Power Electronics

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Lecture - 1

Electric Drive

Today, we will start with the topic on industrial drive system. In this industrial drive system, in this course, we will be mostly concentrating on the electric drive part. So, we will be talking about the electric drive part. A basic definition of an electric drive system can be an electric drive is defined as a form of machine equipment designed to convert electric energy into mechanical energy and provide electrical control of this process. So let us say, let us write that one, electric drive.

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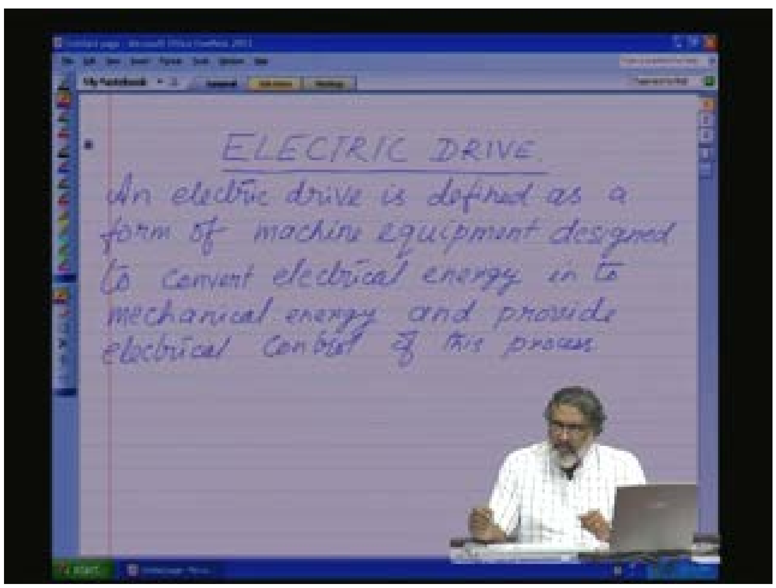

An electric drive is defined electric drive is defined as a form of as a form of machine equipment machine equipment designed to convert electric energy designed to convert electric energy into mechanical energy, energy into mechanical energy. So, in an electric drive, what we are doing? We are trying to convert electrical energy into mechanical energy and provide electrical control of this process or electronic control of this process.

That means when we convert electrical energy into mechanical energy; so the load, the output system required in a particular fashion. So, we require a process, a necessary control of the system. So, all the controls nowadays we do it with electronics control. So, we will say, to convert electrical energy into mechanical energy and provide electrical control of this process electrical control of this process; this is very essential. You are converting electrical energy into mechanical energy with a necessary control. So, this is the basic definition of an electric drive system.

Now, this definition, I have taken from a very famous Russian book by Prof. Chilyken and I feel that is a very good definition of an electric drive system. Now, based on this definition, let us form a blocks schematic so that we can clearly understand what is the conversion process? What are the blocks inwards? And, where the control is? For control, what are the inputs required? So, basic block diagram let us write about.

Now, the basic block diagram for an electric drive system may look like this; so, we are converting electrical energy in the mechanical energy. So, we should have the source, what we call the power source. Power source, we will put it like this; this is the power source, this is the power source.

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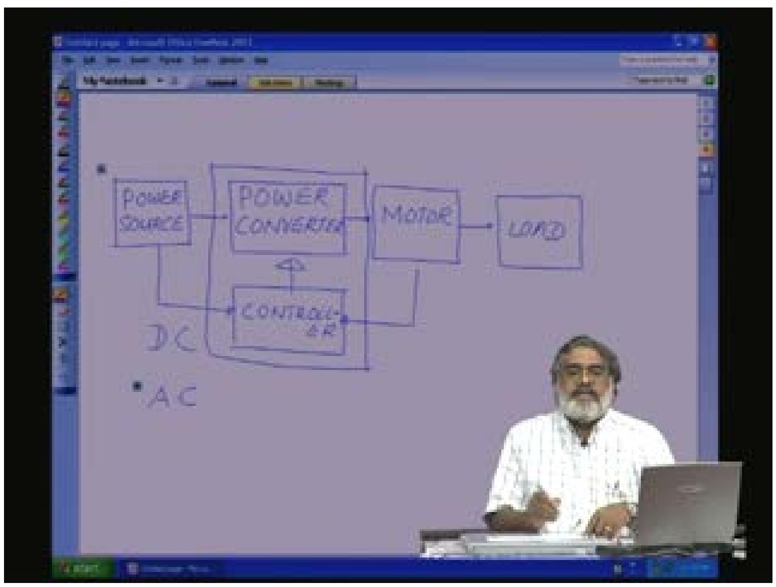

Now, this power source, our basic power sources are our mains; the voltages and currents will be in AC. Sometimes, the power source can be a battery where the voltage and current are DC; sometimes we can have solar power. So power source, the output of the power source should go to a power convertor. Why?

This power convertor, the output of the power convertor brings the power source to the required level; the voltage level, current level, frequency level last required by the load. So, we require a power convertor where the power source can be controlled and modified or changed AC to DC, whatever it is; so, power convertor. We will come to each block soon. So, power convertor.

We are converting electrical energy to mechanical energy; the source and the power convertor convert to the desired level and for any mechanical energy, we should require a motor. In electrical drive system, a motor is a part of… and motor will be connected to the load. This is the basic open load block schematic of an electric drive; we have the power source, power convertor will convert to the required level and give to the motor, motor will give the required speed and power to the load.

So, in our electric drive system, what we are controlling? Conversion of the electrical energy to mechanical energy means the source is electrical and the load is mechanical. So, we are converting into electrical energy mechanical energy that means basically speed and the torque.

Now, in our basic definition, we should give the necessary control of this process. So, let us draw the block diagram like this, controlled. Controller - that is our electronics controller; now controller output will control what? We do not have any control of the power source, power source is what is available to us given to us and load is suggested by the customer, what he wants.

So, once we select the motor, then all the control; motor parameters we cannot change, we have to control the whole thing through our power convertor. So, controller output will mainly go to the power convertor. So, to take the necessary control action, controller requires some inputs. So, as many as inputs are always good for a good controller but the more input means more devices, more sensing equipments are required. Then the system will become very costly. So, the controller input depends on a cost effective design, we will limit to what is their minimum required.

So, controller input can be from power source. Why from power source? Suppose, if for AC, our mains, we are using as the power source; sometimes the voltage can fluctuate, frequency can fluctuate, then the power convertor should control it such that the motor gets the required steady voltage and current irrespective of the fluctuation in the power source. So, there is an input from the power source is required.

We can also have input from the motor; speed can be one input, motor voltages and current can be one input. Suppose, due to some sudden change in load, motor drives very large current which is beyond its requirement; suddenly controller can, we can control that one through our power convertor. Power convertor, through power convertor we can control the motor input parameters such that the current can be controlled or sometimes the load require more torque, it is rotating. So, motor should drive more current. So, this can be controlled through our power convertor. So, the basic inputs, we can have power source and from the motor load and the power convertor. This is the basic block diagram of an electric drive system.

Now, in our course, we will be mostly studying the power convertor side and the controller. Why? because, as a designed engineer, we have only access to these two. We can only control and we can select and choose these two and motor is selected for decided base from the load requirement. Once these are selected, these are fixed that means power source, motor and the load. Then any control parameter, we can only control through these power convertor and the controller. This is only in our control.

Now, let us again go to further definition of our power convertor, whatever is a conversion process happening here. Let us take the power source. Power source can be, we can basically, we can we can specify as DC and AC. So, we will go to the next page.

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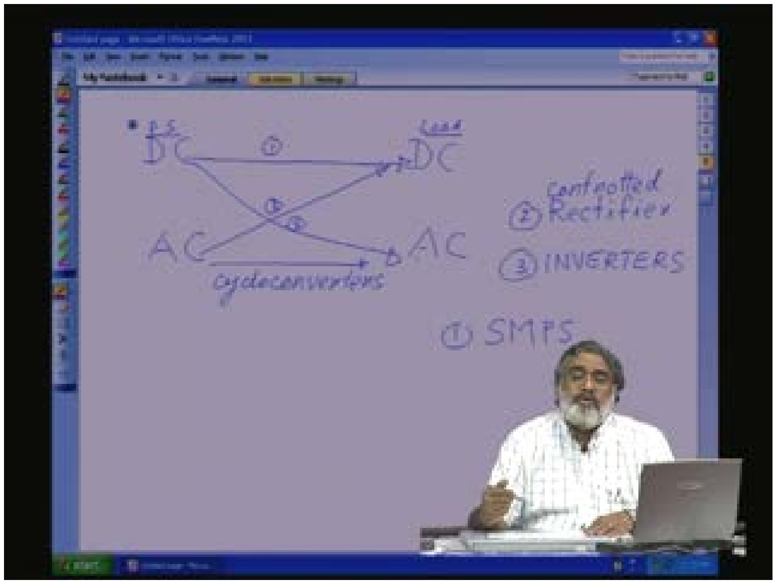

Depending on the power source available; either battery or mains, power source can be basically define as basic form DC or AC. Now, our output of the convertor also we can very basic with the basic form of output, we can say either DC or in AC. So, here also there is a power convertor; DC or AC. Now, we should have conversion, the power convertor convert the power source, a DC voltage of one level should convert to a voltage level to a different voltage level as required by the motor. So, there is a DC to DC conversion. This has to be achieved through our power convertor.

So, basic DC to DC power convertor; you know it, it is a 1, it is at SMPS - switched more power supply, SMPS - switch more power sup supply, one example. Then AC to DC that is our mains that means AC power source with alternating voltage and current, we are converting to a DC voltages and current. The basic power convertor of this one, we can call as the rectifier.

But if you see in electrical, as an electronic engineer or electrical engineer; you know how to rectify? If you have the diode, a three phases or single phase rectification is possible. But we will not be this is not the required rectifier what we want. Why? We require control of the process. So, what we require here into is a controlled rectification, like using thyristors, phase control convertors; so one example. So, it is controlled rectifier, this is controlled rectifier that is AC to DC.

Then the next conversion; this is power source, this is on the load side or the motor side, DC to AC that means a DC source battery or a rectifier output that means what is available to us is DC source but we want AC. One example is UPS that is basically invertors. These types of convertors are called, power convertors are called invertors, these are called invertors.

We will be studying in the due course, the basic control of the invertors, various invertors topologies for speed control applications, we will be concentrating more on that one later. Then another one AC to AC. That means voltage, current or frequency of one into another voltage and current and frequency of different level. These are basically in old books; we can see one class of convertors is called cycloconvertors, one example. But we will not be studying about this one now. We will be mainly concentrating the AC to DC and the DC to AC convertor in our main course.

Now, after going through the classification and block, we set our control of the whole processing through the controller. That means we have to design the controller such that the system will quickly adapt to the change without much translates. So, controller design is very important. Nowadays, simulation tools are available, so we can have a mathematical study and we can simulate and we can tool the controller before a hardware implementation is started.

Why? That will say lot of time and money; otherwise we have to learn from the failures. The hardware if keep on failure fail and leave be if we learn from that process, the cost of the whole system will go up. So, the controller design and the controller tuning, before I control the implementation; a controller design and tuning can be done through a simulation study.
For a simulation study, the whole system should be modeled. That means equivalent mathematical representation of the system is required. That means the representation for the power source, power source basically we can AC or DC, we can do it; then the power converter, then the motor. So, a mathematical model of the motor required based on, for our controller design.

As I told you before, the whole process is converting electrical energy into mechanical energy, mechanical energy through our; what is the output of the load? The mechanical energy, the torque and the speed, from there we are generating the energy. So for motor, a basic input output relation, a torque speed characteristic is required torque speed characteristic required. That means various speeds, what are the torques required? Then for the torque; what are the parameters we have to control at the input side of the motor? That is the voltage and current. For that voltage and control, corresponding controller has to be initiated for the power converter.

Now, the basic load that is now the mechanical load; we can basically divide the torque speed characteristic into four category. Let us take the torque speed characteristic of the load.

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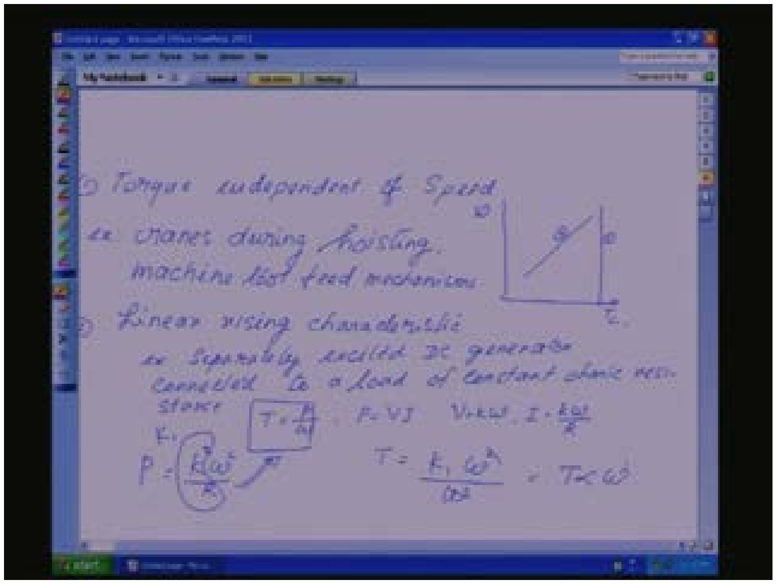

One; torque independent of speed. Let us write the graph, power speed characteristic of this load. The graph, this is our speed that is speed in electrical radiance per second and this is the load torque. So, torque is independent of speed. So, the curve will be, the speed torque characteristic will be like this; steady. That means irrespective of the speed, it will always generate constant load. So, what are the examples for this one?

Example; low speed hoisting, that is cranes during hoisting during hoisting that is one, then machine tools for feed mechanism; these are some of the examples. Many examples you can find in many text books and these are some examples. Then two, linear rising characteristics; what you mean by linear rising torque speed characteristic? What do you mean by linear rising torque speed characteristics?

That means whenever the speed changes, torque will also change proportionally, this is one this is our second example. The torque speed characteristic for a linear rising low torque is like this. What is the example? Let us take a separately excited DC generated connected to a load of constant ohmic resistance that is example. Separately excited DC generator connected to a load of constant ohmic resistance that means a separately excited generator; the generator that means machine is working as a generator and the generator is feeding a load of constant ohmic resistance. Then let us see, the torque speed characteristic is linearly rising.

Now, we know torque is equal to P by omega; omega is radiance per second. The torque generated, the power developed by the generator divided by the speed give the torque. Now, what is the power generator by the separately excited generator? P is equal to that is the temporary voltage into current I. Also, we know that this V, the voltage generated by the excited separately excited DC machine DC proportional to speed that is proportionality constant K into omega. So, V is proportional to k into omega.

Why? We want to bring the basic relation between the torque and the speed. V is equal to K omega and what is the current given or taken by the load from the generator? I is equal to V by R, V is equal to proportional to speed K omega divide by the, this is our constant ohmic resistance R, K omega by R. So, we got I. Now, what is the power? In this, this is the basic equation. In the basic equation, we require the power. Power is equal to P is equal to V into I, V into I is equal to that we can substitute V and I; this will be equal to when you substitute K square omega square divided by R. Now, let us substitute this one to this equation. Then what will happen? Torque is equal to K square by this is a constant for a machine, this load is also constant; so the whole thing, we can represent by a constant K_1 another constant K_1

So, this will be equal to K_1 omega square, PV we have substituted here, these part we have substituted here divided by omega. Now, this will be equal to omega square goes, this will be equal to, torque will be proportional to omega. So, as the speed increases, torque also will increase. Power will increase, torque will also increase. So, this is the equation, linearly rising characteristic.

Some simple examples, I am telling here. Now, let us take here nonlinear rising characteristic. Let us go to the next page. Nonlinear rising characteristic; now the third example is nonlinear rising that is parabolic characteristic.

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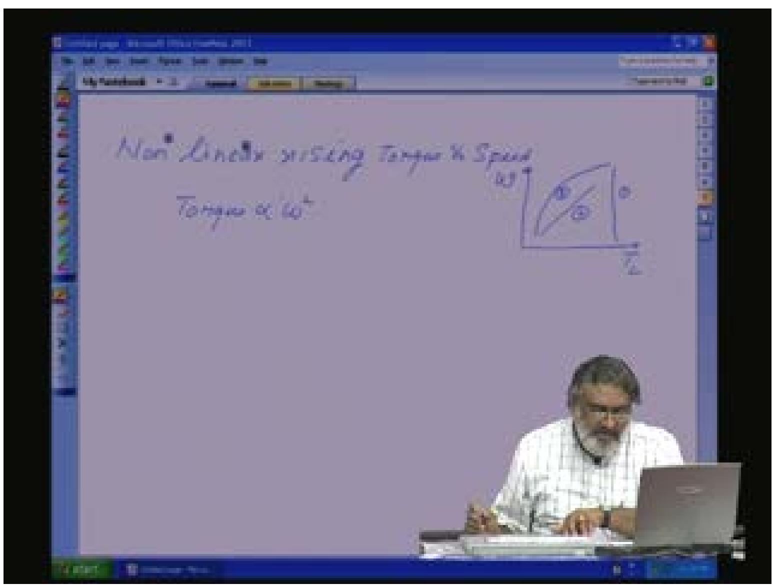

Nonlinear rising torque speed characteristic; torque speed, torque versus speed characteristic that is parabolic. How it will look, nonlinear rising? The speed let us again draw the axis, this is our omega speed, this is our torque. So, it will be something like this, third characteristic. Previously, the constant load speed characteristic that was one, linear rising was like this, this is the third one. Third one is this one.

Most of the final loads belong to this one that means torque will be proportional to omega square. Most of the loads will be most of the load final loads will come under this. You should see; constant, linear rising, then nonlinear rising, then the next one will be for nonlinear falling characteristics, nonlinear falling torque speed characteristic.

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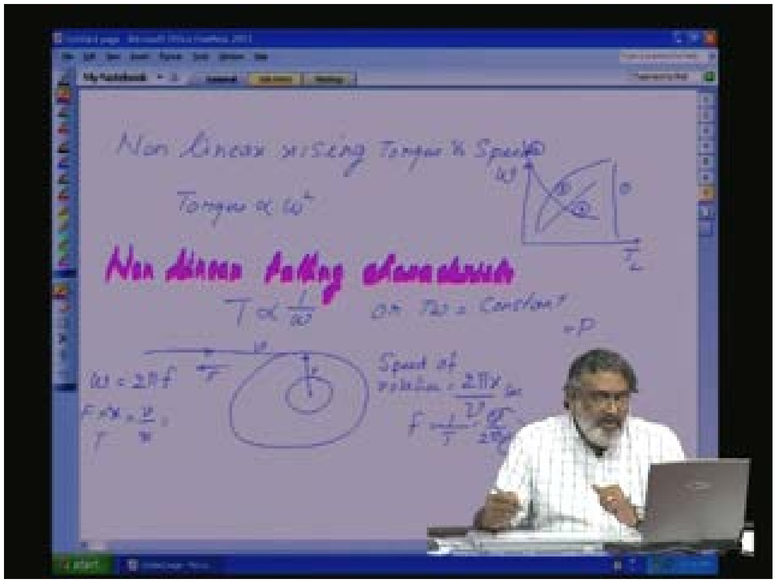

Are we to look. So, nonlinear; here let us take that is torque is proportional to 1 by omega. This is nonlinear rising, nonlinear falling characteristic that is something like this; this is nonlinear falling characteristics, torque is proportional to omega. That means or we can again say T into omega is a constant.

Let us take, one example, rolling mill. In a rolling mill, the paper comes out from the mill, the constant speed and it will be a thin roll to a drum. So, paper is the radius r. As the paper gets rolled on to the drum, the radius will keep on increase. Now, the paper is coming from the mill with the constant velocity and we should take care of the speed of this drum has to be adjusted that we have to keep constant tension, we have to keep a constant tension such that the paper should get rolled on to the drum properly. So, what is the torque speed characteristic it shows?

Now, if you see here, the speed of rotation, what is the speed of rotation? Speed of rotation is distanced by the speed B. So, speed of rotation speed of rotation is equal to 2 pi r divided by V, this is the speed of rotation. This is second, period in seconds. Now, what we are attempting with this equation? We have to get a torque speed that is torque and the speed that is the angular speed omega; we have to keep a relation.

Now, what is frequency here? f is equal to that is the frequency is equal to 1 by T, 1 by T is equal to V by 2 pi r; frequency we got. Once frequency we got, we know omega. Omega is equal to 2 pi f. So, from the speed V, this V, we can get omega – 2 pi f. Now, what is the power exerted by the torque by the drive?

Power exerted by the drive, see we have to give a constant torque opposing force here. This is force f. So, what is the power? Power is equal to torque is equal to the power exerted by the drive p is will be equal to that is F into r; r is the radial distance, f is the tangential force. The torque, this will give the torque, this is the torque f into r, torque into, what is omega? Omega is equal to 2 pi f, 2 pi f is equal to v by r, from here v by r.

So, these two we will cancel, F and v; these are constant for this one, so power is constant. That means torque into omega that is p is equal to p is constant, torque into power is equal to that is p constant that is this will give constant wholes power load. These are some of the some of the basic torque speed characteristic.

Now, once we got the torque speed characteristics, let us take the combined system. This is torque speed characteristic of the complete load. Now, in a combined system, there is a driving torque and the load torque. For speed control this should be matching. So, how that driving torque has to be controlled the meet the load torque? That is our basic control purpose. So, let us take the combined system. Now, let us go to the next page again. There is a combined load torque characteristics, combined torque speed. That is torque speed torque speed characteristic.

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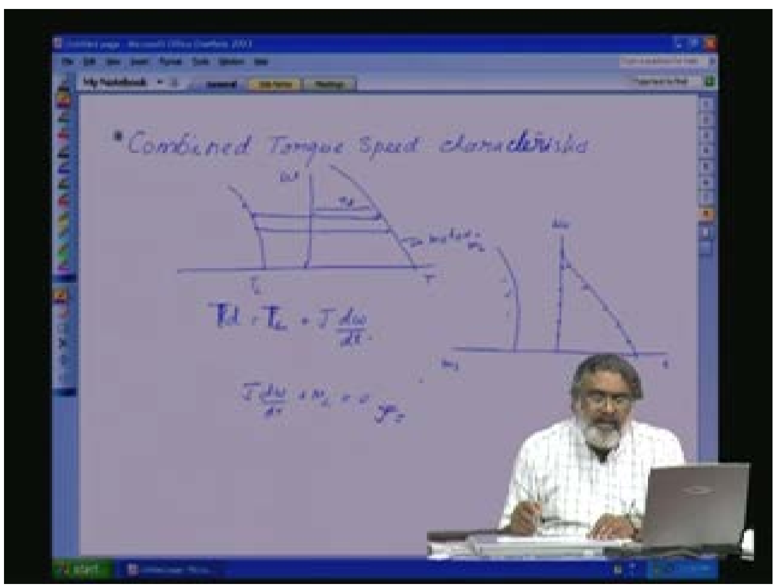

Let us try, draw the axis; this is omega, this is T. Now, the load torque that is not in your control, load torque will keep on varying and for a stable operating speed or speed in speed control system, the drive torque should match the load torque. So, let us take a load torque a typical load or something like this that I have put into under negative axis because this is the opposing force, opposing torque, this I will put load torque.

Now, let us take our motor, the speed torque carries of our motor; let it be something like this. That is our motor driving torque for the motor. Now, in our speed control system, suppose we have to operate, the system will come to a stable state where the load torques approximately this point, load torque will be equal to the driving torque. But the load torque can vary that is not in our control. Load torque can vary means suppose the speed varies, load torque goes here. What will happen?

Load torque goes here means speed has changed. Now, this is the load torque demand by the load. But according the motor characteristics, the driving torque that is T_d is less than the load torque now. So, what will happen? System will slow down and come to this point. Now, let the load torque decrease. In this case, what will happen at this point?

The load torque is less than the driving torque; so this will accelerate it and it will come to the stable point. But in most of the cases, this is for a typical load speed characteristics; in most of the cases, it will not come to the stable system so that depending on the load torque requirement; our motor characteristic torque speed characteristic, we have to control we have to modify through our power converter.

So, our whole control block, the purpose of the control block is to dynamically control the torque speed characteristic so that the driving torque will be always equal to the load torque as demand by the load for a particular speed. So, such cases, we require a close loop control system. Now, as I told you before, see I have so far I have told you T_L - load torque. So, load torque basically, we can define as or the driving torque P_d is equal to the load torque T_d sorry this is T_d, this is T_L plus if the speed is constant, driving torque will be equal to load torque.

Suppose, during acceleration and deceleration; there is more load, there is a torque change requirement or torque demand from the load. So, that can be explained as J into d omega by dt. J into d omega by dt, this approximately J is the moment of inertia. So, whenever acceleration deceleration is there, the total driving torque should be equal to the constant load torque plus the acceleration and deceleration.

Now, how to find out for a particular load system, how to find out the J? There are various techniques available in literature. I will take one from the famous Leonard's book. What we have to do? The complete system under no load, you system machine to the full speed, drive the system to the full speed, then full speed and find out the sorry this is omega $_0$, this is M_L, this is our type two axis. So, drive the system for various speeds for operation. 5, 6 points you take it and tie the system and find out the load torque required. So, you plot the load torque; you got the M_L.

Now, run the system to the full speed and switch off the power supply. Then what will happen? The whole system will decelerate. So, during the deceleration, what will happen? The driving torque is 0, so the decelerating torque generated by d omega by dt will be will be opposed that will be opposed by the friction and windage loss. So, slowly full system will decelerate. So, at various point, measure omega; you note the time and measure the omega. At various point, measure the time and omega and approximately at this point and time, you can find out d omega by dt.

So, d omega by dt we know, the system is under no load at various speeds. So, we know at various speed, what is the driving torque. So, this driving torque at the no load torque, so if you write the equation J into d omega by dt plus M_L is equal to 0 because we are switched on the system and the system is decelerating.

So, at various speed, J into d omega by decelerating torque is the no load torque of the system that we can get from this one. So, from this equation; d omega by dt we know, M_L we know, we can approximately we can find out J. This is the one way of doing the thing. There are other techniques also available; this is the one simple way of finding out J. So, once you know the J, once the speed; then what we know? We now, approximately we can find out the torque speed characteristic of the system during acceleration also.

Now, in this class, in this lecture, we have just basically; the basic definition of the electric drive is introduced and basic block diagram is given. Then depending on the voltage source, whether AC DC and the output requirement, we have classified the power converter where conversion process into various four category. Then the torque speed category of the machine, we have various categories – rising, constant, nonlinear rising, nonlinear falling, we have defined with typical example.

Then we talked about the combined characteristics. Combined characteristics, what we found out? It is required to modify the motor, low torque characteristics through our power converter such that depending on the load variation that is the T_L, always we have to keep the driving torque equal to the load torque. So, there is a close loop control system is required. The driving torque, the load driving torque is not only the steady; note in the acceleration and deceleration also we have to give the transient power also to the system so that the transient power acceleration and deceleration depend on the moment of inertia of the system and typically, how to find out the moment of inertia, a typical system is also we explained.

Now, let us go to the some of the basic power converter configuration so because we require the power converter. Once you select the power converter, then only we can choose the control function. Then once we have studied some of the power converters; first we will study the power converters required for DC modern drive applications, then we will go for the inverters that the power converters required for AC motor drive application, then how you design the closed control for DC motor and AC motor will be discussed during this course.

For the DC motor, we will be mostly talking about the separately excited DC machine because we will not have much time for all other cases; separately excited DC motor that is widely used for motor drive applications. Then the AC motor drive lectures, we will be talking about induction motor drive, mainly induction motor drive applications. During steady state, dynamic equivalence circuit model we will study, then the symbol v by f control, then the high dynamic and the controller like field oriented controller for high dynamic performer application we will be studied later.

Now, let us go to the basic power converter configuration. Let us go to the next page. Here, what we will be talking about is the power converter that is AC to DC converter for DC drive applications. So, control rectification is a must for this one. Let us study some of the basic power converter configuration. So, single phase, let us take a typical converter, single phase, before coming to the three phase control rectification; let us talk about single phase AC to DC power converter.

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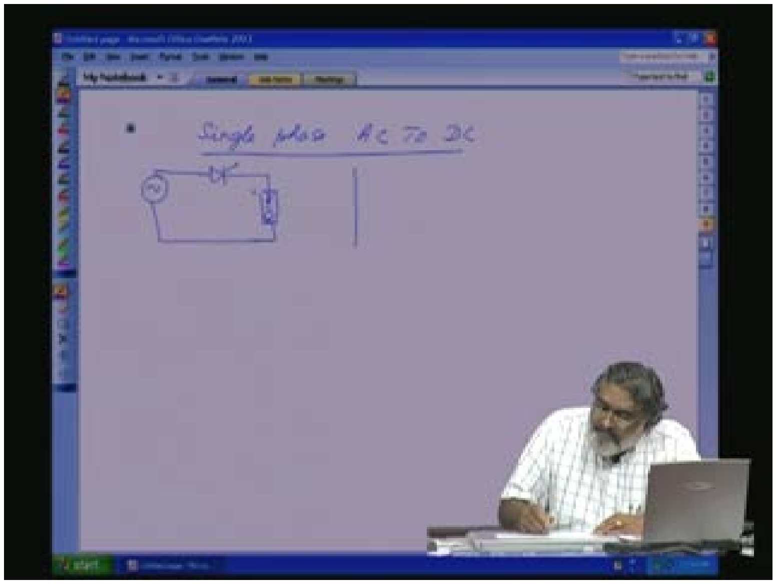

The most basic single phase power converter is, the schematic is like this, let us represent our mains like this; this is our controlling device, this is the thyristor, then you have the load. Load, I will simply represent it like this, it is inductive with back EMF, it can be there. So, we will have inductive plus back EMF alone that is the motor can be represented like this. Then, it will go like this.

Now, how do you control the output DC that is DC this part? So, at the appropriate point of the mains, we will be turning on the device and we will transfer the voltage to the load. So, by controlling the firing angle of the thyristor, we can control the output voltage. How it can be controlled? Let us see.

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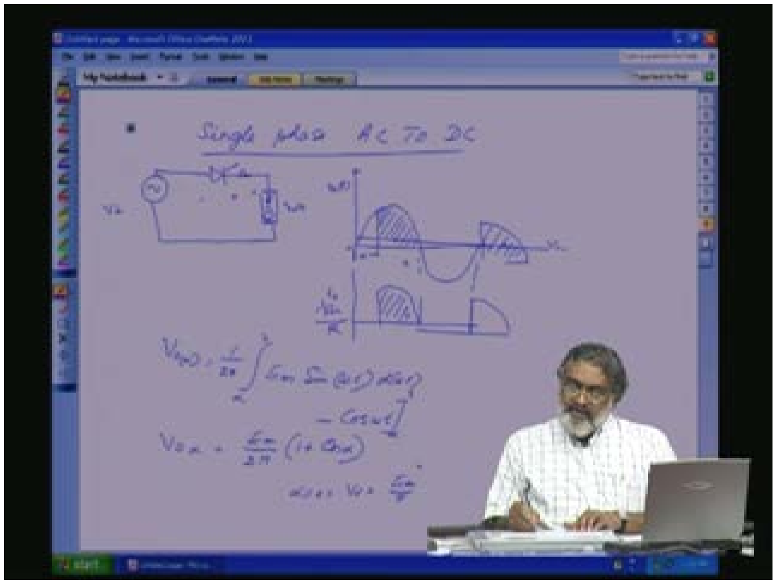

This is our V_0. What is the nature of V_0 for a single phase with a single thyristor controller? How it looks? This is our mains. We will not be whenever, for our present analysis, we will assume the control of the devices our instantaneous; we will not worry about the switching types involved in this one. So, the moment you give the gate pulse, thyristor will be turned on and when the AC mains is getting when the thyristor when across the thyristor reverse voltage is applied, the thyristor will switch off immediately.

So, let us say at this point, we are giving the firing angle alpha. Firing angle we represent as alpha, alpha with respect to this point, the starting point of our mains, here, zero crossing. Now, if the load is resistive that is the simple and the easy load if the load is resistive; what will happen? During this portion during this portion, the voltage will come across the load. During this portion, the voltage will come across the load and if it is purely resistive load, then the current will also be proportional instantaneously proportional to the voltage before but pure resistive load is only a text book answer; we will not have a pure resistive load, you will have resistive as well as inductive.

So pear, you will know in this class will be talking about mostly on inductive loads and with back EMF load also so. Now, with inductive load, what will happen? So, before coming to the inductive load, let us say how for the resistive load; how the current, it will be? Current will be in this form, exactly this will be.

This is our V_{in}; during this portion, this any value of the current I_0 will be equal to V_{in} divided by R. But during the half cycle, the moment the voltage go negative; what will happen? There is a reverse voltage across the thyristor, anode and cathode. The thyristor will be immediately switched off.

So, during this portion that output voltage is, there is instantaneous voltage across the load is zero for a resistive load. Then next half cycle, again this will appear. This is the current, this is the voltage. So, we will see a pulsed wave form will be coming across the load. This pulsed waveform, it will have the DC value and the AC value also will be there, high frequency AC value will be there.

So, we will not talk about but we are worried more about the DC value. So, what is the DC value? That is V_0, average value of this pulsed wave form that can be easily found out. V_0 alpha will be 1 by 2 phi that average value integrating alpha 2 pi. So, this is our pi. So, alpha to pi we will integrate and divide by the P rate, you will get the average value. So, this will be equal to Em sin omega t divided by dm, this we are integrating.

So, Em sin omega t if you integrate, what will happen? You will get minus cos omega t integrating limit is alpha to pi. So, when you substitute this one, finally the V_0 alpha will be alpha is equal to Em by 2 pi into 1 plus cos alpha. Here, alpha can be varied from 0 to pi. When alpha is equal to pi, what will happen? Cos pi that is minus 1, output voltage will be 0, the DC value will be 0.

When alpha is equal to 0, alpha is equal to 0; what will be the output? Alpha is equal to 0, the output will be alpha is equal to 0, V_0 is equal to Em by pi, this is the output and alpha is equal to 0 means we are firing the thyristor at the zero crossing, the positive zero crossing. What it says? It says, this can be replaced by a diode. So, output DC voltage for a single phase half range rectifier with a single diode is equal to Em by pi. But if you see here, during the negative part, we are not using, we are not drawing any power from the mains. That means even though power source is there, we are not fully utilizing the power source.

So, even though in the text book, these type of AC to DC converter using diode or thyristor are available. This is only for the understanding that one, how to get the DC value. So, this value what we talked about, this is the DC value but along with this value because of this variation, we have the repel content also will be there. So, that repel content, the repel voltage will produce its own repel current. That has to be suppressed by the load. But we will not be putting any extra filters to suppress this one.

To put filter means it is a cost effective proposition. So, inductive load; as the frequency high frequency of the voltage waveform, there the impedance of the load that is l omega will increase and the voltage divided by l omega, the current will the harmonic current can be suppressed. So, harmonic current, the amplitude harmonic currents can be suppress only by through the motor inductance. But what we are interested is the DC part.

So, this value gives the DC value. So, this will be another it will be used with, never use for any applications. But for understanding, already it is available in text book. So, whole analysis, what we have done is for a resistive load. So, this is for resistive load with the firing angle control. Now, let us see, instead of resistive load what if we put an inductive load? Let us go to the next page.

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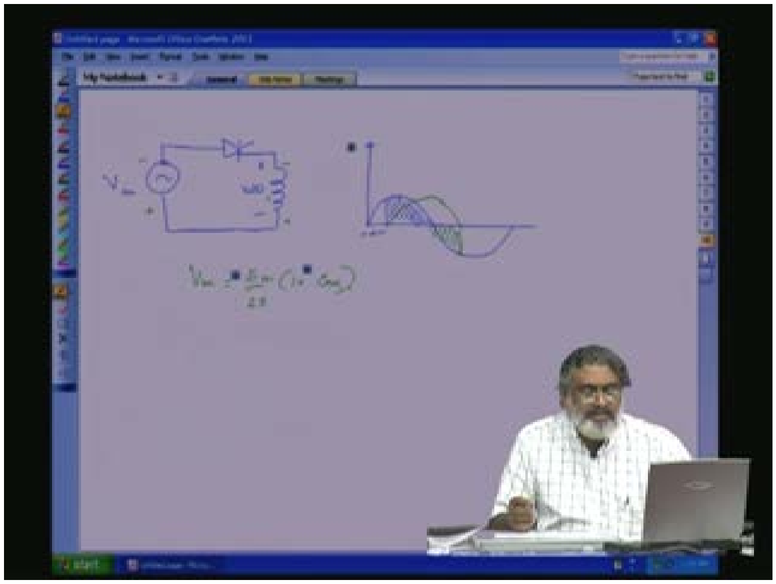

In the case of inductive loads, again let us draw the block schematic of the AC to DC converter with the firing angle alpha, alpha can be varied from 0 to pi. Now, we have the highly inductive load. If we use here; what are the type of repel voltage appearing across this one - V_0 (t)? That is the repel, this BDC plus the repel. Here, this is our V_m. If you see here, this is our voltage wave form, alpha is fired here, firing angle is fired from here; now what happens? Because of the inductance previously when the resistive load was there; the wave form, this repel, the current wave form across the resistance was the nature of the current variation was exactly same like the voltage variation.

But here, in this case, what will happen; the current wave form, current wave form will be starting at this point because currently the inductance cannot change instantaneously. So, what will happen? The current will vary like this. At this point, when the voltage is equal to 0, there is a current in the inductance. So, thyristor cannot switch on, current through the inductance cannot be changed instantaneously.

So, what will happen? Voltage will go negative. Voltage will go negative, then thyristor is conducting; so all voltage has to be suppressed across the inductive load. What will happen? At this point, inductance, the rate of change of current, it will go negative so that the voltage become instead of positive negative here, it will become positive or negative. Here it have the input voltage has changed.

So, this rate of change of current will, the load will take care of such that the rate of change of current is just sufficient to forward bias the thyristor here and current will keep on continuing and this current will be from the stored energy. Till the stored energy is released, current will keep on coming. So, what is the disadvantage here? During the negative portion upto this point also, the voltage was appearing to the load.

Now, compared to the previous equation; firing angle and DC is we cannot apply here because the negative portion also has come here. So, the previous equation of alpha with respect to the output DC with respect to firing angle is no more valid here because the thyristor is conducting in the negative direction also.

Then how to avoid this negative portion? At the same time, we have to give a free varying path for the inductance. This is during this, it is called sorry during the current conduction, the negative portion also we should give an alternative path for the inductance. At the same, this negative voltage should not appear across the load. So, than the previous equation that is V_0 alpha is equal to E_m by 2 pi into cos … one plus cos alpha is valid. How to come to that work; we will study in the next class.