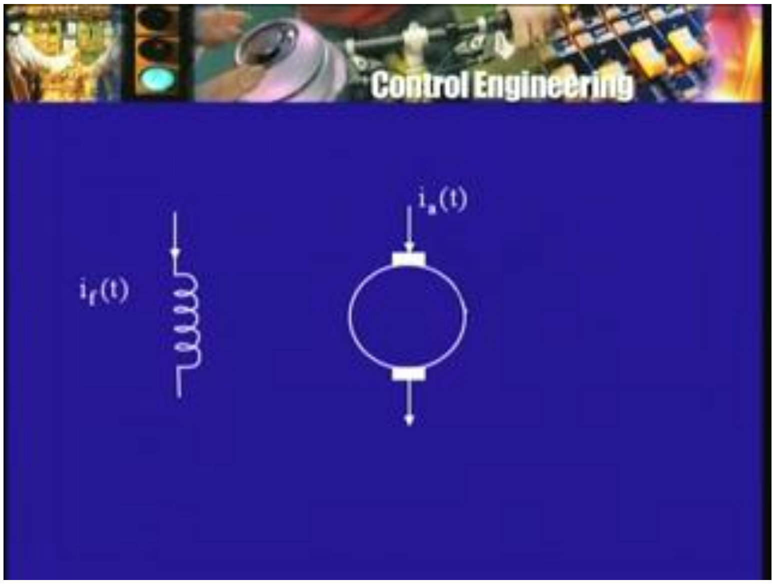

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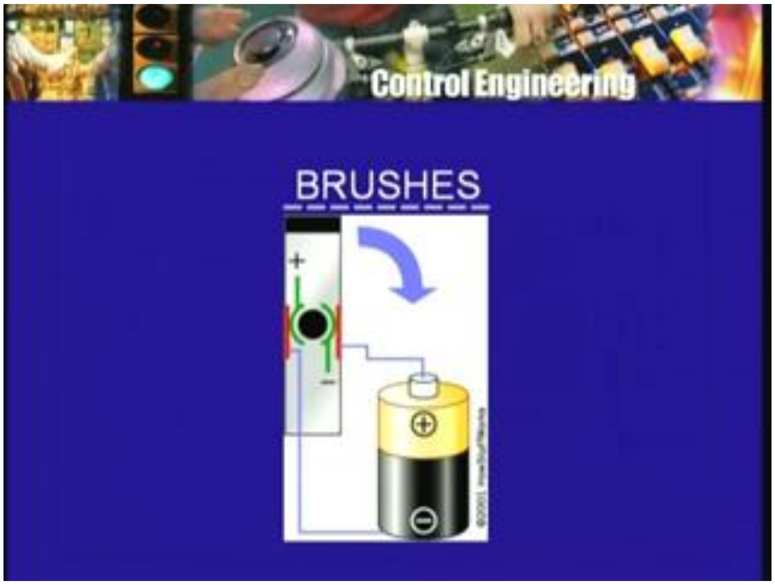

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Now what is the purpose of using the motor, the purpose of using a motor obviously is to make something else turn go at a certain speed against a resistance, a mechanical resistance in other words the purpose of the motor is to generate a torque. There is no fairly standard symbol for torque but again one can use the letter T to remind us of torque, the torque may also vary from time to time and of course one may put the letter M to remind you of the motor.

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So this is the torque which is produced as a result of the interaction between the armature current and the field of the flux, magnetic flux which is produced by the field current. One may have to talk about the flux that the field current produces in what is called the air gap of the machine near the pole area and for that the standard symbol usually is capital phi and if it is varying with times and of course phi shown as a function of time.

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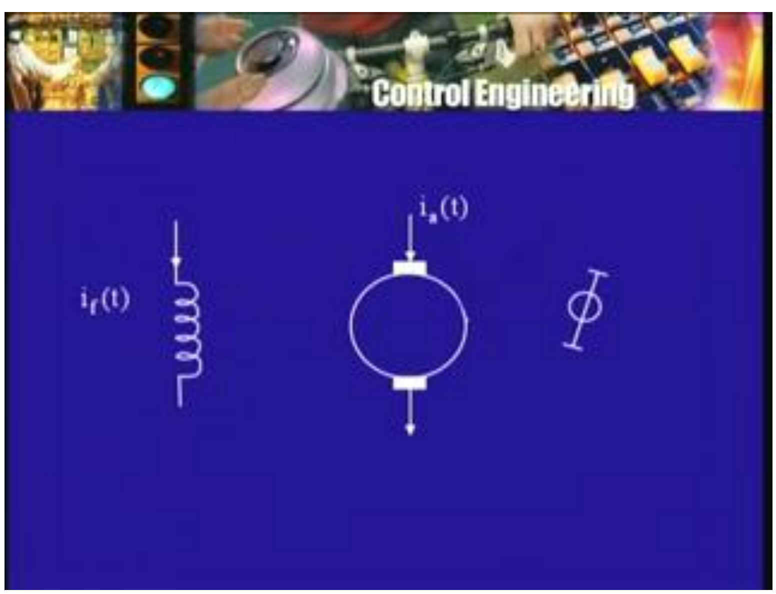

So phi will denote the magnetic flux in the air gap and the way in which by we think about it is that field current gives rise that is the flow of current in the winding produces magnetic flux phi in the air gap passing of course through the core of the armature, the armature is also made of magnetic material and thus there is a possibility of an interaction between the armature current which flows in the conductor and the flux in the air gap as it is called.

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The motor, as I said is going to drive something it is going to make something turn and because its motion, it will be some mechanical device for example the motor could drive or on the shaft of the motor may be mounted a grinding wheel which is used for grinding or it could drive the shaft of lathe and the lathe in turn may be used for some machining operation such as simply turning or screw, thread cutting and so on.

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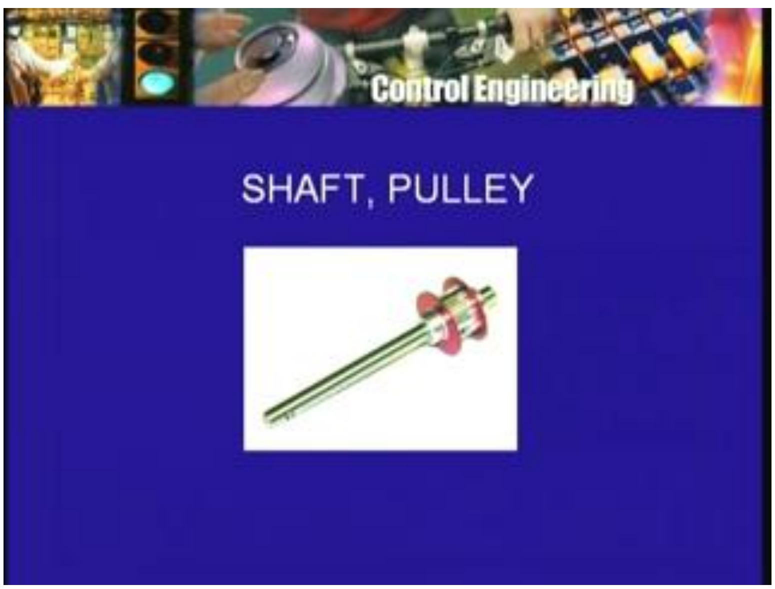

So we show this again on the diagram by showing what looks like a shaft going from the armature or the armature, shaft and the shaft of the device which is being driven and I will show it here simply as what looks like a disc or a pulley and to indicate to us that the shaft is rotating one puts an arrow around it this way. Now the shaft will be turning and so we need a symbol for the angular velocity or angular speed of the shaft. For this normally the Greek letter omega is used and the speed may change with time.

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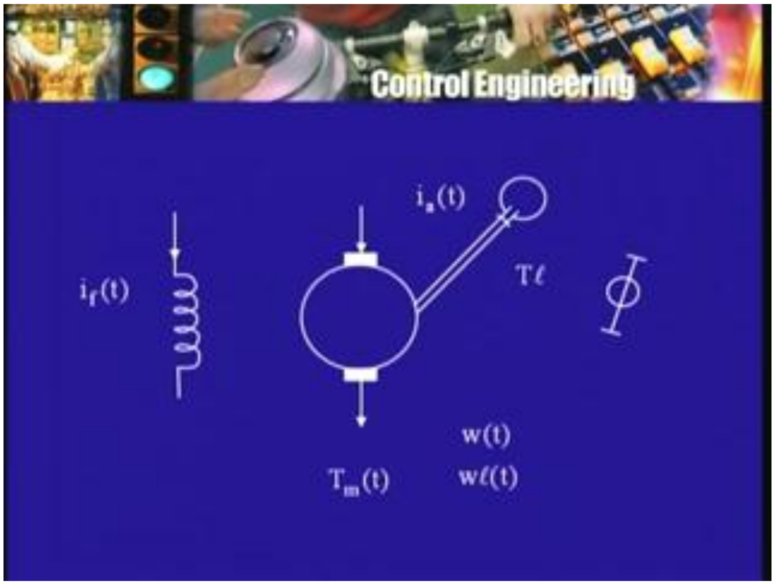

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So we will call it omega T, I have shown the motor driving the load directly that is the load is directly coupled to the motor, this may not be the case there may be gear train involved between the motor shaft and the load shaft and so we may have to distinguish two different speeds the speed of the motor which may be different from the speed of the load. We can think of the load as something which has to be rotated and that requires some torque to be applied to the shaft. So this torque is referred to as the load torque.

So for the symbol we will have T, capital T with subscript small L that is the load torque, what is the difference between torque produced by the motor T M and the load torque T L. There may not be much of difference for the figure that I have shown where the armature shaft is directly driving the load but as I said if there is gear train in between then the two torques will not be equal because the two angular speeds are not equal more over there may be some friction in the shaft at various bearings as a result not all the torque which is produced by the motor will be used in driving the load.

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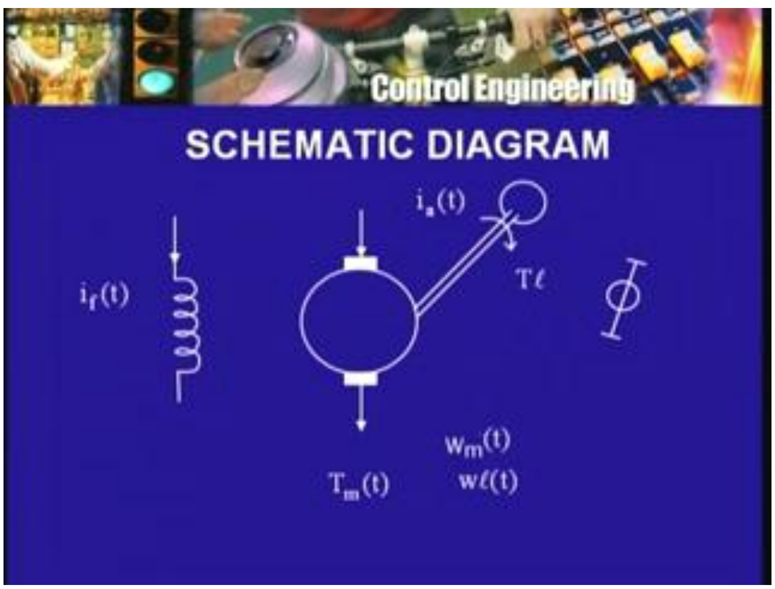

So T M may not be equal to T L and if I want to distinguish between the motor speed, angular speed and the load angular speed I may of course do it with subscripts omega M T for the motor speed and omega L T for the load speed, diagrams like this are extremely important as you know in fact this is what makes one good engineer if you are able to put down with the help of the standard symbols whatever you are thinking of or whatever you are talking about and similarly if you can understand a diagram such as this one because this diagram is still not complete and we will complete it such a diagram is known as a schematic diagram in fact there is redundancy of words because the word schema in Greek itself means a figure but this expression is very commonly used.

So what I have started drawing is a schematic diagram of what may be a drive, a mechanical load driven by an electric motor. Now what is the control system here strictly speaking we should and I have done that earlier also. We should distinguish the two parts of the thing that you see here one is the load in this case and the whole purpose of what we are doing is to make that load may be that pulley or whatever this grinding wheel to turn against a mechanical resistance. So that is what is the purpose of the whole thing that is why it is called a drive?

Now of course there are various ways of trying to meet to that purpose. For example, a very crude way would be to put a handle at the end of the shaft and to turn the handle by hand that is crank the handle manually but of course one will not do it normally because the speed will be very low, the torque that a human being can apply will be also not enough. So in other words you go beyond some simple solution like this and let us say by the time you are thinking about this problem the electric motor has been invented. So you say all right somebody tells me that there is this thing called an electric motor which can do this job of driving the grinding wheel it can drive it at sufficiently high speed as you know grinding requires quite high speeds and also it requires a high torque.

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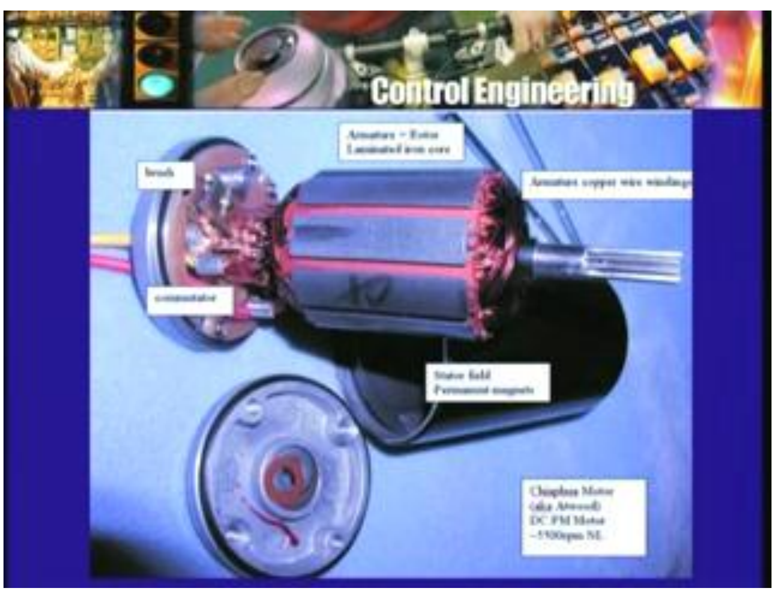

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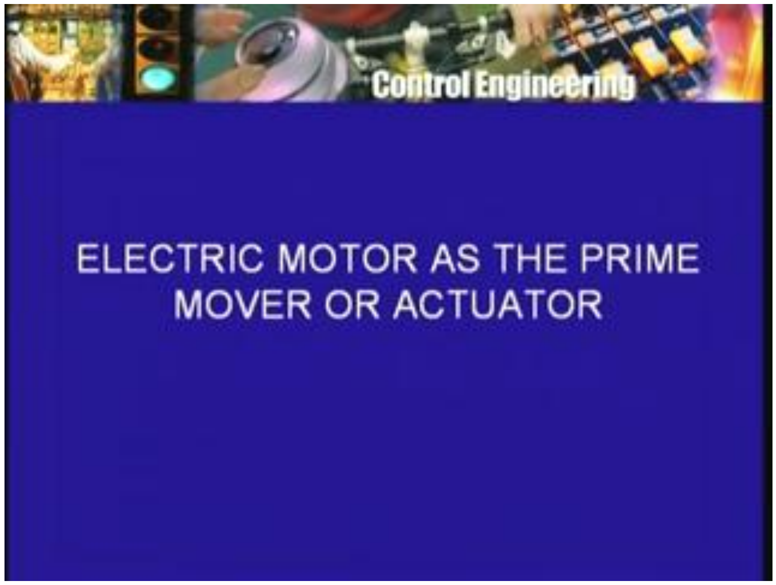

So, one has decided that the load will be driven an electric motor. The electric motor can be said to be in this case the prime mover or in other context it is called an actuator and now the shaft of the load because it is connected to the shaft of the motor, we are no longer going to crank it by hand. So whatever we want to do to the grinding wheel onto the mechanical load will be done through the agency of the motor. So the motor becomes the controlling system the system that ultimately controls the load what happens to the load but the motor in turn needs to be controlled.

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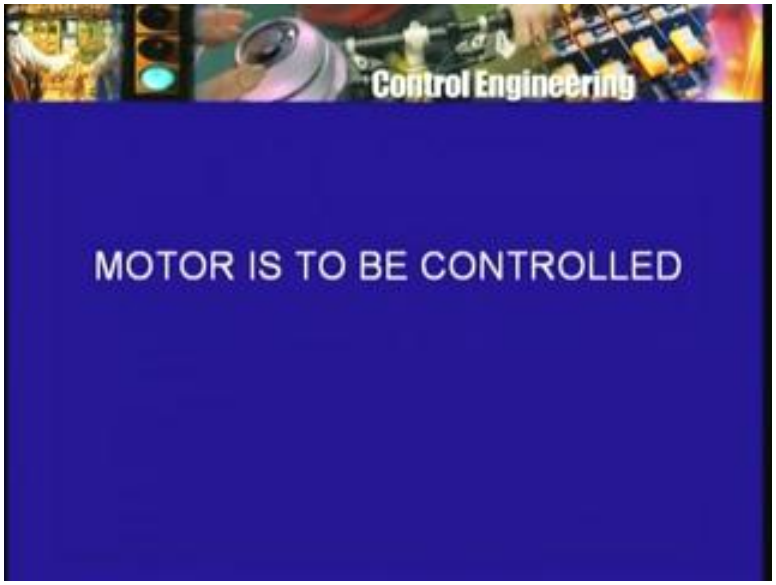

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Now before we go into that I said motor, I did not say what kind of motor so there are of course various kinds of electric motors. One obvious classification is into DC motors and AC motors.
Nowadays, you do not find a DC supply coming to your house or even your industrial establishment, what you have provided by the supply company it AC alternating voltage and current that too may be of the voltage level which is not what an electric motor that you are thinking of may be using.

So one has to make choice shall I use an AC motor which will run directly on what is provided to me or that may be expensive I may therefore use a transformer to step down the AC voltage to a level such as say 230 volts, RMS and then use an AC motor which will run on that lower voltage. One has to make a choice now from a practical point of view such choice is very important because ultimately you have to put something there you cannot say do anything put something you have to know what you are going to put. Now such choices are rather difficult to make and to put down in a course, such choices require experience. So we are now going to look at such choices or am I going to use an AC motor of what voltage or I would use DC motor in that case I will have to put a rectifier for DC power supply for my DC motor if I have only AC supply available. Now, that will cost some money and so on.

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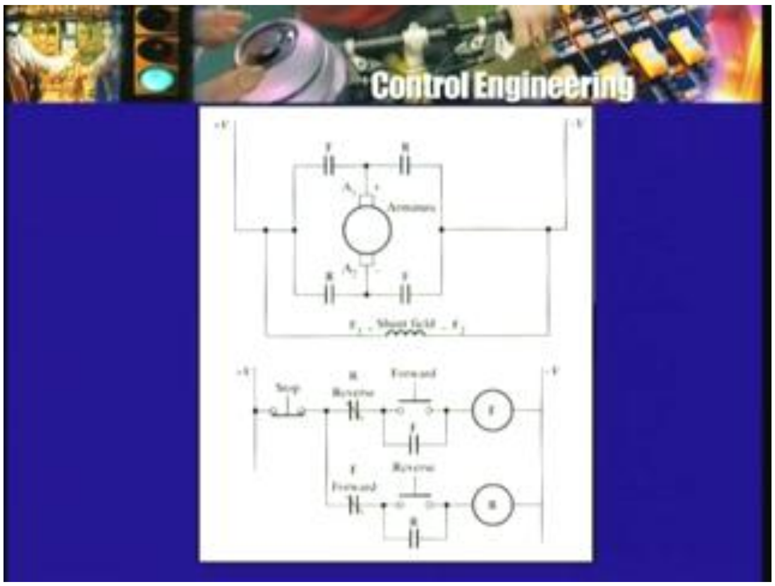

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So I will have to look at those alternatives, we assume that we have chosen or somebody has chosen to use a DC motor. Of course again DC motor is not enough because DC motors again come in a various classes, a simple classification is between what are called series motors and shunt motors, what is the difference between series motor and a shunt motor in electric locomotives such as those operating in a city like Mumbai. The motors which are used to drive the wheels are DC motors with a series connection where as in many industrial applications the motors will be DC motors with a shunt connection or even with what is called a separate excitation.

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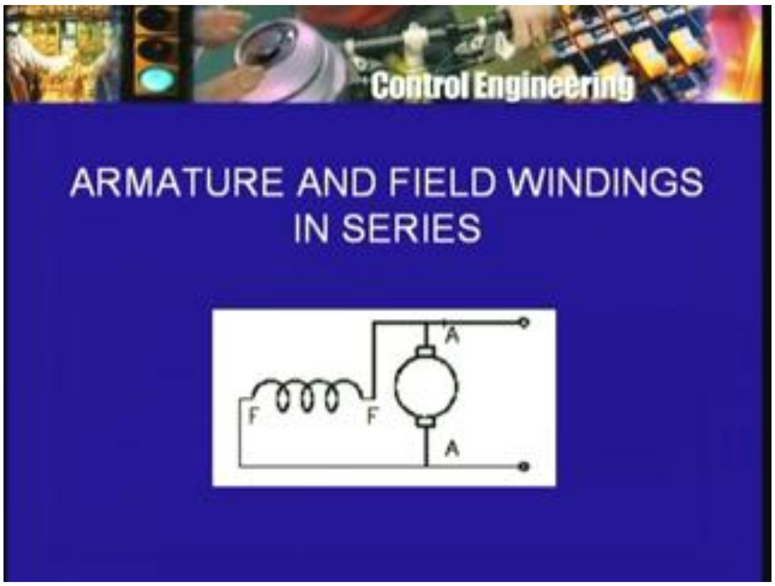

So what is the difference between a series and a shunt connection, as the word series suggest in the case of series motor, the armature is connected in series with the field winding that is the same current flows through the both windings, the armature winding as well as the field winding whereas in the case of shunt motor as was shown in the diagram earlier, here is the diagram once again. In the case of a shunt motor the two currents will be different, armature current will not be equal to the field current and in fact they may come from two different power supplies for example one way is to connect the field winding to a DC voltage source which is kept constant. You do not change the voltage of the DC supply such a scheme is known as separately excited DC motor, separately excited because excitation the power source that produces the current in the field winding is separate from the power source that produces the armature current.

So we have a separately excited DC motor here and as you can see in the case of this separately excited DC motor, the field winding is connected to some power supply hopefully that power supply voltage will remain constant and therefore the field current will remain constant. So although I have shown it here as a function of time I F is function of time in this particular application it will happen that I F actually a constant may be 2 amperes or 5 amperes or whatever and hopefully the field current will remain constant at the value.

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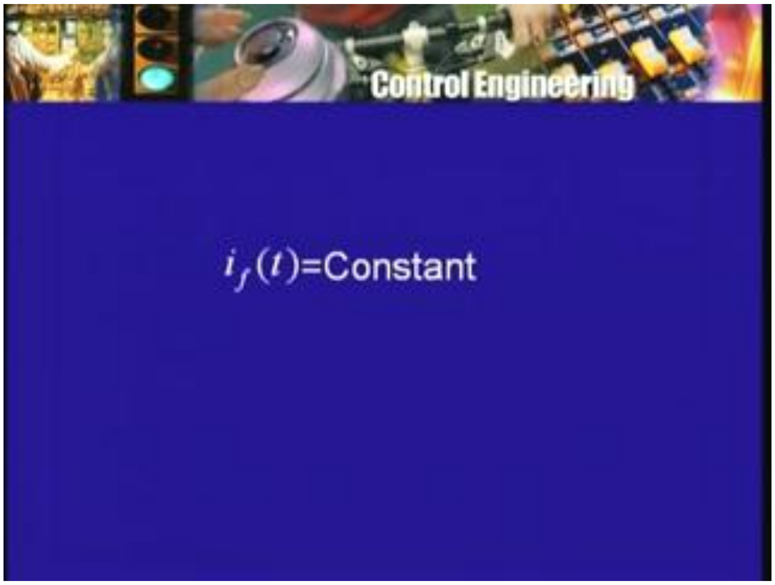

We may not make any provision for changing the value of the field current or making sure that is the field current remains constant at that value. One simple way in which the field current, one can provide for the field current will remain constant in spite of changes taking place in the power supply voltage is of course the following simple connections you have the field winding but in series with it you connect a resistance or a resistor whose resistance is R F, R for resistance, F for field circuit resistance and the arrow here what it is suppose to tell you that this resistance can be varied or this resistance can be changed, changed how perhaps by an operator and this series combination is then given to some power supply voltage.

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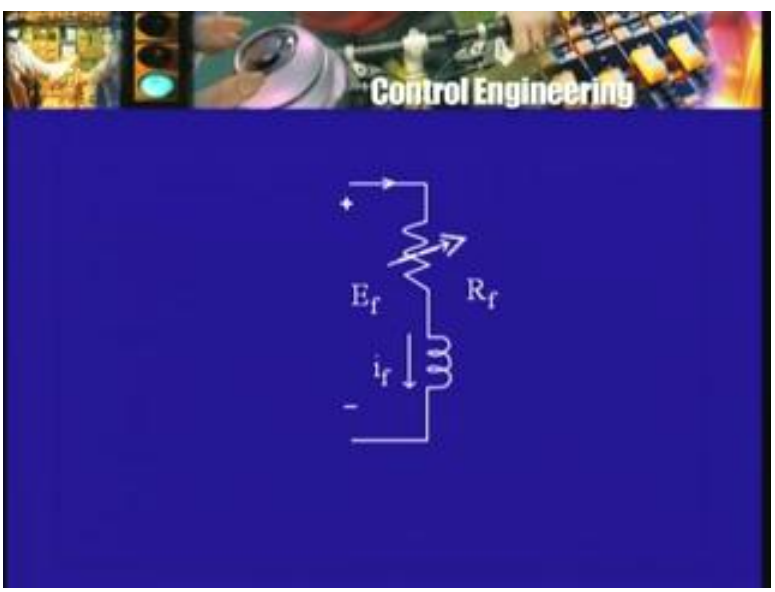

Let us say E F, E for EMF or voltage F for field and this produces the field current in the field circuit or in the field winding and an operator who is watching the whole thing may find out what the field current actually is at any moment of time. So there may be an ammeter connected here in the circuit to show the field current and on the ammeter dial there may be a red mark to show the desired value of the field current and so here is the operator who is sitting there and in the field current value deviates from that specified value, the pointer on the ammeter is not against the red mark then the operator will intervene and adjust the resistance either decrease it or increase it as the case may be. So that the field current is kept at chosen or specified constant value.

Now we are assuming that the field current is kept constant and we are not worried as to how the field current is kept constant in other words whether it is done automatically or by a man whether the control for the field current is manual or automatic or the adjustment, we are not going to look at that at the moment so we will simply assume that the field current remains constant at some pre-calculated or specified value I F. So we have chosen that we will use the DC motor and we will use it in the separately excited way keeping a constant field current I F.

Now the load grinding wheel it may be or it could be a lathe which is connected through some belting to the same motor and so on. These different devices may require different speeds of operation and may require different torques so my motor depending on the particular application will have to produce a specified torque at a specified speed. So this is something which begins the specification of the control system we cannot simply say motor DC motor I am going to use it in the separately excited fashion because as you electric devices have associated with them power, electric power.

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So in this case it is not enough to say give me a 230 volts DC motor you have to say, what power. So depending on the various loads that the motor is expected to drive the torques and the speeds at which the load has to be driven one can calculate the power that will be used up by the load this is called the mechanical power. So P load, load power and that as you know some mechanics is the product of the torque T L and the angular speed omega L. So the power that is set to be delivered to the load which is consumed by the load ultimately for example there is grinding going on, so there is friction there would be heat produced some job is being turned once again there is friction heat will be produced in addition to motion and so on.

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The load power P L is given by T L into W L, check that this formula is correct by looking at the unit and the dimensions of the quantities that are involved, what is the dimensions for angular speed omega L although on the shop floor one will talk in terms of the R. P. M speed, the speed in revolutions per minute because that is a convenient thing to talk about and think about although I, I am sure you do not really have a very good idea of what is the difference between say 500 RPM and 1500 RPM except that 1500 RPM is faster than 500 and sort of 3times as fast but we really have no feeling about how fast is 1500 RPM. But anyway the speed on the shop floor will usually be specified as revolutions per minute.

So, one may say that this particular load is to be driven at 1500 RPM, 1500 revolutions per minute. But for theoretical work, the preferred unit is not RPM but is radians per second, why because the second is the unit of time at least in physics and the radian is the unit of angle in many applications rather than degree. This combined unit radians per second, radian is suppose to a dimensionless second of course has dimension of time it is sometimes referred to as Neper, after Napier but one may use just the expression radians per second.

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So the angular speed omega L is in radial per second what about torque? Well what is torque torque is nothing but moment of a force on the moment produced by two forces as one says moment of couple. So torque is force is distance we can think of a torque being produced by force being applied at a particular lever arm length. So torque is force into distance, so we have force into distance then we have multiplied by radians per second force, of course what is the unit for force? The unit for force is Newton and you should recollect the definition of Newton the unit of force the what is it called the international standard system of units. The Newton is the unit of force for distance the unit will be meter.

So the unit for torque will be Newton meters, this gets multiplied by the angular speed which is per second. So you have Newton meters per second or Newton into meters per second and that has the same dimensions as power, of course mechanical power by definition is this product torque into angular speed. So when you think of the load and the application the thing that has to be specified for somebody to select the motor and then to build the control system and so on is what is the requirement? What are requirements of load power, load angular velocity or speed and therefore the load torque?

So in a particular application you may say that we require a torque of so many Newton meters at an angular speed of let say 1500 RPM are so many radians per second. Now of course as you know mechanical power at an earlier era used to be specified as so many horse power units or HP and in some shop floor establishments you may still find the unit horse power being used. So you may say that the load requires 5 horse power as a result you will use a motor which is capable of producing more then that but today of course the unit of power is not horse power but it is a Watt named after James Watt, Watt or it could be a kilowatt a practical unit of power will be a kilowatt and you should know the conversion relationship between horse power and kilowatt just in case, you are faced with specification of the motor in terms of horse power, power specification in terms of horse power rather the in terms of kilowatts.

So we may even speak of the load power requirements in terms of kilowatt and we may say the load consumes power at the rate of say 5 kilowatts and the load has to be driven at the speed of 1500 RPM. So naturally, now the motor that you have to choose has to be such that it can deliver power of in fact more then 5 kilowatt at a speed of 1500 RPM and perhaps even higher speed if it may be required. So accordingly then one will choose a motor, so one will say we want a DC motor of about say 6 kilowatt and 1500 RPM you may not have a motor available exactly with these specification.

So you choose something which is commercially available which fits the requirement as closely as possible. If 5 kilowatts are required you do not want to use a motor which can produce up to ten kilowatts the motor will be bigger and you will not be using its full capacity where as you would not use a motor which is supposed to produce 5 kilowatts because that may be just enough. Similarly, the speed if the motor runs at a lower speed then you will have to use gearing arrangement between the motor and the load to produce the desired speed. So, one chooses the motor which fits the specifications of the load all right.

So here is the load 5 kilowatts at 1500 RPM and then we have chosen a motor which will produce more then 5 kilowatt but not much more and will run at 1500 RPM and may be even at a higher speed and now I am going to connect the motor to the load and I am going to control the load not directly by cranking the handle but by controlling the motor. So now I have to device a system with which I can control t motor the aim is still to control the load, the aim is not to control the motor. I am not interested in just making the motor run, the motor has to drive a load what motor I have chosen as depended on what load is given to me.

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But instead of worrying about the load all the time, now we should worry more about the motor and how to control the motor. I said that I already assumed that the field current will be kept constant now suppose the load torque requirement changes or the load speed requirement changes. Right now it is a grinding wheel but then I may disconnect it remove it from the shaft and put on the shaft something else which requires somewhat different power and somewhat different speed.

Now of course if the new application requires the speed which is much higher than the speed for which I choose the motor 1500 RPM then it may not be possible to do it very easily as I said one may have to introduce a gear train in fact something like this happens in an automobile. As you know as in automobile and even in the scooter one uses the gear mechanism and one shifts or changes the gear. So what is happening is that you have one shaft and the another shaft they do not run at the same speed and they do not transmit the same amount of torque and you have gear wheels on the two shafts and depending on the ratio of the teeth on the gear wheels, the speeds and the torque have certain ratio and by changing these gear wheels you can change the torque ratio and the speed ratio.

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So one way to install such a mechanism, so that starting from as high as speed of fifteen hundred I may be able to get a lower speed by going into a lower drive or a lower gear shifting into a lower gear and of course because my motor can still produce 5 kilowatts, if the speed is lower then I can produce a higher torque and this is exactly why you change gears when riding a scooter or an automobile to start the motor or to start to make it go or when going up hill you require more torque. So you shift into lower gear where as once the motor as acquired I am talking about the automobile, car, motor car once it has acquired enough speed then not much torque is required just enough to over come friction and whatever little unevenness may be there on the road.

So you require much less power however the IC engine, the engine which is the source prefers to run at more or less at a constant speed that is one of the features of a petrol engine or a diesel engine. It is not that it has to run at a consistent speed or it will run at a consistent speed but varying the engine speed itself directly is much more difficult. So we will have the engine which is going to run at more or less the same speed but the drive shaft or the car speed is going to change and this you achieve with the help of a gear train or the gear box of the motor car or of the scooter. But it may the case that you do not have a gear train and therefore you may have to operate a load at a lower speed than the 1500 RPM and perhaps with a greater torque it may not be possible to produce more power then what the motor is designed to do.

As I said it is a 5kilowatt motor then you could do not expect out of it 10 kilowatts, it will just not produce that power the winding may get over heated if you try to draw more current and things like that. So may be with the same power requirement however or with lesser power requirement you could operate a load at a lower speed. So your application may be such that what is required is only a constant speed I am only going to use the motor to drive a grinding wheel and the speed of the grinding wheel is going to be kept constant, in fact it may be higher than 1500 RPM.

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So such a drive is obviously is going to be called a constant speed drive the object is to keep the speed consistent. So as the grinding wheel does its jobs depending on the surface which is being ground, the amount of torque required may change but I may want the grinding speed to remain constant. So this will remind you what we talked about earlier trying to keep something constant irrespective of or in the face of something else disturbances. In this case change in the load nature of the load itself the material which is to be ground, whose the surface which is to be ground depending on its nature if the grinding speed is kept the same, the torque that is required may be different. Of course the amount of the material which you want to remove by grinding.

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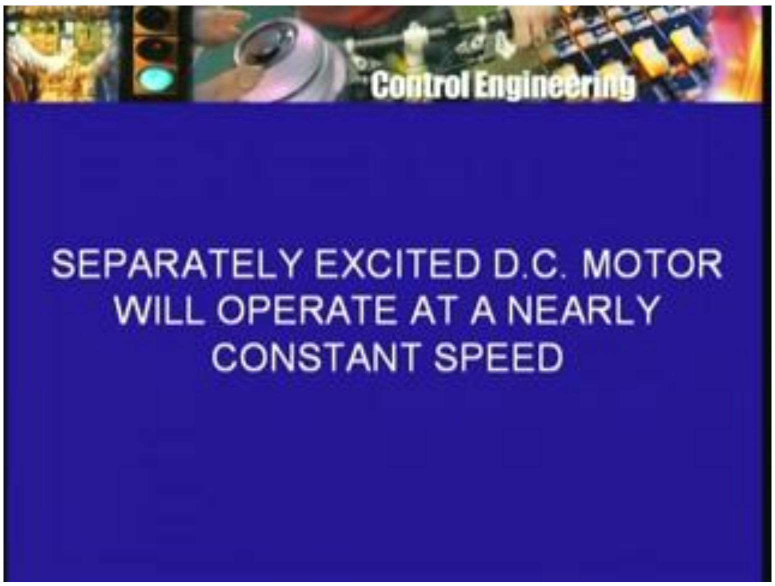

So the depth also can be different but we want constant speed, so you want that the wheel should run at a constant speed irrespective of the torque changes the load torque changes that may take place as the grinding job proceeds. So here is one application use a DC motor to provide a consistent speed drive and in fact we will see that DC motor separately excited DC motor comes very close to being a constant speed drive but unfortunately not a 100 percent constant speed drive as we will see. But in any applications one may just put a motor there separately excited the DC motor, of course you have to make arrangements for starting it properly and what not, so there are cares to be taken in that regard but by its very nature as we will see when we write down some equations very soon.

The DC motor speed will remain very nearly constant and if that very nearly is acceptable for your application that is good then you do not need to do anything more then what is the control system going to be nothing much except turn on the motor and turn off the motor. When it is required and when it is not required of course make sure that the field current remains constant and if that also the power supply is fairly reliable no need to worry field current will remain constant and the motor speed will remain nearly constant.

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But this nearly may not be good enough it may remain constant within say plus minus 5 percent but a job may require the speed to remain constant within 1 percent this we referred to earlier as regulation, so the job requires the regulation that is better that is the percentage variation is less then what the motor will do on its own then you have to do something the speed control system cannot be simply turn the motor on taking care of this starting current and what not and that is it. But there may be applications where the speed is not to be necessarily kept constant but to be changed from one job requirement to another or as things happen on the same job the load torque and the speed therefore may go on changing the power requirement may go on changing and so such drives are referred to as variable speed drives.

Now DC, separately excited motor DC motor by itself is not going to make a variable speed drive. If there is nothing else there but the armature connected to the DC power supply the field winding connected to another DC power supply both the power supply voltage is have been kept constant, reasonably constant then the thing is not going to be have as a variable speed drive. It can provide torque which varies but it will not provide you speed which can vary but in some application the speed may have to very right from 0 or very close to 0or very slow speed to what may be called the full speed and at one time you may want the motor to operate at 100 RPM at another time you may want to operate it at 1000 RPM, so such a thing is called a variable speed drive.

Now if you want to use a separately exited DC motor for this purpose then you have to do something more then what we have thought of and therefore the control system design problem is not over here, you have to put some more things and we have to see how they can be adjusted or controlled. So that the speed can be changed as and when it is required. Of course today one may find that instead of DC motors one may prefer to use AC motors and that one of the reason of course is that what is available to you as power supply is not DC but AC. So AC requires rectification to DC and then use the DC motors this is still going on in the sub-urban railway system of Mumbai.

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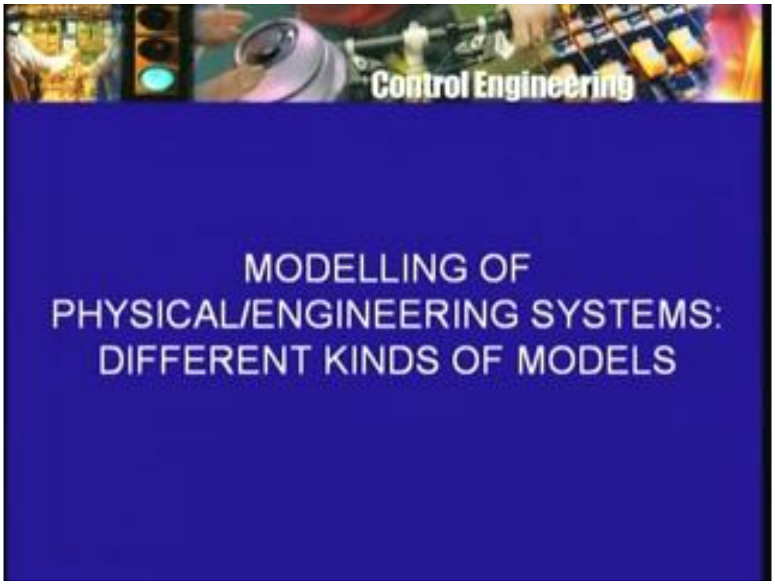

So there are rectifiers and then there are the DC series motors under the coaches. But one may prefer to use an induction motor then it is a different problem all together because now we will be looking at an induction motor rather than a DC motor as the prime mover or as the actuator for the load and so one will have to look at different considerations all together. For the moment let us assume that we stick to a separately excited DC motor but I want it to run at different speeds depending on the application and perhaps produce different amount of torques too how shall I do it. Now when one tries to do something like this get into design will you need to know something about the motor I just put down some crude calculations 5 kilowatts 1500 RPM, you can calculate the load torque that will be produced but one will require something more that I have to relate the torque which is produced by the motor shaft that is because of the interaction between the field or the flux and the armature current I will have to find out how it depends upon the armature current and also on the flux part.

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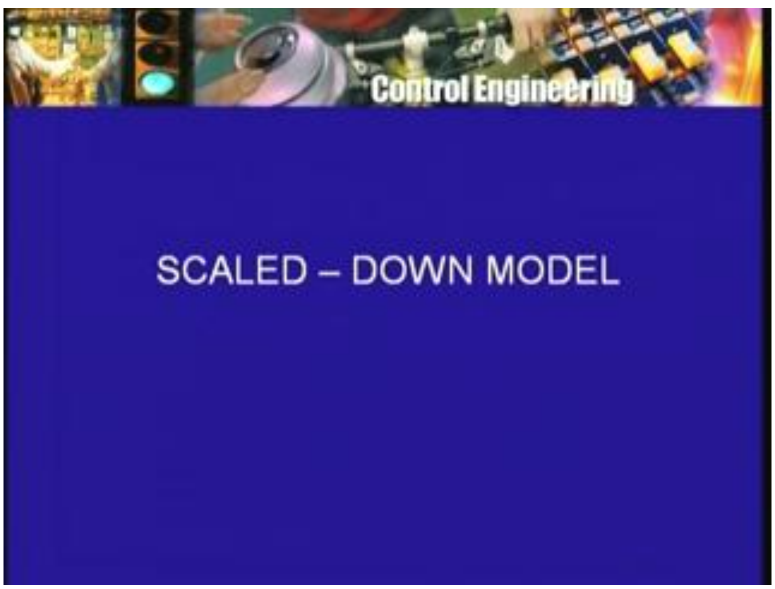

Now this is where we enter the area of what is called modeling, it is a very fashionable word of course I am not referring to modeling in the commercial sense of that term. I am referring to modeling of engineering or physical systems, what do we mean by modeling in this case. Of course modeling or models can be of different types one of the earlier ideas in connections with modeling was what is called is a scaled down model, instead of a big motor I may have a small motor, much smaller motor in fact such modeling is done even today as a sport or as a hobby one talks about aero modeling.

Since perhaps you cannot buy and a fly big aircraft, you make a model of it which has a small engine driving its propeller and then you play with this model. Now for that scaled down model to actually fly it has to be made carefully and there is a relationship between the aircraft that actually flies in the air commercial and this model that will fly only up to smaller height and over smaller distances and at much lower speeds. But there are many things which are similar for example the wing, both of them require a wing, both of them require thrust, this one has a propeller and other one may have jet engine but the thrust is required, wing is required to control it to make it go up and come down and and turn and so on it requires control surfaces. So there are lots of similarities between that big aircraft and the small one, so this is based on the idea of similarity and the similarity is a physical similarity, the model aircraft looks like the bigger one and in fact it has wing that is like the wing. So not exactly in size of course but not necessarily even with the same proportion as the wing of the bigger aircraft but physically it is the same kind of thing this model aircraft is also going to fly in air as the bigger aircraft does.

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So this uses the concept of similarity there are similar laws in operation. The laws of aerodynamics are to be used for both the big aircraft and the small aircraft and in fact one may make studies of these smaller models in wind tunnels for example, wings of wings sections new designs may be tested in a wind tunnel and therefore the actual wing that is studied may be much smaller than the wing of aircraft for which the wing is being designed. So such modeling still plays a very important role and it is based on the knowledge of the underlying physics of the laws governing the phenomenon in the case of aero modeling, the laws of aero dynamics.

Now so in a similar way you may have a big motor 5kilowatt motor and you may have a much smaller motor what used to be called at one time fractional horse power motor these were not for fun but for small jobs for example a mixer will required much smaller power although it may require higher speed, a few Watts perhaps the motor will be much smaller but again it will be governed by the same principle. This motor like the other motor will have winding and one will talk about voltages currents and since it is an electric or electro magnetic motor, one will talk about magnetic flux or field and things like that. So the physics or the laws that are used will be similar so this is modeling based on similarity or scaled down model there is another sense in which the expression model is used which again was being done quite extensively in the Second World War and period immediately following the Second World War.

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Now a day is one does not find those things but some of you may have heard of analog computers, you can spell it in two different ways analog (ue) computers. I have seen and worked on an analog computers setup many years ago and they are quite interesting things to work on. Today you can build or make an analog computer or analog computer system by simply using what is this symbol of an operational amplifier. So by using a number of operational amplifier along with resisters and capacitors you can build an analog computer system which could be a model of something else for example, there may be a mechanical system consisting of what is called a mass, a spring and a dashpot being activated by some force.

So you have a purely mechanical system and the variables of interest or relevance are mechanical variables, position, velocity, acceleration, force, the parameters that one talks about are mechanical, mass, stiffness of the spring, the equation of friction or viscosity of the dashpot. So something mechanical, so here is a mechanical system on the other hand the analog computer system or setup will consist of purely electrical or electronic devices and what you can talk about there are usually only current and voltages. In the case of an analog computer setup it will be really voltages that one will talk about. Now in what sense that analog computer setup be a model of the mechanical system, it is a model in the sense it is an analog of the mechanical system. So you talk about an electronic or a analog computer setup which will model a mechanical system.

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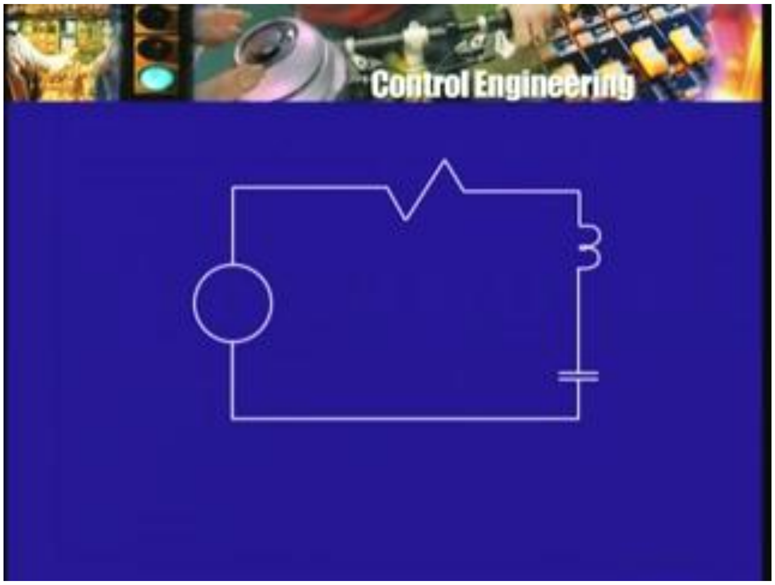

So this is not like the natural the similarity model in based on similarity the op amp based system is not anyway like the mass spring dashpot system, it is made up of totally different things then what we mean by analog, what we mean by analog is that one can setup a correspondence between the variables in one case and the variables in the other case. In the mechanical system the variables are position or displacement, velocity, acceleration, force, torque and what not in the case of electrical or electronic system the variables will be mostly voltages, outputs of various op amps, in your op amps circuit. But you can setup the analog computer system that is the op amps circuit choose the resistor, capacitors values in such a way that there is a correspondence between the voltages the output voltages of this several op amps and between the various mechanical variables like position and velocity of the mechanical system and usually this is done through the help of equations. It is possible to do such analog modeling without worrying too much about equations for example one can even have a more primitive model of the mass spring dashpot system and I will draw the circuit diagram.

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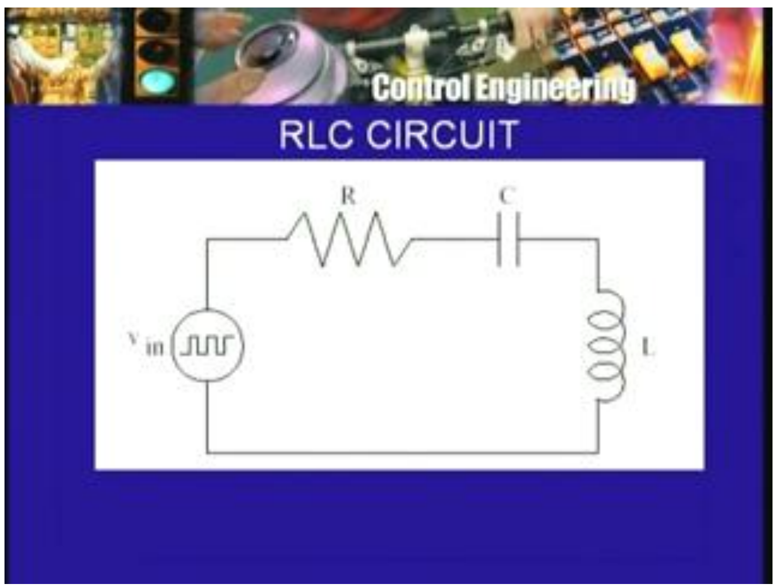

Here, it is a resistor in series with an inductor, series with a capacitor connected to a voltage source or we referred to as a RLC series circuit. In this manner of course what can we talk about, we can be talk about various voltages source voltage, resistor voltage etcetera and in this case because it is a series circuit only one current namely the current in the circuit. So these are electrical variables or electrical quantities current and 3 or 4 voltages in the case of the mass spring dashpot system acted upon by an external force you have various positions, velocities and forces. Now one is said to be an analog of the other or an analog model or a model of the other the RLC series circuit can be used as a model or to model the mass spring dashpot system and one way of doing it seeing that it is a models is by writing down the set of equations that governs the behavior of each one and this is an exercise which you should carry out.

So this will be a home assignment for you as electrical engineers of course you are familiar with RLC and even more sophisticated electric circuits but you should also have some feeling for a simple mechanical systems or components like the mass, the spring and the dashpot. Write down the equations for the electrical circuit, write down the equations for the mechanical system and then see for yourself if there is some correspondence, some resemblance, some similarity between the 2. I am saying one should use the word correspondence rather than similarity because the symbol V in electrical engineering will denote voltage whereas as the symbol V for a mechanical engineer will denote most probably velocity, the current is denoted by I whereas the force denoted by the symbol F, small F or capital F.

So it is not similarity or resemblance in the crude sense that is in the same symbols are letters are used but the equations there is correspondence between them. I would like you go through this and be able to see that okay this source voltage here V corresponds to what does it correspond to the force in the other case or it does not. The current in the circuit what does it correspond to does it correspond to the position of the mass or the position of one or the other end of the spring. First we will assume that the mass is point mass, so it is specified by only one coordinate X coordinate but the spring of course is extended, so X 1 is the position of the mass to which one end of the spring is connected, X 2 is the other end of the spring and so the spring will have a length X 1 minus X 2 or X 1 depending on which way the coordinate axes are and depending whether this is less than or greater than the natural length the free length of the spring, the spring will be in compression or in tension therefore will produce or it is being affected by a force of compression or a force of tension.

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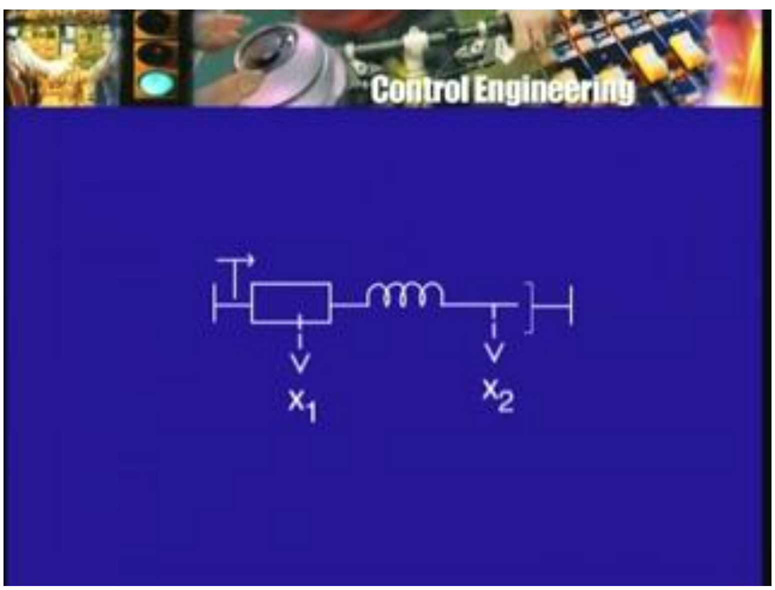

Similarly, the dash pot one end of it is fixed the other end of the it is connected to the spring, so the plunger of the dashpot moves therefore one can talk about its velocity and so on. Now in order to do this of course what one does is first one looks at the components of the two systems in the electrical circuit case the components are simply the resistor, the inductor, the capacitor and the voltage source. For the mechanical system the components are the mass, spring, dashpot the support to which the mass and dash pot are fixed and the driving force or the displacement source as sometimes it may be thought of that is rather than force you produce a motion of the mass and then see what happens.

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So the system is built out of components and one may start by writing equations for the components first and then looking at the equations together or combining them to get the equations for the system. So do it for the RLC series circuit start at the very basic level, start with each of the components, resistor, inductor, capacitor, voltage source, write down the equations that describe only the components, each component separately, write down an equation that describes only the resistor, an equation that describes the behavior of the resistor under normal conditions, what is that equation? It is simply as simple a thing as the voltage of the resistor is resistance R into the current of the resistor, V equal to R I Ohm's law, statement of Ohm's law that is the equation for the resistor V equal to R I.

Similarly, there are equations the for inductor, for capacitor, for source, voltage source write down those equations but that is not all you just do not have the resistor, inductor, capacitor and the source. They are connected together in a particular way which is called a series circuit. Now this particular way of connecting them together in a series circuit is associated with some more equations. So it is not just the equations for the whole component but you have some more equations, what are they in this case the components are set to be connected in series, so what does that remind you of it reminds you of 2 laws or rules which are named after Kirchhoff notice the spelling of the word, of the of the name you may not know who he was when he worked what he did he do but the least courtesy you can do to him is to spell his name correctly.

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Kirchhoff with 2 Hs do not call him Kirchhoff or do not write a single h where there is a double h and there is a double f also at the end of course as the name suggests he was a German or worked in that part of the world. So there are these 2 laws or ways of writing equations that are named after Kirchhoff, Kirchhoff's current law and Kirchhoff's voltage law using these two then and using the component equations one can write down a set of equations for the RLC source, series circuit. For the mechanical system again there are similar laws for the mass what is the law this is law of course goes back to Newton and it simply says the force is mass times the acceleration or mass multiplied by the second derivative of the position or displacement.

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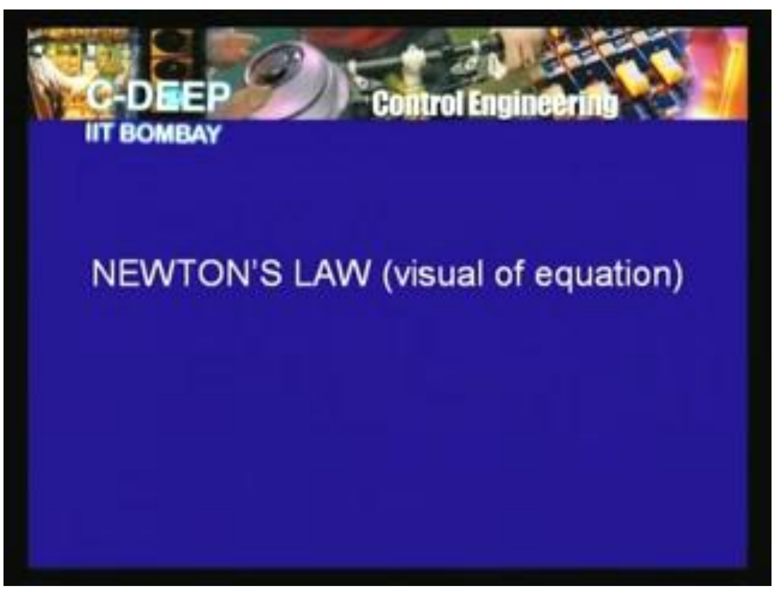

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So that is Newton's law for just a point mass or particle of mass M, F equal to MA what are the laws or what are the equations for the other two components the spring and the dash pot then these 3 and the supports at the 2 ends are not just there they are connected together in some particular way and there are laws involved here although they do not have any particular names associated with these laws. These laws are nevertheless involved one may of course if a mechanical engineer is given this problem he will at once write down the equation for the whole system but as an electrical engineer it may take you some time to write down the number of equations and then from them obtain may be one single equation that describes the mass spring dashpot system.

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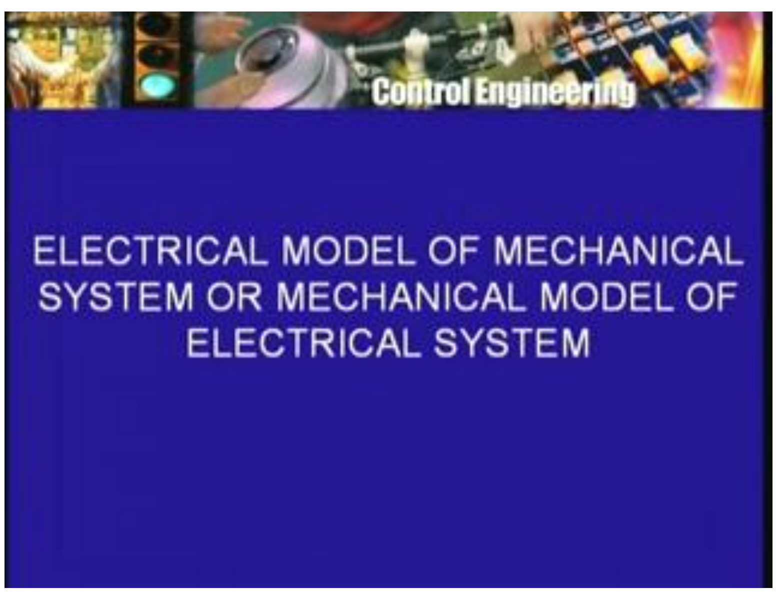

So write down this for the mechanical system go through the fundamental steps, component equations, equations that arise out of the interconnection then from them get some equations then on the one side you will have the circuit equation or equations on the other side you will have the mechanical system equations and now see for yourself if there is some correspondence or if there is some resemblance or similarity then you could say that the RLC source series circuit is a model of the mechanical system or you may even think of it the other way the mechanical system is a non-electrical model of the electrical system. This is a second use of the word model, so do carry out this home assignment.