Power Electronics

Prof. K .Gopakumar

Centre for Electronics Design and Technology

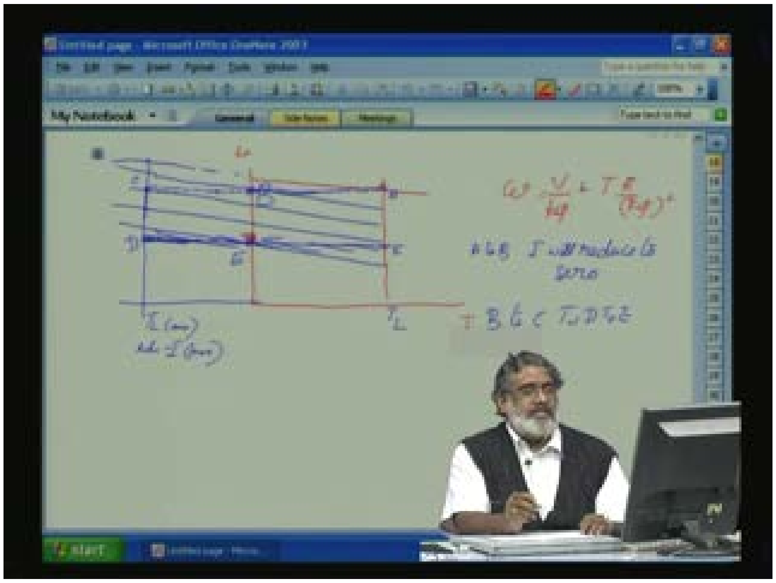
Indian Institute of Science, Bangalore

Lecture - 17

DC Motor Speed Control-Block Diagram Representation of the Control Loop

Last class we were talking about how to control the speed of a separately excited motor with four quadrant operation. So, if you see here, this is the torque speed characteristics.

(Refer Slide Time: 1:22)



We will control the voltage armature voltage, V such that the current will quickly come to 0 from A to B. A to B, as far as the speed is concerned; it is a same speed, parallel line with respect to T_L with X axis. So, speed cannot change instantaneously because the back emf cannot change instantaneously because of the mechanical time constant. Mechanical time constant will be always greater than we can assume here, it is greater than the electrical time constant.

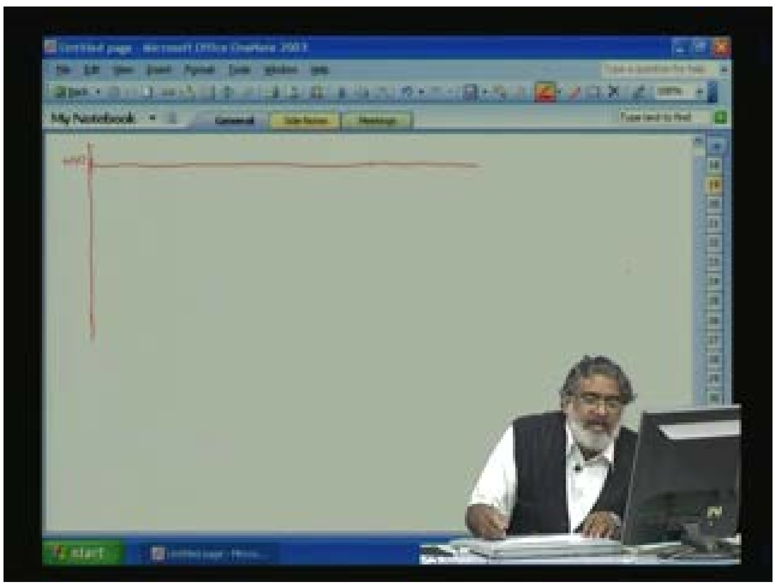
So, A to B the current will come to 0 immediately and still we are controlling the voltage. So, slight reduction in the voltage, at this point, the torque is 0. That means our back emf plus the back emf will be equal to our applied voltage. So, current will be zero. Further reduction in the voltage, current will start flowing from the motor. That means from the back, due to back emf, it will flow from the motor to our convertor side. So, the equation will be like this; previously it was minus, it will be plus. So here, that means instead of dropping here, here it will slowly increase. Slope is this way, same slope.

So here, from D to C, current is negative. So, the torque is also a negative. So, quickly it will come to C. This T_L maximum that is this point has to be limited by our controller, this point. That means your applied voltage, through applied voltage, we have to control so that always maximum torque is applied, negative torque is applied to the motor or maximum current is taken from the machine such that machine will decelerate. So, A to B is current is 0. That means machine is, from B to C, current will start in the opposite direction. Then from here onwards, maximum negative torque is applied and C to D is the deceleration. That means we want the speed from B to D.

So, D is the point, the horizontal point where we want the speed here that is we want the operation from A to F. So, the moment it come to the correct speed that is the back emf, our motor come to correct speed; we will adjust the voltage such that slowly we increase the applied voltage so that the negative torque, current will slowly reduce, so it will go along the many parallel lines in a horizontal way here, it comes to zero here.

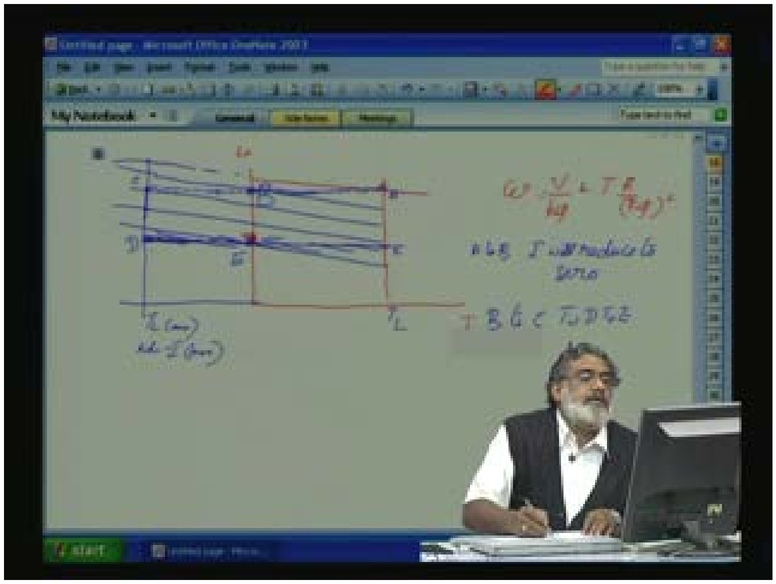
So, these all depend on the electrical time constant but C to D, it is a slow process that depends on the mechanical time constant, machine is slowly decelerating. So, it will go, it will come here, again we apply voltage such that motor should not slow down, we have to apply a positive torque. So, motor will slowly come to this position. So, this is how we have to do the thing. But with respect to time, a typical torque speed characteristic, how it looks.

(Refer Slide Time: 4:38)



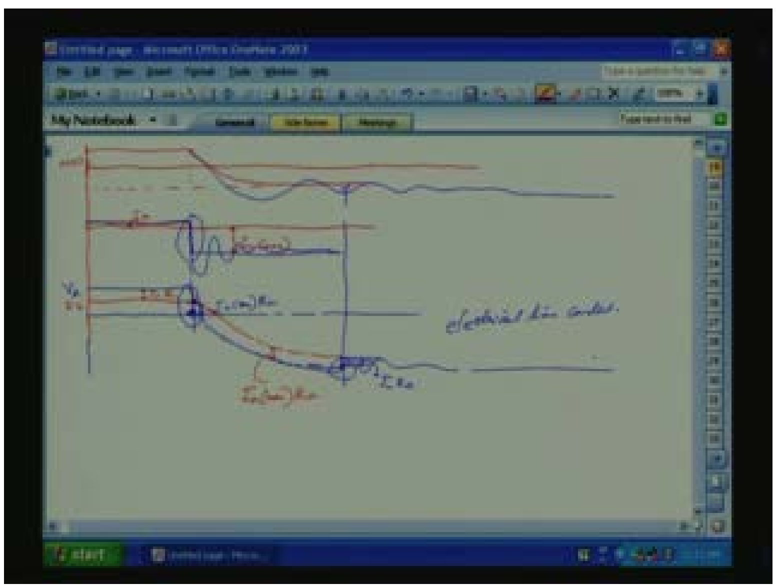
Let us us take, this is our speed N; N, I will take it like this, speed. This X axis goes for the speed. Now, machine is running with a constant speed that means according to our pervious case, the machine is running here, machine is running at A.

(Refer Slide Time: 5:08)



Now, we want to come to F. So, machine is running here.

(Refer Slide Time: 5:14)



Now, we are asking the machine to go to a instead of speed reverse speed reduction, it will go to a negative speed. So, from here, ideally it should go, quickly as good as. But this is not possible, this is a step change. So, the next response is a first order lag with mechanical time constant. It should slowly go and come to the required speed like this and stay there. It should not have transient like this; smoothly go, our controller should take care there.

Then what will happen to that? This is our final speed. So, what will happen to the current here? Let us take the current axis here, armature current. So previously, for this speed and the torque, the armature current was like this, let us assume. This is our I_A. So, may be for clarity, we will do with a different colour we will give. So, this is our I_A. Now, the moment we give a speed command change command, we want to give a negative torque. So, quickly compared to this mechanical, quickly this will come to the maximum, I_A maximum, rated maximum current here quickly. But if you expand this one, this will also with a first order lag, it will go, depending on the electric electrical time constant. But with respect to the mechanical time con this is fast and it will come there and current will stay there till it again reaches that speed.

When machine reaches that speed? Let us see, we are controlling the armature voltage. So, armature voltage; let armature voltage and back emf, let be this is the axis. Let us say, this is till this point, let us say this is the armature voltage V_A. Now, where is the back emf? Back emf will be somewhere here. We can use a different colour; back emf will be somewhere here. This difference is equal to our I_A R_A, this is equal to I_A maximum rated value. So, this is our E_b, this is our E_b.

Now, the moment it changes, what happens? V_A will immediately change here. That means V_A will change, V_A will immediately change and come here such that, so V_A will come here such that, now this E_b this difference will be equal to mu I_A maximum into R_A. Now here onwards, back emf cannot change instantaneously, speed cannot change instantaneously; here onwards, till this speed is reached, we are applying the varying the armature voltage so that armature voltage from here onwards slowly comes here.

So, as the speed decreases, what will happen? We always maintain the I_A maximum. So, this from back emf will also slowly decrease with respect to speed. So, back emf will vary like this such that throughout this variation as the speed varies, we will control this armature voltage such that this drop I_A maximum, that depends on the maximum load current rated motor current. I_A is always like this. The moment it comes here, speed has reached.

Now, we want the previous I_A only required to drive if it is the load is the same. So here, V_A will quickly come down to this point and stay there so that now the new, this is equal to our old I_A and R_A. So, this will slowly reduce from here and come here. So, if you expand these points, this one and this point and this one, this all happens with respect to electrical time constant. That is electrical time constant L_A by armature inductance divide inductance divided by R_A electrical time constant and this speed change from here to here that is due to the electric mechanical time constant. So, all the electromechanical time constant, we will come to that one.

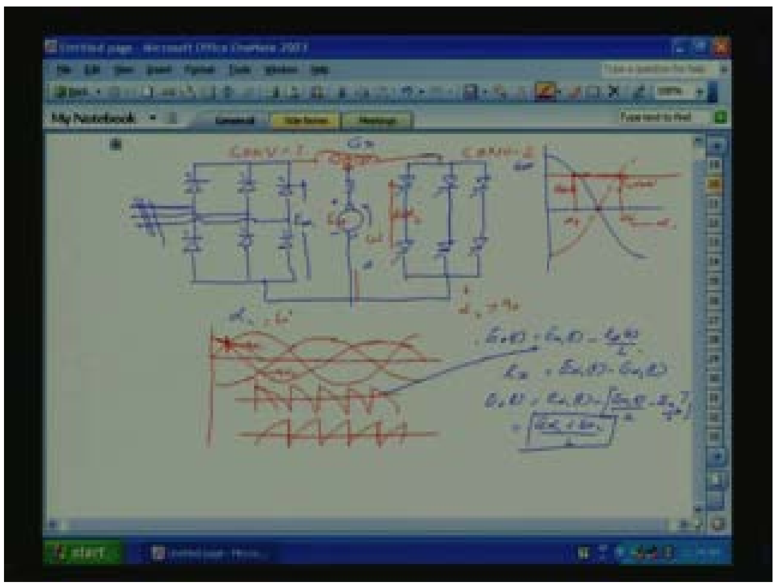
So, what we want? Here the control, all this smooth transition is possible because we are controlling this armature voltage such that always maximum current is negative current is taken from the machine as the speed varies and once it comes to the required speed, quickly we come to the required current for the driving torque.

So, if we do not properly control, what will happen? The machine can go like this and large oscillations and can settle line after some time. So, here also if the control is not proper, this current can go like this, oscillations can happen. So, here also, that reflects here also. Here also, it can get it oscillation. So, instead of settling here, it may if the controller design is not proper, it will take long time. So, we have to design the controller like that.

So, how to design the controller? So, we will like our AC to DC controller; we will form a closed control block and from the block, we will have the speed control and other control like in AC to DC if you require an inner current control, we will also have an inner current control here, then we will choose that controller. So, before coming to that one, AC to DC convertor that is four quadrant operations is possible.

Now, let us take if you use phase control convertor for high power applications, we are using how we will control the four quadrant operation with DC motor or quickly go through that one? And then, how you make the firing sequence, firing control for a phase control convertor? Sin triangle PW, it is easy to generate sin triangle and phase control how you generate, then we will come to the close loop controller design of the design.

(Refer Slide Time: 13:01)



Let us talk about the phase control convertor, how we can have four quadrant operation. Let us take the convertor like this; this is our phase control convertor, three phase like this, this is our mains, our A B C or system coming here, three phase mains. Now, our motor is here connected. Now, if you see here, previously we said we want to take back energy from the motor. So, current has to reverse. But if you see here, here current can only go in one direction because of the thyristor. So, we should have another convertor, we should be able to take current in the opposite direction.

Suppose the back emf, for this rotation, suppose the back emf is here, if I want to reduce the speed in the same direction, rotation, we have to take current; previously current was going like this, now current we should take in the other way. So, we require another convertor connected in an anti parallel way. This is called Dual convertor.

Now suppose, if you have a switch like this which can be opened and closed like this; now for the machine to run in this direction if we want a positive voltage like this, we will close this one and we will give the correct firing angle alpha $_1$ here so the machine is running with a particular voltage.

Now, if you want reduce the speed; what we can do? We can slowly reduce the firing angle, this voltage appearing here that is E_0 alpha $_1$ that is this one coming from here, we can reduce so that the current, this one will slowly come to 0. We can sense this current; once the current is 0, we can close this one and we can open this one. See, this can be opened and this we can close it. So, what happens?

Now, current is 0, machine will slowly send current in this direction. So, we can control this firing angle such that now this voltage is controlled, so this inverter is working in the inversion mode. So, for both the convertor, it is firing angle is equal to cos alpha. So, for one convertor it will be working like this; for other convertor, so this is our E_0 alpha, other convert convertor it should be the other way, this way.

So, for this convertor; this is the rectification mode, this is the inversion mode. So, power is that is voltage is negative. For this convertor alpha if it is rectification rectify mode; then positive will come here, negative will come here. Now, we want the positive here, so it has to go to the inversion mode here. So, firing angle has to for this one, alpha $_2$ should be greater than 90 degree. So, it will be in this direction. So, we will come to that one now. So, we can take back the energy here and once the speed has come to the correct speed, we can slowly increase this one; in the rectification mode, slowly we can increase so that the current can be current from the motor can be made 0 and the moment zero, quickly we can open this one and again we can close this one. So, that way we can control.

See, but here the problem is there is a, this is a slow process because there are switches; we have to sense, on and close. For fast control, automatically the system should or controller should be able to sense and the system should be able without this mechanical switch, it should be able to send power back to the mains as well as receive it also, so four quadrant operation. Instead of that one, what is done is this switches are removed; so, let us remove the switches. Now, this switches this portion, we will remove; now we will connect a reactants here and at the center, this is connected.

So, for this convertor, this is alpha $_1$; for this convertor, this is E_0 alpha $_2$ and this is our speed omega and this is our E_0, E_0 is here. Why this? See, by appropriately choosing the firing angle here, E $_{01}$ and E_0 alpha $_2$, we can make it same that means same voltage like this. For firing angle, for this one if it is this one, for this, it is here, alpha; this is alpha $_2$, this is alpha $_1$ such that both convertor will be having the same voltage. But because of this polarity, if the motor invert, current will go only from here to here.

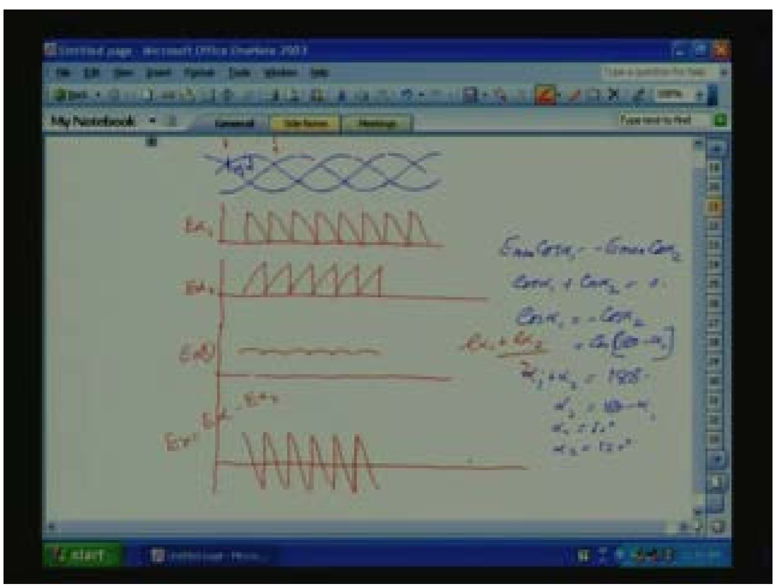
Now, why this inductance is, this is dual convertor in circulating current; see we are talking about the E $_{01}$ and E $_{02}$, the DC may be same, the instantaneous repel may not be the same. Let us take a typical example ABC wave form, here. This is our A, so ABC wave form. So, for the alpha $_1$, it has to be started from here alpha $_1$; alpha $_2$, it has to start from here because this convertor.

Now, for alpha $_1$ and alpha $_2$ for same voltage if you take, so for a particular firing angle of alpha $_1$ is equal to 60 degree if you take, then the wave form will be approximately the repel wave from we can draw it, it will be it will be like this. From here sorry it will be like this, this is 60 degree duration, we can draw it, this is not matching. So, for the convertor one that is this is convertor one, this is convertor two; so with the same firing angle alpha $_2$, the DC voltage is the same. But if you see here for the convertor, other convertor, it will be in this case, in this way, it will happen. So, if you see here, the average for this one and the average for this one are the same but the instantaneous repel are not the same. So, instantaneous difference in the repel has to be dropped that is why we are put this inductance such that we will draw this wave form slowly such that the difference in the voltage should be dropped across the inductance.

So, let us take let us take this voltage is equal to E $_r$ repel voltage, I will take it E $_r$. So, this is stopped at the center point, so E $_r$ by 2. So, voltage across the load, E_0, E_0 with respect to time instantaneous time including repel voltage is equal to this is our E alpha $_1$, not 0 E alpha $_1$ with respect to that is the repel voltage that is this one; E alpha $_1$ T minus E $_r$ $_1$T E $_r$ T divided by 2. Now, we know E $_r$ is equal to because of the center torque, E $_r$ is equal to E $_{a1}$ E alpha $_1$ T minus E alpha $_{22}$. This will include the DC as well the repel part.

So, DC will be cancelled, only the repel will come across this one because both has the same DC. So, inductor will only support the repel current only. So, if you see here, E_0 is equal to E_0 T is equal to E alpha $_1$ T minus E $_r$ by 2 so that means minus of E alpha $_1$ T divided by 2 minus E alpha $_2$ E $_{a1}$ alpha $_2$ divided by T. So, this will come to E alpha $_1$ plus E alpha $_2$ by T. This is the repel voltage coming across including the, coming across E $_0$. Now, for a typical firing angle of alpha is equal to 60, how the wave from will, we will try to draw that one.

(Refer Slide Time: 24:49)



Now, so this is our E_1 or abc. Now, Eb 120 degree phase shifted, Eb. Then, this is our Ec. Now, alpha $_1$, alpha $_1$ is starting from here, so alpha $_1$ is 60 degree. So, alpha $_1$ is equal to 60 degree means it will be here. What should be the alpha $_2$? So, we are firing in the converter one and converter two such that for the convertor one, the output voltage is equal to E max E $_0$ maximum, it is E maximum into cos alpha $_1$ should be equal to E maximum to cos alpha $_2$. That means cos alpha $_1$ plus cos alpha $_2$ is equal to 0. That means cos alpha $_1$ because other convertor is in the inversion mode, so it is more than 90 degree. So, cos alpha $_1$ is equal to minus cos alpha $_2$ is equal to cos of 180 minus cos 180 minus alpha $_2$. So, this shows that alpha $_1$ plus alpha should be equal to 180 degree. So, to get the correct DC voltage for the two convertors if alpha $_1$ is fixed, alpha $_2$ will be 180 minus alpha $_1$. If we can take care of this one, for alpha $_1$ is equal to 60 degree, alpha $_2$ will be 120 degree. Then the DC voltage will be the same. So, lets us draw the wave form now.

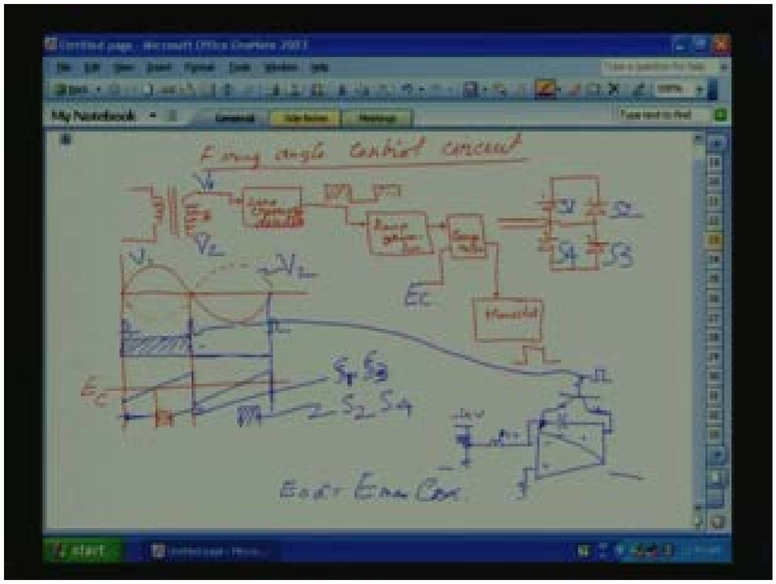
So, this is the alpha, alpha is equal to alpha $_1$ is equal to 60 degree. So, alpha $_2$ should be 180 degree. So, if you see alpha $_2$, it will be from here; 180 degree means it will be somewhere here. So, this is alpha $_2$, it start from here. alpha $_2$ alpha $_1$ is 60 degree, alpha $_2$ starts from here. That will be 180 degree. So, if you draw the wave forms, repel voltage wave form, we can draw it like this for the convertor one, it will be this is the axis.

See, you can see the 60 degree duration repel for alpha $_1$ is equal to 60 degree. What will be for alpha $_2$? alpha $_2$ if you take with 60, 120 degree, it will be like this. Now, A is equal to output voltage will be output voltage will be this one; this is E alpha $_1$, this is E alpha $_2$. So, E $_0$ T is equal to E alpha $_1$ plus E alpha $_2$ divided by 2. So, if you do that one, this will be approximately, repel voltage will be something like this it will happen. This way, it will go with respect to a DC value.

So, this we can draw it. See, any way if you see here, the DC waves, there is repel here. These repel will be repel current and this voltage will be controlled by the armature inductance of the machine. Now, what is our repel voltage for this occasion? Repel voltage that is coming across our circulating that inductance, to suppress the induct circulating current that is E $_r$, E $_r$ is equal to E alpha $_1$ minus E alpha $_2$. If you see here, it will be something like this, here the average value will be 0 to show that. So, average voltage drop will be so this repel voltage will be dropped across the convertor.

Now, see, so far to complete the phase control convertor, all these firing angle all depends on our reference sinusoidal voltage. So, with reference sinusoidal voltage, how do you generate the firing angle? A typical example, many books are available but we will just for sake of continuity and completeness, we will try to give some books, schemes, discuss about that one.

(Refer Slide Time: 31:21)



Let us take a, instead of three phase, let us take a single phase convertor. Three phase can be derived from this one. So, firing circuit, firing angle control circuit; here, this is our, let us draw our convertor here. This is our mains single phase, this is S_1, S_2, S_3, S_4. Now, how do you control the circuit? Let us all the firing angle is with reference to our main circuit, mains is 230 volts. So, to control level, we have to step down that one. So, we will have step down transformer may be 230 to 10, 230 into root 2, that 230 are one in the root 2 is to 10. So, we can have a control level of plus or minus 10 level. So, we have a transformer like this.

We will use a center tapped transformer, so V_1 and V_2. This V give to a zero crossing detector, zero crossing detector, zero crossing detector using operation amplifier we can use it. So, zero crossing detector, the output will be a, what? It will be a, you can make zero cross detector zero to positive. So, when it is positive, it can be it can be like this, zero crossing positive like that. This you give it to a ramp circuit, ramp generation. To a ramp generation, we will give it to a comparator circuit and low comparator using operational amplifier or three one end comparator, each one give it. Here, we will give the control voltage E_c, this variable.

So this, from the convertor output, we can give to a mono shot and we can generate the required pulse, gate pulse duration for the thyristor. So, how it will look? We have the sinusoidal reference, after stepping down, its negative also. So, this positive side is for generating pulse for S_1 and S_3 and the negative the opposite waveform this one, this is for S_2 and S_4. So, this we can get, so V_1 with respect to the center torque; this is V_1, this is V_2. So, this is our V_1 and this is our V_2.

This we are giving to our, we will talk about the firing pulse generation for S_1 and S_3 for the positive half cycle. Same thing can be used for the negative half cycle also. So, zero crossing detector, so zero crossing detector, it will be; now we have a ramp circuit during the positive side. So, ramp firing will be its positive side, this same ramp circuit, we can use it for the negative also.

How do you generate firing angle? And, this is compared with E_c our control voltage for firing angle variation. So, this is our E_c signal, this we can vary. So, when this compare as a point, the mono shot output will give the required pulse, here for S_1 and S_3 and this is for and this is for S_2 and S_4. So, this is for S_1 S_3 pulses and this is for S_2 and S_4, this is for S_1 and this is for S_3. So, by controlling the firing E_c, we can have firing angle at 0 or 180 degree. Now, how do you generate this ramp? It is very easy.

See, give to an operational amplifier circuit, I will draw this one here. See, let us take using operational amplifier, many a ramp generator circuits are available in the book, so you have this one. Some, 22 K you can put it and a 10 K port you can make it minus 15 volt, so give it here and there is a capacitor here, you can choose your capacitor so that R_c time constant, we can adjust so that this capacitor will slowly charge. Then this charging portion charge at this point at zero crossing, we should discharge it. So, for that purpose this zero crossing points, you have detect again through a mono shot at these points and here also small pulse.

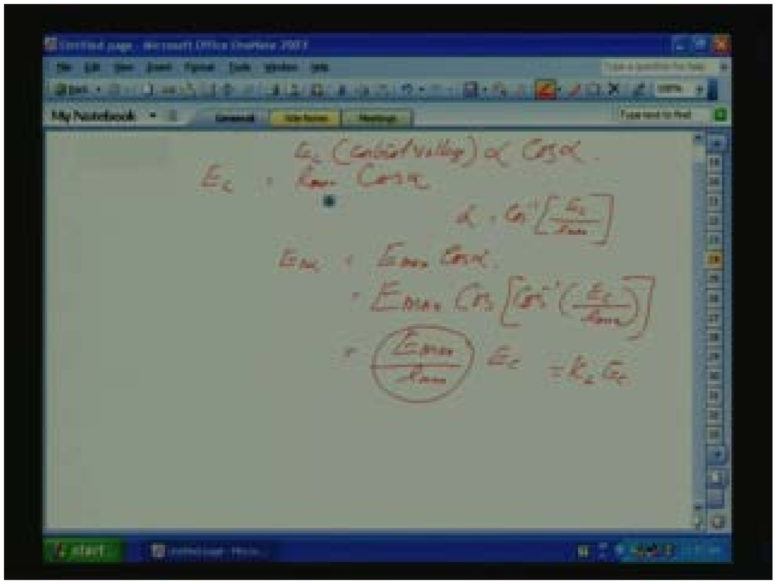
These pulse at this point, we should capacitor should discharge quickly. So, for that one, we will connect a transistor here. We can put a small resistance also here and give the pulses here, these pulses, these pulses we can give it here. So, whenever the zero comes, it will quickly discharge. Output is always positive negative, it goes like this. So, ramp we can generate. This is a typical circuit, this is this point here, this comes here, this across here.

So, whenever the pulse is there, it will quickly discharge and when the pulse is not there, it will charge that is pulse is not there that is these pulses are not there, this is the point and by varying the E_c, we can have the firing angle control from 0 to 90. So, in this circuit if you see, for phase control convertor, we know it is E_0 alpha is equal to proportional to not alpha, it is cos alpha. For three phase, it is we know, it is E $_0$ alpha. The output is equal to E maximum into cos alpha.

Now, see this is for the single phase. Suppose if you want to make it for three phase; what you have to do? See, S_1 and S_2 and S_3 are switched 180 degree phase shifted with respect to S_1 and S_4. Now, in our three phase circuit, this A phase and B phase, C phase are 120, 120 degree phase shifted. So, instead of generating this 180 degree, you generate 120, 120 degree pulses phases by step down the mains. Then for the each step down voltage, we generate this pulse from the individual, based on the individual phases; generate this pulse and give to the top and bottom. And for the next one here, B phase, from the B phase top and bottom you generate and C phase we can generate it, 120 degree also possible.

But if you see here, output is proportional to not alpha, our V R varying the output based on this alpha, E_c is proportional to, we are varying E_c from zero to alpha here, 180 degree. So, the firing angle that is the alpha here, from here to here, here to here; alpha is varied from 0 to 180 degree with E_c vary. But output is very proportional to cos alpha, this is not a linear control. For linear control, input E_c varies, output also should vary proportional to E_c. So, how we can do it? This is called ramp comparison technique for simple power supply generation we can use it. For motor drive application, we should have linear control. So, there we should use cosine comparison.

(Refer Slide Time: 41:43)

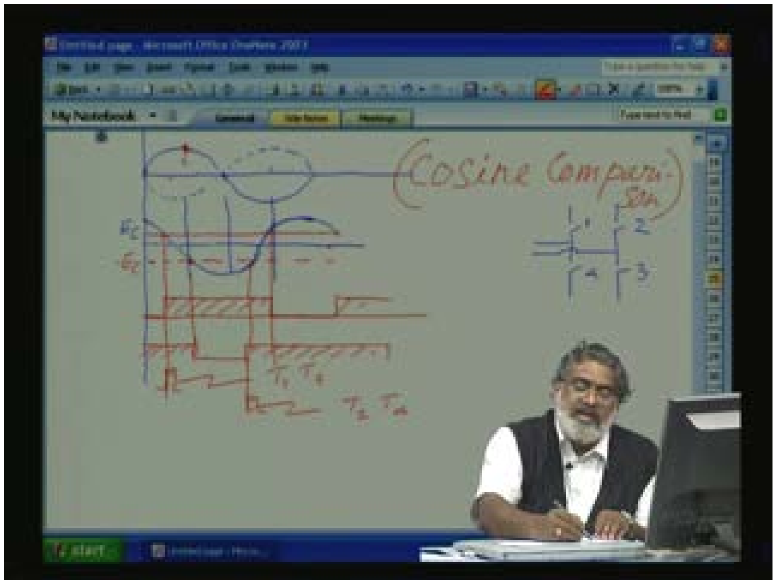


See, we want E_c to vary not proportional to alpha, E_c to vary our control voltage; E_c to vary proportional to cos alpha. Let us take, our control voltage E_c is proportional to cos alpha that is some E maximum into a control voltage, E maximum into cos alpha. Now, what is alpha? Cos alpha is equal to, from this one alpha is equal to cos inverse E_c by E maximum. Now, our output voltage E_0 alpha is equal to E_0 E max the maximum for alpha firing angle alpha is 0 into cos alpha for a three phase fully controlled convertor.

This, we substitute this one, if you are varying E_c, E c is proportional to cos alpha that means our control voltage E_c control voltage is proportional to cos alpha. So, here it will be E max into alpha we are substituting, cos of cos inverse E_c by E max, it is the control voltage maximum. This will be equal to E maximum divided by the control voltage maximum may be plus or minus 10 volt plus into E_c.

So, here if you see, if you vary the E_c proportional to alpha, our output voltage will be this is constant will be proportional to E_c. That means this is equal to, this is always constant output maximum. So, this will be equal to some constant K_2 into E_c. So, output will be proportional to E_c. This is called cosine control. So, let us say, how it can be done.

(Refer Slide Time: 43:59)



Again we will take, for single phase only we will take; three phase, corresponding reference sin wave 120, 120 degree we have to generate from the mains. Now, let us take a single phase control. I am representing switches like this, this is 1, 3 and 2, 4; this is our wave form and let us draw the wave forms. This is our reference wave form, step down wave form from the mains. This is the negative part.

Now, we want E_c to proportional to the cos alpha. So, what we do? The same E_c, here we will integrate the main this wave form and make it a cosine, we will generate a cosine wave form here. If you see here, the cosine wave form will be like this, this way it goes. Now, we will generate E_c positive as well as negative. This is E_c positive, let us take E_c positive as well as E_c negative, minus E_c. Now, we will generate comparison, using comparators we will generate various signals like this.

So, let us take the positive side here, then again it will be 0, then again it will go high here, negative side using comparators here, we generate signal like this. Again, we will go like this that means that is whenever we are comparing E_c with our this wave form, cosine wave form; then all these points, positive going points that is we will generate a pulse and here also, here positive going here, next one.

This one, we will give it to T_1 and T_3, this one we will give to T_2 and T_4. So, firing angle is proportional to cos alpha. When firing angle is equal to 0, firing angle is here, it will come, with respect to main at 90 degree we are finding. So, cos 90 is equal to 0, output will be 0. When the firing angle E_c is maximum, we are firing at alpha is equal to 0, we will get maximum output. So, we get maximum positive and voltage control for positive as well as negative which are which is not proportional to cos alpha, it is proportional to alpha. That means proportional to E_c that is when E_c is maximum, output is maximum. E_c is maximum here means automatically firing angle is 0, so output will get maximum and variation of E_c is proportional to cos alpha. So, it is comparing with cos alpha wave. So, this way we can have output voltage wave form.

So, many text books give circuits, how to generate for cosine comparison, cosine comparison cosine comparison that is control voltage is compared with a cosine wave, cosine wave derived from our step down mains wave form. So, this is for one phase. For the three phase system, the next 2 and 3 will be at B phase. So, you generate another sin wave which is 120 degree phase shifted and generate its own cosine wave form and the next one, 250 generate cosine wave and fire it like this and generate only these pulses T_1 T_3. So, this way you can have voltage control, cosine comparison for voltage control.

Now, so far we have studied about control rectification, AC to Dc convertor using phase control convertors, its problem, what is output voltage, how do you control the firing angle and what way the output varies with firing angle and how we can generate the firing pulses, also how we can have a convertor with a four quadrant operation that is a dual convertor and then circulating current to take care of the repel voltage level; we have talked about it.

Then we also studied about front end convertor has the power factor problem, then we have studied about how we can control the front end convertor, the phase control convertor, a semi convertors; we have studied this portion also. Then we have talked about four quadrant chopper, four quadrant choppers is a single phase inverter circuit where we can have four quadrant operation and proper PWM controller, we can have a unity power factor. So, various convertor controls we have studied.

Now, we have introduced in last class, how a speed control of the Dc motor, we should do such that we should have a smooth speed change and we have to accelerate and decelerate the machine as quickly as possible within the permissible time constant of the system without much transient; how we can do it and how the response should look like, what we talked in the beginning of today’s class.

In the next class we will do the close loop control. We will draw the closed loop block diagram for the separately excited DC motor control and how we choose the controller parameter same like an AC to DC convertor such that the motor will respond, we will have the optimum response without too much transients. This we will study in the next class.