Power Electronics

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Lecture - 3

Controlled Rectifier Part – II (Three Phase)

Last class we concluded with single phase half controlled converter. That means we have only even though the positive and the negative cycle we are making use of but the control, we are doing only with 2 devices and the other two are diodes. Then we found the voltage, the voltage vary, output DC voltage, it can go from 0 to positive value.

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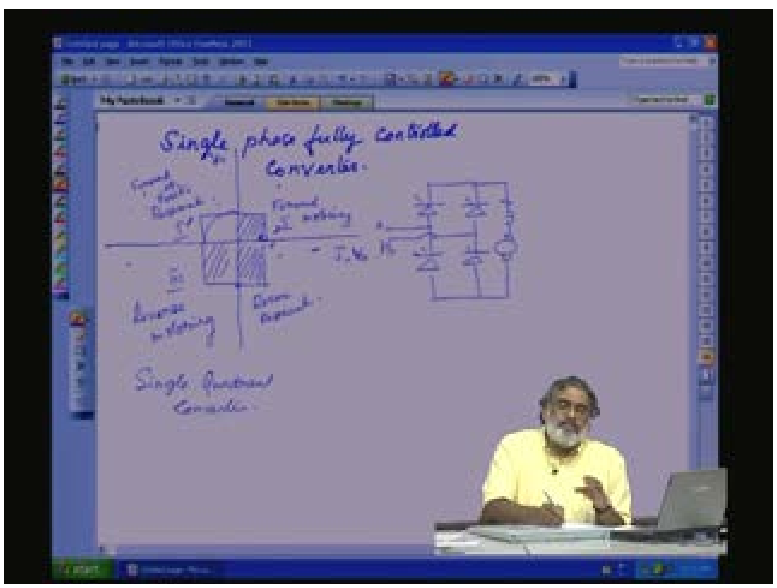

But many motor drive applications, we want 0 to positive as well as 0 to negative also that means the DC voltage should be variable from minus value to 0 to the positive value. Then what will happen to the quadrant region if you see in this figure with the voltage here?

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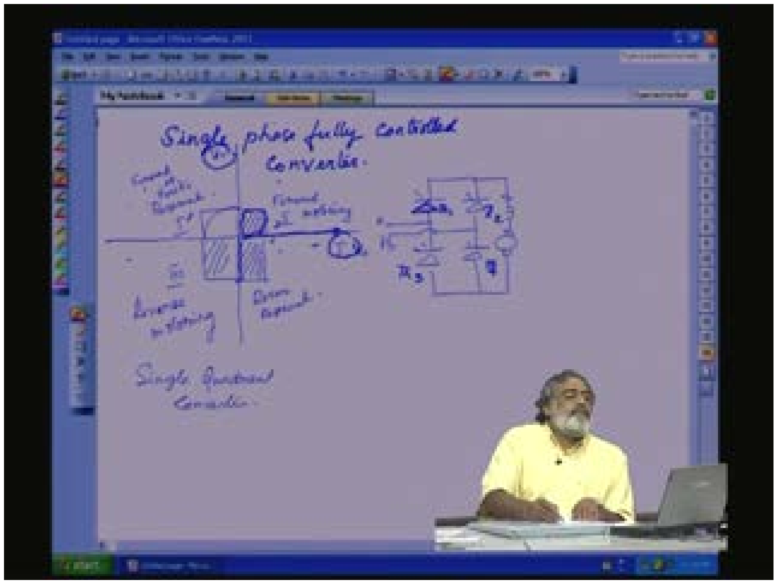

That is this part voltage and this part we have I_a, voltage can change from positive to negative but the current will be only in one direction that is this direction that is this direction. So, current is only from the positive that is from the source type to the load. But if you see here, two quadrant operations is possible that is one is this quadrant, other one is this quadrant; the reverse regeneration is not reverse regeneration, forward motoring, this part is possible. The current is one direction, this part is possible, not sorry not the other part, this part sorry this part is possible.

So, we will change it. See, when the current is voltage is negative and the current is positive; we can have only this direction only possible. So here, the four quadrant operation, so here the current can conduct only in one direction because of the thyristor or the diodes, for the silicon wire. So what will happen? Current will go only in the positive direction but the voltage can go in the negative direction. Voltage cannot go in the negative direction for the previous converter.

Now, if we use all thyristor instead of diodes; all 4 thyristors are shown here in this figure. That is thyristor 1 that is Th 1, then we have Th 2, Th 2 is this one, then we have Th 3 here, then we have Th 4. So, if we use this one; we have all 4 thyristors, so we will soon we will see that we can have voltage in the negative direction also. So, we can have two quadrant operation is possible. So, we will come to that one now. So, we will go, we will study now, single phase fully controlled converter. So, let us go to the next page now. So, we will talk about single phase fully controlled converter. That is single phase fully sorry that is a fully controlled converter.

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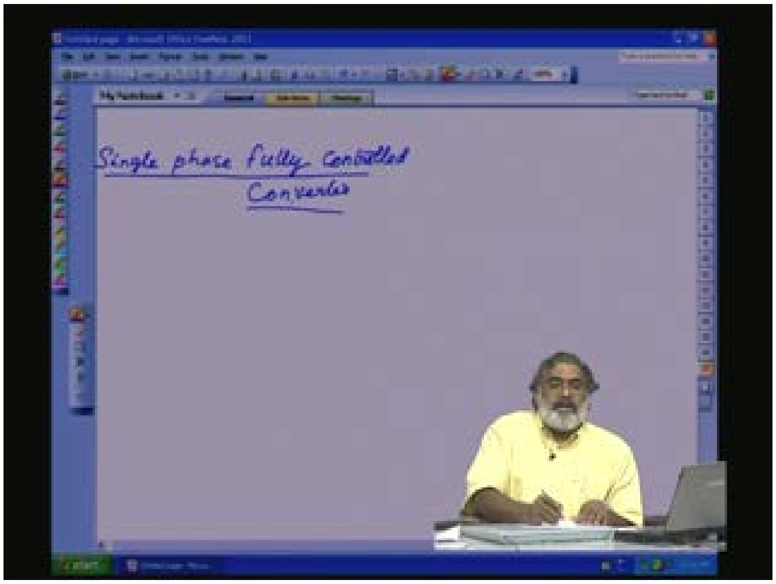

So, let us again draw our power circuit schematic.

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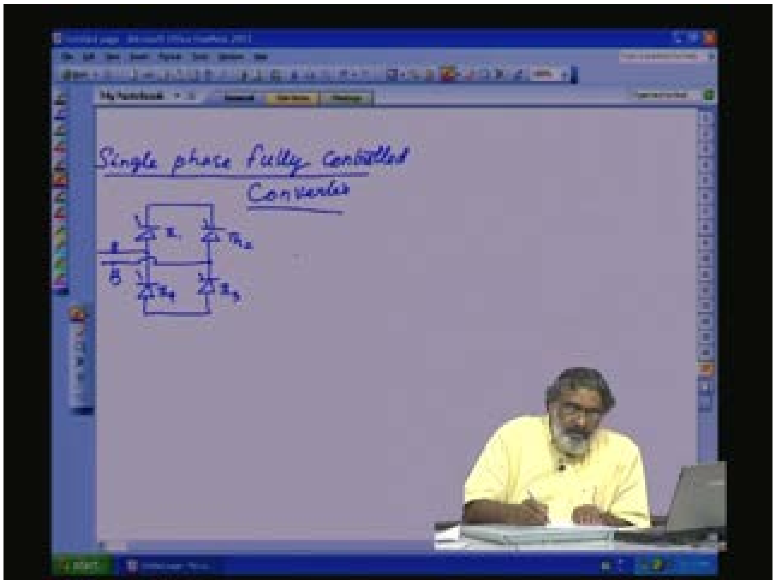

Now, thyristor 1 that I will mark it as Th 1, then you have Th 2, here you will have bottom also we will have controlled device that is Th 1, Th 2, Th 4 and Th 3. This is our mains, so here we will represent as a and b here, phase voltage V_4. Now, see here, all the 4 devices we can control. So, how we can get here positive as well as negative DC voltage? We will see now.

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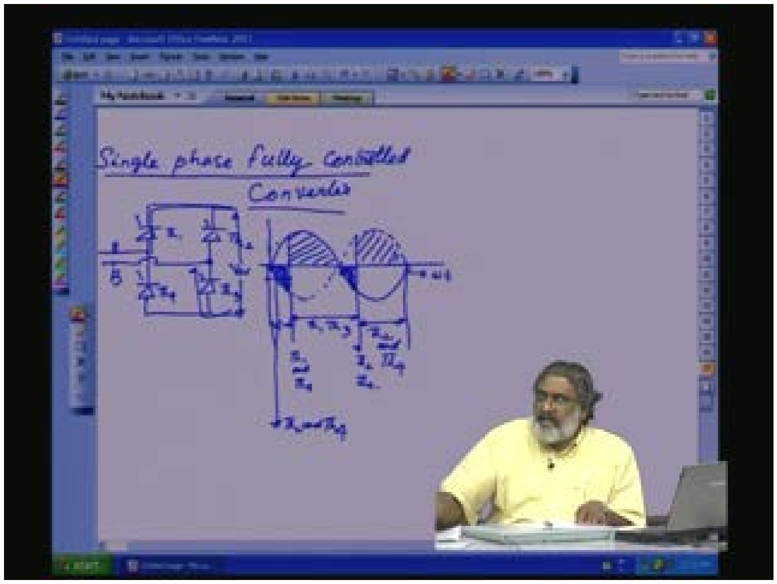

Let us draw our mains voltage V_4 here, this is V_{ab} and the inverse also we will put here like this. Now here, this is our y axis that is amplitude, this is our omega t axis. We are firing with respect to a firing angle alpha so that means we are firing here. So, if you see here, alpha starts from here. When we fire this one, which are the thyristors we have to fire? That is V_{ab} is positive at the positive side. So, whenever we fire a thyristor, the most forward, the only forward bias devices will only be conducting. So, we have to fire the forward bias thyristors.

If you see, a is positive here, so during the portion Th 1 will be forward biased; this point is negative that is this point is negative, so Th 3 will be Th 3 will be also forward biased. So, at this point, we will be turning out Th 1 and Th 3. So, till that what point, it will happen? So, next thyristor, so for symmetry operation, if we are firing Th 1 and Th 3 here that is Th 1 and Th 3 here, the next thyristors for symmetrical operation during the negative portion; we should also same firing angle alpha, we should fire next thyristors.

That is at this point, you will be firing Th 2 and Th 4. So, if you see here, till this point, this part of the input mains will be coming across the load. So, the load we have marked, we can assume there is a load here, across this one that is V_0, here, across this portion that is our V_0 alpha. So, Th 2 Th 3 will be fired. So, what will happen when the voltage goes negative here? We are assuming the load is highly inductive, so current will be flowing through this path to the load and returns through this path. So, the moment voltage goes negative, current cannot die instantaneously. So, the di by dt changes, the voltage negative; so the current will slowly slow down. So, load will force the thyristor to conduct till the next 2 thyristors that is Th 2 and Th 2 are turned on.

So, the load will keep on conducting; Th 1 and Th 3 will keep on conducting during this portion. So, during this portion, Th 1 and Th 3 will be conducting. Now, when again we are turning on Th 2 Th 4, this full portion that is upto here, Th 2 and Th 4 will be conducting. So, what happened to this portion? This portion also, if you have continuous operation, this portion also will be that is this portion also will be Th 2 and Th 4 are conducting.

So, if you see here; whenever a thyristor, two groups of thyristors that is 1 top and 1 bottom are turned on only, the previous conducting thyristor will be switched off. This is natural commutation because from the mains voltage without any extra circuit, we are trying to turn off the devices this is called natural commutation.

So, depending on the firing angle, the negative excursion can go still further. So, what will happen here? There is a positive side positive part of the voltage wave form coming across the load and the negative portion also coming across the load that is this portion that is here also. So, average value, if you take like the previous case, if you find out the average value, integrate the waveform that means we are trying to find out the area, the positive or negative, the total area will slowly get reduced, positive area will slowly get reduced because of the negative conduction. That way the average value will get reduced. Let us take a case where positive or negative are equal that is the case like this. We will go to the next figure.

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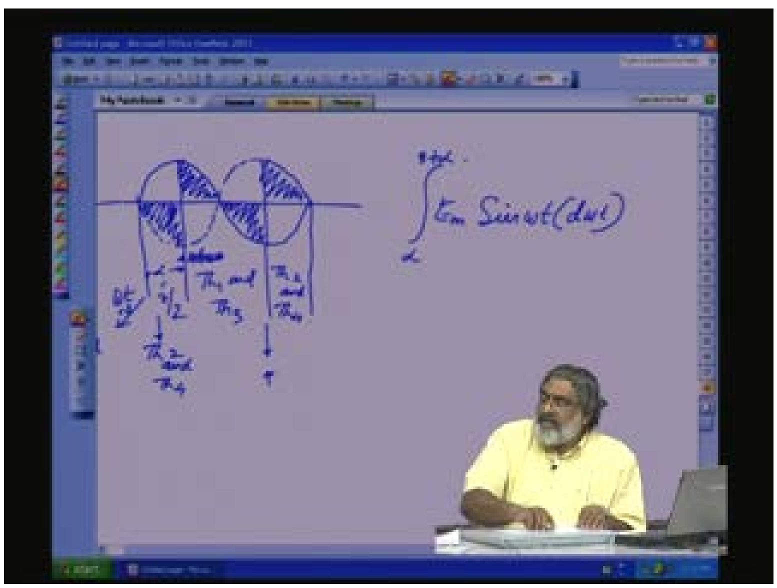

So, I will draw the waveform; this is our V_{ab}, this is our the V_{ab} negative. Let us take a case where positive or negative are equal that is this portion. That means from the symmetry of the figure V_{ab}, we know alpha is equal to 90 degree is equal to omega t is equal to pi by 2. Then what happens? There is equal positive area and equal negative area that is here. This is positive, this is negative and this is positive.

So, as before from the previous circuit, this period Th 1 and Th 3 and this period Th 2 and Th 4; again this period, Th 2 and Th 4. So, if you see the 2 pi s that is Th 1 and Th 3 and Th 2 Th 4, they will be conducting for irrespective of the foreign angle, they will conducting for 180 degree duration but here depending on the firing angle, the duration of the 180 degree period that is 180 period during that period, the two pairs either Th 1 or Th 3 or Th 2 and Th 4 are conducting, slowly get shift and the positive and negative area becomes equal.

So, if we find out for this equation the average value; how, do we find out the average value? We are integrating the Em sin omega t d omega t. We will be integrating between sin omega t sin omega t omega t series omega t 0 will be here, omega t is equal to 0 sorry omega t is will be for sin omega t, it will be omega t will be at this point. Here is the omega t equal to 0 sorry so omega t will be 0 here; omega t will be 0 here.

So, what is the limit of integration? Lower limit is equal to alpha, upper limit is equal to pi plus alpha. So, the next firing next thyristor is fired here, alpha starts from here. So, for the sin omega t, this is pi plus alpha, here it will come. So, pi plus alpha. Now, if you see for present dashed area integration, the positive and negative will be equal. So, that average if you want, it will be 0. So, during this portion, during this firing, for this firing angle when alpha is equal to pi by 2, the output V_{dc} will be 0.

Now, let us say the load is highly inductive or with back emf load whether it can send power by from load to the source; then what will happen? The thyristor can be forced to conduct that is Th 1 and Th 2 can be forced beyond this region also. Let us take a typical example. Again, let us go to the next page again also. Let us draw the waveform here.

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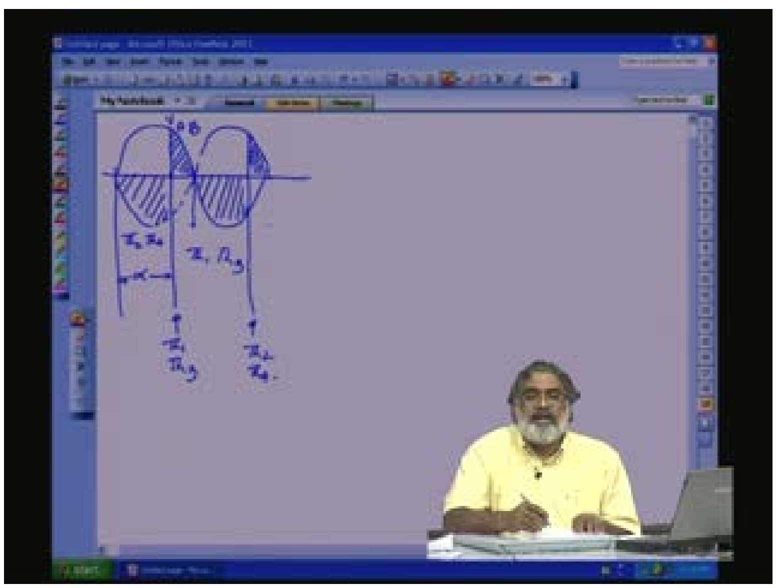

So V_{ab}, this is the negative part, this is V_{ab}; let us take the firing angle starts from here, let us take we are taking the firing angle here, alpha. So, at this point, here, we will be turning on Th 1 and Th 3. So here, the moment it turn on assuming its continuous operation, this much positives area will be shifted to the load side. Again, same equal distance starting from this point, the next thyristor is fired that is this is somewhere here. At this point, we will be turning on Th 2 and Th 4.

So, till this portion, negative portion if the load is highly inductive, it will force Th 1 and Th 3 to conduct. So, at this point if you see, during this portion, the negative side is more than the positive side. Again at this point, the voltage polarity or the part of the voltage waveform coming across the phase will be positive.

So, this will keep on continuing. So, till the firing angle is concerned, this portion also if you can see for study state operation, this also will be during this portion also Th 2 and Th 4 will be conducting Th 2 and Th 4 and this portion, Th 1 and Th 3 will be conducting. Now, if you see the previous integration, if we can see, we can see that what will happen? The net average voltage is negative. So, the load is capable of forcing the current in the negative portion also. That means that is road is capable of regenerating; then we can have output negative also negative voltage also output DC.

So, let us find out the general equation for this semi for this single phase fully controlled converter with firing angle alpha varying from 0 to pi, theoretically 0 to pi. We will come to the practical limitation later. So, what happens? When the voltage is negative, current is always in one direction. So, power can be positive as well as negative. So, we can have two quadrant operations. What you mean by two quadrant operation?

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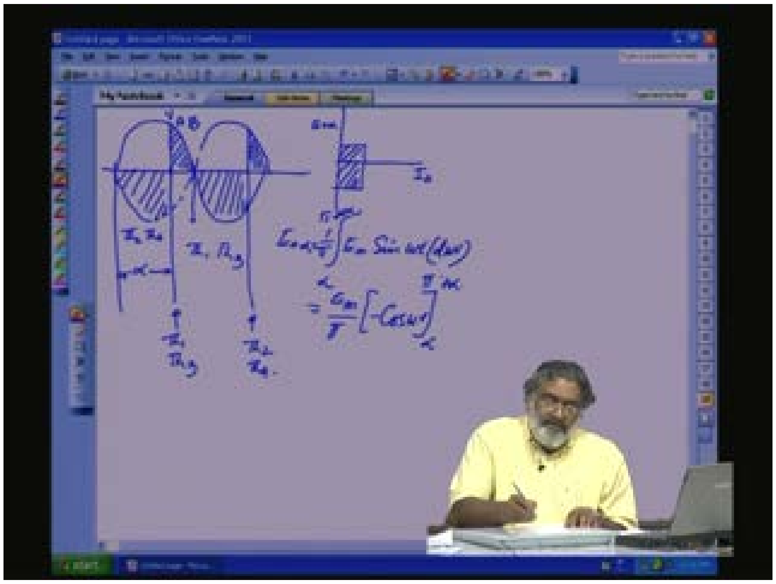

If you have axis here, this is our E_0 alpha, the output voltage with respect to firing angle, this is our current I_0, then we can have operation in these two regions, two quadrant operation is possible. Now, let us find out what do the general output DC voltage equation where we are worried about the output DC voltage with respect to firing angle alpha. So, let us V_0 alpha is equal to alpha to pi plus alpha Em sin omega t d omega t.

Now, you know integration cc, this is equal to Em; Em is the peak value of the sinusoidal voltage, Em by when you integrate, we have to find out the value, we have to find out the average value also that means it has to be divided by 1 by pi. Previously, it was 2 pi, why 1 by pi? The periodicity, every pi it changes. So, the period is pi not 2 pi as before. So, you will have Em by pi into minus cos omega t integrating limits alpha to pi plus alpha. No, this easily we can integrate it symbol ((… 20:39)).

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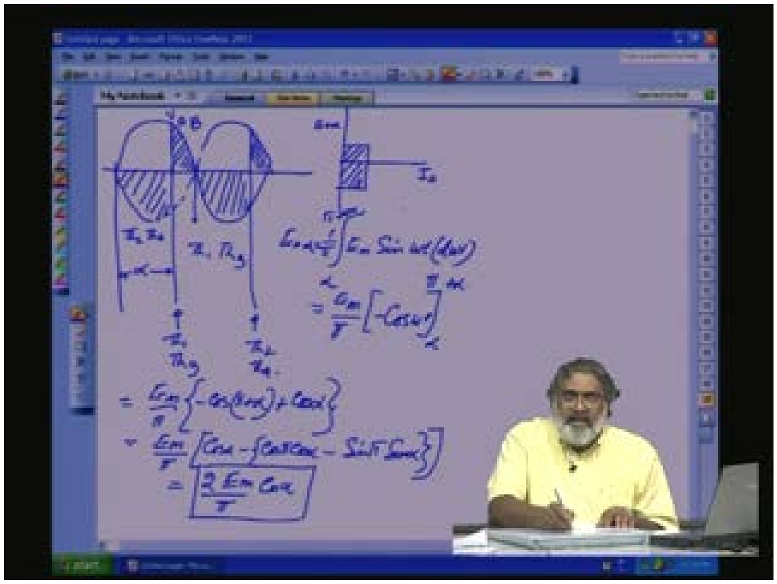

So, this will equal to Em by pi minus cos pi plus alpha plus cos alpha. So, this will be equal to Em by pi cos alpha minus cos pi plus alpha, we can cause a plus b form. That is cos pi cos alpha minus sin pi sin alpha. This will finely come to Em by pi, you can derive this one by cos alpha. So, here also we found previously, it was 1 plus cos alpha. Here, the output DC voltage is proportional to cos alpha. This is for a single phase fully controlled thyristor converter.

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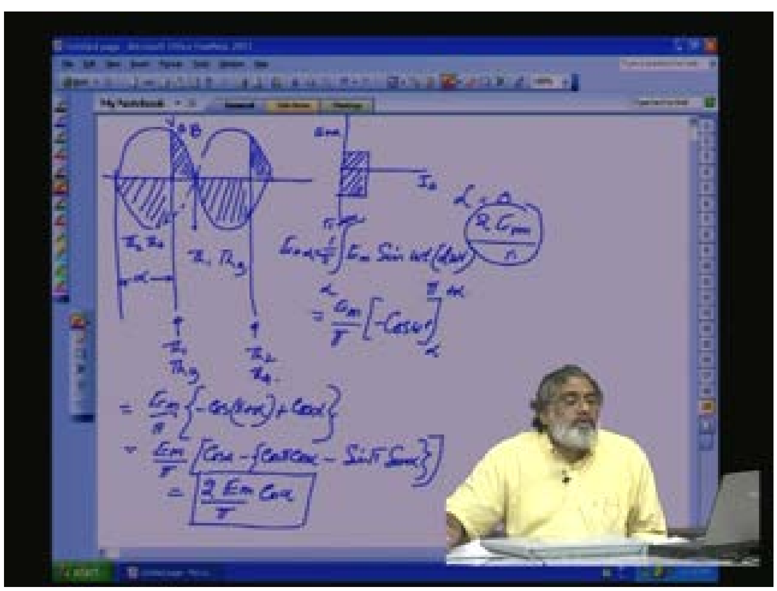

Now, let us see let us see if alpha is equal to 0 that means firing angle starting at the zero crossing of the waveform. Then what happens? It is equivalent like a diode. So, you will have single phase rectifier fully rectified waveform like all the thyristors are replaced with diodes. So, final, for a diode, for a diode case, single phase converter, AC to DC converter with diode; the output maximum voltage is will be equal to 2 Em 2 Em by pi. This is the one you will get.

So, what we have studied from the single phase case? We have gone through a half controlled converter where you want only the voltage 0 to positive. You can appropriately choose the diodes, two diodes and we can have only the control function using only two thyristors. Now, if you want to have the output voltage both positive and negative, then we should have gone for a full three phase fully controlled converter where the maximum output voltage will be 2 Em by pi for a firing angle alpha is equal to pi or for the zero voltage, output DC voltage zero, you should have firing angle alpha is equal to from the equation you can alpha is equal to pi by 2 that is 90 degree, then cos pi by 2 will be 0.

Then the next when for negative maximum, you have to have firing angle alpha is equal to pi assuming the load is able to send back that is force the thyristor to conduct in the forward direction that is load is able to regenerate back to the source. So now, that way, we can have two quadrant operation is possible. But we have used only single phase rectification. Some many applications for high power where more power is required, we cannot draw all the power from the single phase. Then, you may have to go for a three phase rectification so that output voltage will be more, also the output repel that is also very important.

So far, we have not talked about the repel content; we are assuming that load is highly inductive, the repel frequency will be high for the repel frequency, then impedance l omega will be higher and current will be repel current will X plus. But for the single phase if you know the symmetry of the waveform, we can see the repel frequency will be two times the input frequency.

So, the harmonics, the repel frequency, the harmonic and frequency also shifted to the higher to the frequency say compared to the input frequency. Now, if you go for three phase rectification, we can have increase DC voltage. At the same time, the repel frequency can be either three times or six times depending on whether it is half bridged converter or fully controlled converter.

So, let us start from the half bridged converter. So, in many of the text books, it is called three phase midpoint configuring, half bridged. That means we are trying to do only with the positive side that is one side only. Let us see the configuration, let us go to the next page. So here, three phase midpoint configuration, midpoint configuration.

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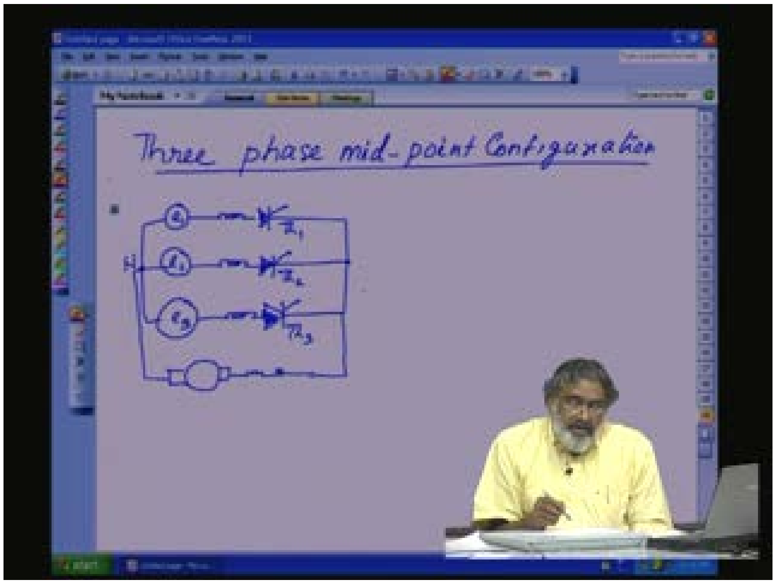

So, our three phases or AC source; let us represent it by source e_1, it can be a_1 b_1c_1 also but I will put e_1, then e_2, then you have e_3. So, this is our neutral, this point we will say as N, our three phase mains neutral. Then we will have I have put some inductance here, I will come I will talk about that one later, some small leakage inductance. Then you have the thyristors according to our source, source e_1 e_2 e_3. We can also name this one as Th 1, Th 2, Th 3.

So, we will more talking about the diodes and you know from the single phase technique, for hiring angle alpha is equal to 0, we will get the equation for a diode. So, thyristor will give the general equation whether diode or thyristor control rectification. So, we will start with thyristors. Then where the load is connected? Load will be connected here at this point assuming we are using for high power operation. Let us a take a DC motor load, this is the inductance and the armature inductance and the resistance here, it is like this.

Now, let us see how, what we have to know about when we are going to fire the thyristors? We know for the thyristor to be turned on, it should be forward biased or we are using natural commutation. Natural commutation in the sense, the incoming thyristor; there is a thyristor which is turned on now turned on and the corresponding voltage phase voltage at that thyristor when it is turned on, we will assume the thyristor voltage again on thyristor is 0, thyristor is turned on, the top is negligible and that phase voltage should be able to reverse bias the previously conducting thyristor and should be able to switch off immediately.

So, this point, we have to take care of when we decide about the firing angle range. So, for that one, let us draw the three phase. Previously, we are drawing about the single phase wave form; now let us draw the three phase wave form.

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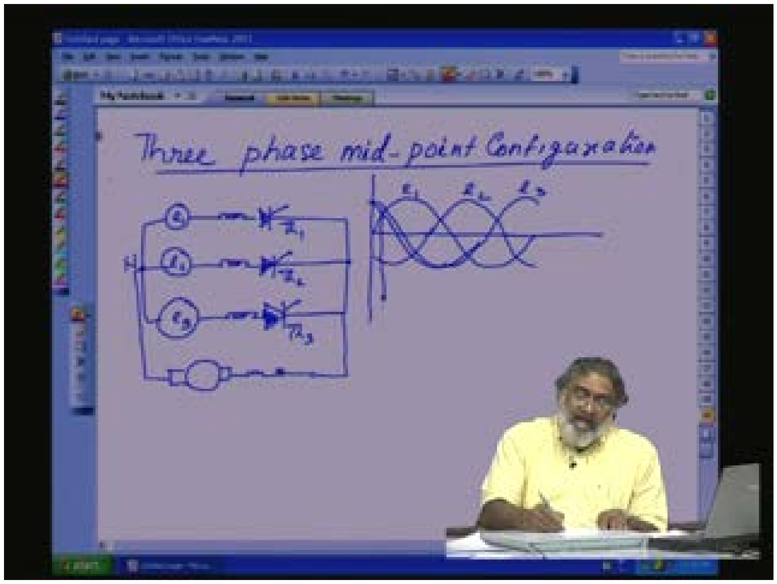

So, I will try to draw a symmetric three phase waveform. This is the 120 degree one, then you have this is our e_1 e_2 and e_3. Now, let us take the acceleration with respect to thyristor one. So, when the thyristor one is turned on, if you say e_1 e_2 e_3 is taken, the previous conducting was Th 3. So, Th 3 means this is the phase voltage waveform that where in that limb only the Th 3 is connected from the figure; so, this one. So, when the thyristor connected to the e_1 phase is turned on; as I told before, the e_1 should be able to turn off Th 3. So, we are talking about 1 2 3 sequence.

So, at this instant or instant from that onwards e_1 should be positive than e_3, then only e_1 can reverse bias e_3. If you see here, when T 1 is turned on at this point, full e_1 will come across Th 3. Previously, T across conducting, it will come here and Th 3 will be e_1 is more positive than e_3; so thyristor will be reverse bias and we can assume that thyristor will be immediately switched on.

So, starting point of e_1, assuming we will assume the thyristor conduction is instantaneous, the starting point of turn on is this point. So previously, for single phase, alpha $_0$ was when the zero crossing. Now, if you see for a three phase, alpha $_0$ is equal to for a sign wave it starts from this degree is equal to 30 degree that is pi by pi by 6. After that only alpha $_0$ starts, the firing angle starts. We can ensure the firing angle so that label commutation will happen. So, this is the starting point of thyristor one Th 1.

So, we can turn on Th 1 here, at this point also we can turn on, at this point also, at this point also we can turn on, at all these points the voltage given will be greater than e_3. So, if you take the region, the duration of the region along which e_1 is always more positive than e_3 is this region. That is from here to here, this region. So, what do the advantage here? If you see here sorry we can fire thyristor Th 1 at any of this point with respect to e_1 that is from here to here. This is the firing range.

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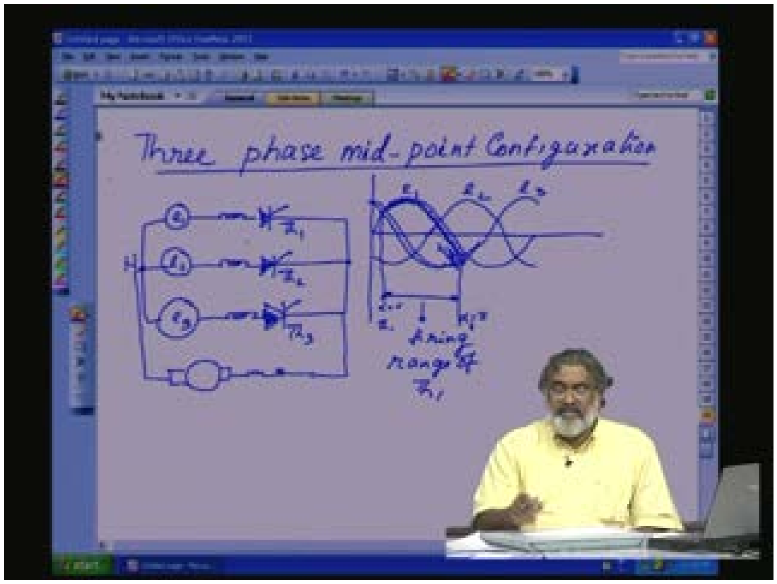

Alpha, firing that is gate pulse you can give it to firing range of Th 1 so that Th 3 will be, the previous conducting Th 3 will be successfully switched off. Now, what do the range? Firing range is a full one, there is a 180 degree range is there. Alpha can be zero, alpha can be 180 degree here, alpha also firing angle for thyristor one as alpha $_1$; alpha $_1$ is equal to pi.

So, anywhere we can turn on thyristor assuming the load is highly inductive; load will force the thyristor when the voltage also goes negative. So, at this portion, the e_1 voltage, at this portion if you see here, the e_1 voltage is going negative here, from here to this point. So, this is a firing range. So, also we should know for symmetry operation, we should also at equal duration, for both the output DC watts, so constant DC; every thyristor should forward the same firing angle with respect to its starting point.

And three phase, for three phase operation, so here, it is if you see here, there are 3 thyristor. Each thyristor will be conducting for 120 degrees. 123 into 3 is 360 degree and firing angle range is alpha to alpha $_0$ to alpha is equal to pi. This is true with the previous single phase also but alpha $_0$ was equal to omega t_0 for our sin omega t. Here, alpha is equal to 0 means for sin waveform, omega t is equal to pi by 630 degree.

Now, why I put this inductance here? These are some of the particle limitation. We assume that previously the conduction is instantaneous but there will be for any thyristor to turn on and turn off, there will be some finite time required that is turn off minimum. So, even though Th 1 is turned on, at any of the point as marked here; Th 3 will not be immediately turned on. it will take some time. So, momentarily there is a short circuit Th 1 and Th 3 is conducting. It can be a converter grind all times, it can be microsecond range 20 to 30 microsecond range, it can be both Th 1 and Th 3 is on.

So, during this portion, the mains are e_1 e_2 and e_3 are short circuited. So, heavy circulating current can flow. To take care of the difference in voltage and to avoid the various heavy short circuit current, these inductance are provided in series with the device, small inductance. How to come design this inductance? We will come to that one later. That is very easy.

You know, if for a thyristor is a taken, what is the T of minimum? So, during the T of minimum, these both inductance voltages across the inductance should be the difference between e_1 and e_3. So, based on that one, we can decide the inductance and for a highly output DC voltage with much repel current, for DC current, we can assume the drop across the inductance is negligible. These are theoretical assumptions to start with but there are practical polo's associated with it.

We come to the practical problems because of the non-ideality of the devices and the other components in the power circuits later. Let us see, here also, our aim is to find out the output voltage with respect to the firing angle. The firing angle also, it can vary from alpha to pi by alpha to alpha $_0$ to alpha pi is equal to pi. Let us find out the output e_0 alpha for this one. Let us go to the next page. So, expressions for the output volt with inductive load, here, for a three phase midpoint configuration; so, let us find.

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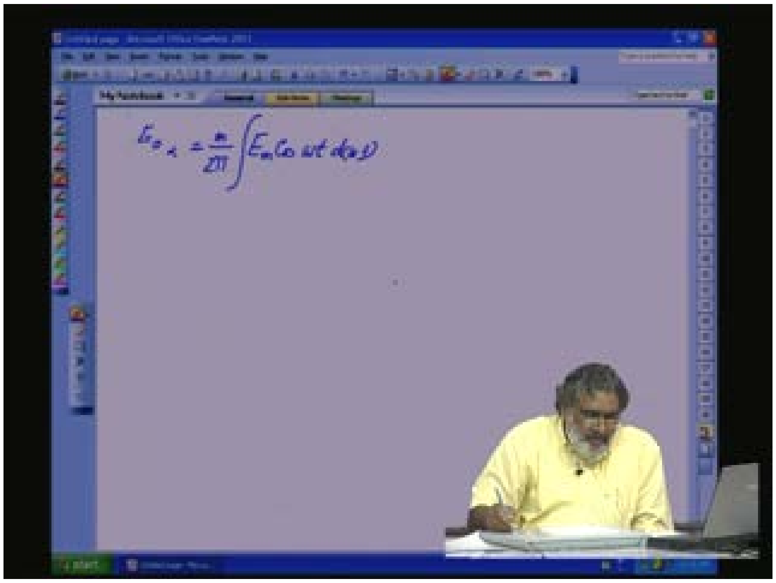

This is our e_0 alpha that is equal to… as I told, every device will be conducting for 120 degree that means period is equal to 120 degree. So, for a three phase, what is the period? Period will be 2 pi by 3, so for a three phase. Then, what is that for a general m phase? It will be, now we will be deriving with for a general m phase to more generalize it. So, it will be 2 pi by m. So, the average value that we divide by the periods; so for three phase, it should be 120 degree that is 1 divided by 2 pi by 3 for a general m phase, one divided by 2 pi by m that will be equal to m divided by 2 pi, then integrate.

Now, integral limit, we take either we can use it sin omega t or cos omega t. So here, I am taking Em cos omega t, Em cos omega t d omega t, we are integrating. What do the lower limit with respect to the, let us go to the previous slide.

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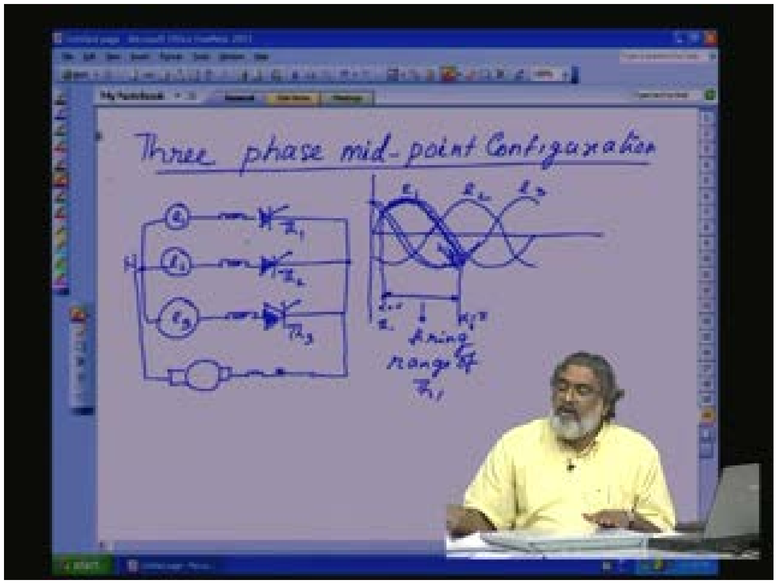

This is our, if you see the lower limit if a cos omega t is this one. This is the point where we have the omega t is equal to 0.

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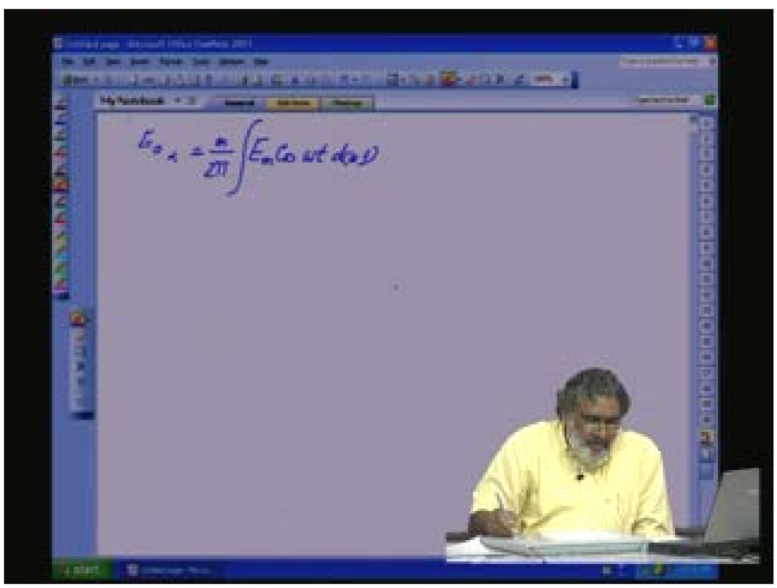

Now, for understanding, again we will draw the waveform. If you see here, this is the sin wave form.

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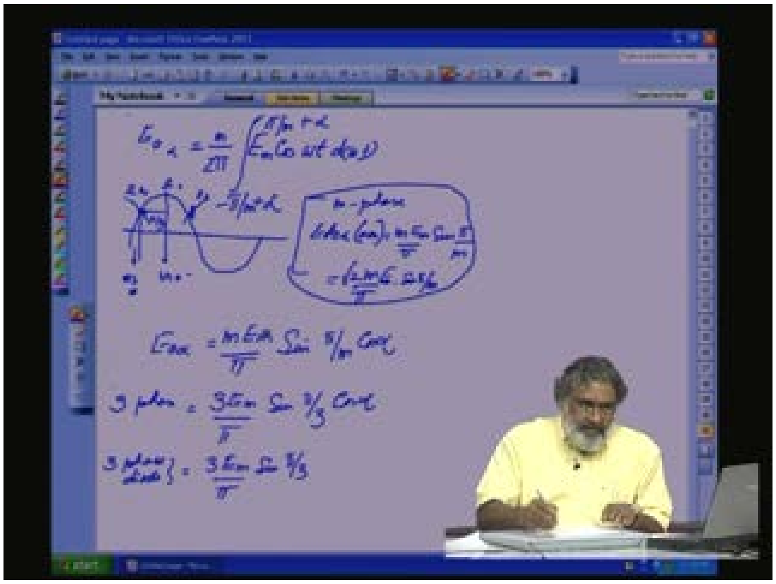

Let us take the e_1 waveform. Because of the symmetry, we can only we have to integrate only the any part of e_1 e_2 or e_3 for 2 pi by m say 3 phase 2 pi by 3. So, Em sin omega t, we are integrating between I am taking cos omega t, so cos omega t means omega t is equal to 0 here. But our lower limit integration can be for a three phase, it is pi by 6 as I told below, this is 30 degree pi by 6, this is the point where e_3 will be touching here. So, this is the point, pi by 6 or for a three phase, this is pi by 6.

Now, when we want to generalize this one; what is this one? Lower limit omega t_0, we are going this direction that is negative. How much it is going? If it is pi by 6 here, for a general m phase, this period is equal to pi by 3 for a three phase and for a general m phase, it is pi by m.

So, omega t_0 is equal to 0, we are going to negative side that is the lower limit of integration that is the firing angle at which only we can start firing. So, for a general m phase, it will be minus pi by m that is the starting point. From there, alpha we can increase; alpha from 0 to whatever values. So, minus pi by m, general alpha if you take this way, then what is upper limit? Same thing; other phase also, we should start where for alpha is equal to 0, for other phase also, it will start from here that is this is e_3, this is e_1, this is e_2. Alpha is equal to 0 for e_2 starts from here. So, with respect to e_1, this point is equal to if it is pi by m, this is upper limit also pi by m.

Now, alpha increases. So, the upper limit will be pi by m plus alpha. So, that means if you see, from this waveform, lower limit for a general m phase, we are starting from this point omega t is equal to 0 comes to this one that is this point then from here lower limit. Then the alpha whatever starts from here alpha starts from anywhere. So, minus pi by m plus alpha and the upper limit pi by m for the other phase again alpha, alpha has to be equal for every phase.

So, if you do here, what is the output when you integrate this one and find out it will be $e_{0\ alpha}$ is equal to m Em by pi sin pi by m and cos alpha. So, this is the general equation for a general m phase with respect to firing angle alpha. Now, for three phase, you put n is equal to 3, then it will be for three phase, let us say for the three phase, three phase midpoint configuration, this will be equal to 3 Em by pi sin pi by 3 into cos alpha, this is the one.

Now, for the three phase diode rectifier not the thyristor that we have divide the general phase, three phase diode rectifier that is semi controlled say half bridge; we can say from the single phase terminology, three phase midpoint configuration with diode, three phase diode rectifier diode. Not fully controlled, semi controlled; it will be equal to alpha will be 0, firing angle will be 0.

So, 3 Em by pi into sin pi by 3; so we can easily derive this one. Now, with firing angle alpha is equal to 0, the general equation for a general m phase for a general m phase, the maximum output voltage that is Ed_0 alpha maximum. We are more interested in maximum value because we have to choose our devices based on that one. It will be equal to m Em by pi into sin pi by m, this is the maximum equation.

Now usually, our mains voltage we are electrical engineers, we represent it as a rms value not the maximum values. So, how do we represent this one if it is rms? It will be root 2 m by pi into Em ef note e, rms value, so we will represent as E; E into sin pi by m. This is the maximum value we get from this one.

Now, firing angle as a tool, powering firing angle range is for 180 degree, alpha 0 to 180 degree; now output voltage is sin pi by m into cos alpha. So, alpha is equal to pi by 2 $E_{0 \text{ alpha}}$ will be 0. Where is the pi by 2 ranges? Where is the pi by 2 point? Let us see. We will go to the next figure now. Let us again draw the three phase waveform from this point for us to understand.

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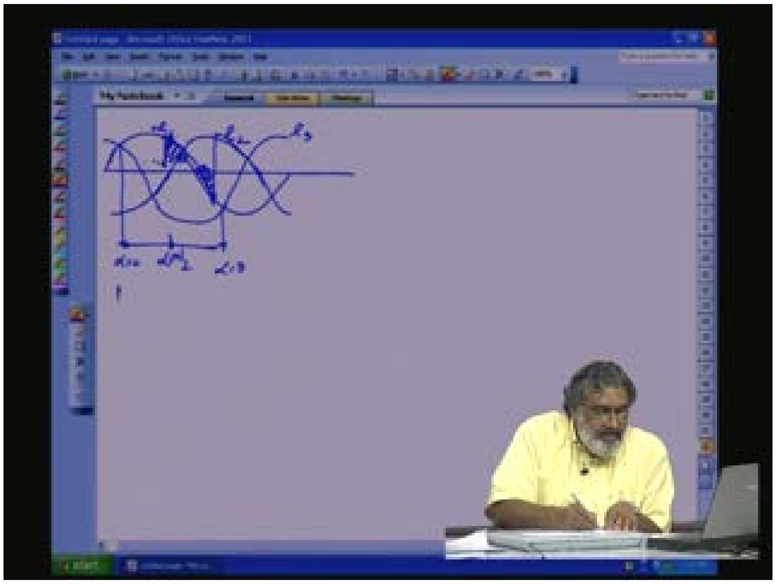

This is our a phase and e_1 voltage, this is the e_2 voltage. From experience, we can also equally approximately draw it. Alpha is equal to 0 starts from here for e_1; this is e_1, this is e_2, this is e_3.

This is alpha is equal to 0 starts from here, alpha is equal to pi is this range, this is the range. So, the half distance is the pi by 2 periods. So, at the pi by 2 period, what will happen?

Suppose for the output voltage to be 0, the repel voltage is still coming across the load, there should be equal positive and equal negative region will be there. So, the firing angle if you take at the pi by 2 period alone; so there we will have the approximately equal voltage duration somewhere here. So, alpha is equal to 0 here and at this point, this is from here to here pi by 2 will be, for a sin wave from here to here, it is pi by 2. Already pi by 3 is gone here, so next pi by 3, we have to add here. So, somewhere here, it will come. Also, the next waveform, it will start from here.

So, if you see here, for pi by 2 something like this will happen; equal positive and equal negative, positive and equal negative. So, when you draw neat waveform, you can say with respect to alpha is equal to 0, alpha is equal to pi by 2 that is the starting point of the firing angle, we can have equal positive and equal negative repel and output voltage will be 0.

So, let us find out, see our converter, we are controlling the firing angle only depending upon the voltage what we require. So, let us have the graphics, the output Ed_0 alpha with respect to our firing angle. So, we will draw here.

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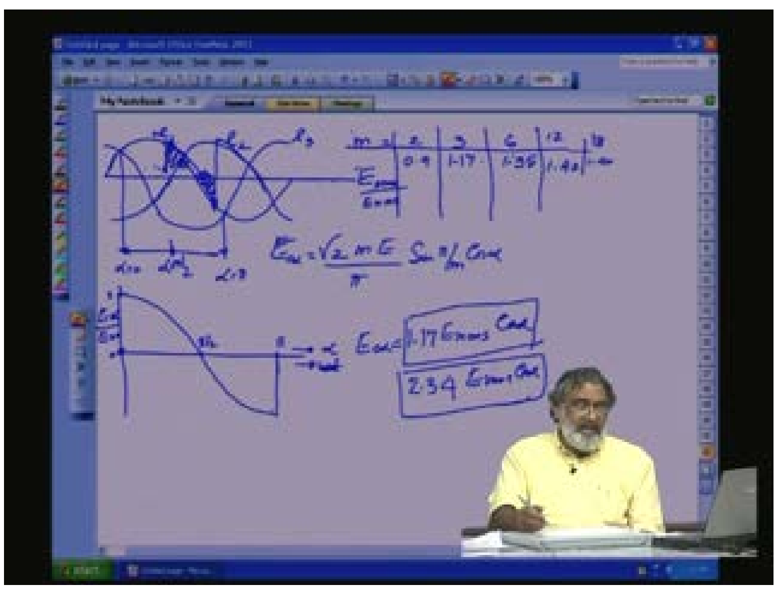

If you see, draw here, let us take Ed e_0 alpha here, e_0 alpha divided by the e_0 maximum e_0 maximum. So, maximum will be at point one that is one. Then the output DC from the equation we know it that is e_0 alpha is equal to root 2 m E by pi sin pi by m into cos alpha. So, the output e_0 is a function of alpha, not alpha cos alpha. So, the output with respect to firing angle, it will as a cosine function; so this is our omega t, this is pi that is alpha, alpha, this is not omega t, this is alpha in radians per second; when you represent, this is pi, this is 0, this is pi by 2.

So, if you see when alpha is equal to 0 that is at this point, at this point, we will have the maximum voltage, when alpha is equal to pi by 2, the output voltage is 0; then alpha is equal to pi, it will be negative maximum. So, it will go like this.

Now, let us go for a general m phase. We have calculated this one for a general m phase. If you see here, let us mark m is equal to 2, 3 then 6, it can go back to a. Then, let us also mark it here that is e_0 alpha by the e_0 maximum. If you put it, for the two phase operation, it will be 0.9; for the three phase, our midpoint it is 1.17 that is the ratio - the output DC with respect to the maximum value that is what is happening here 1.17; then for six phase, it is 1.35 sorry I have made a mistake here, the ratio it is maximum, it cannot be 1.17, it is with respect to Ed E_0 maximum given by E rms.

So here, what we are going to write? It is not rms, it is not the output voltage, the ratio it is with respect to the maximum value divided by the E rms value that is with respect to maximum; so it will be e_0 maximum output maximum divided by E rms. So here, if you see here, it will be 0.9 that is here; for three phase, 1.17; then for six phase, it is 1.35; we can have a twelve phase that is extend this one and write twelve phase here, here it will be 1.40; again we can have eighteen phase, here it will be approximately again 1.40.

So, as the number of phases if it can increase; so why I am saying this one, from two phase to three phase we have gone then what we found is the repel, the output repel will be three times the fundamental frequency that is also clear from this figure from the output repel frequency, three times the fundamental frequency.

So, as the number of phases increases, the output repel can also increase but we are not going to get a considerable margin in the output DC voltage. So, what we are mostly interested in the three phase side and the single phase. So, three phase half bridge; the maximum value with respect to E rms is equal to 1.17. What is meant by this one? For a three phase, the output e_0 alpha is equal to 1.17 E rms value into cos alpha. This is for a three phase midpoint configuration.

We will assume a symmetrical operation like the single phase; if we can go for the full phase control three phase fully controlled convert, then we have the positive side equal way controlling, negative side also. Then what should be for any firing angle; if you generally think what would be the maximum output voltage? Multiplied by 2, it has to be 1.17 into 2 that means 2.34 four into E rms into cos alpha.

So, now we will go for the three phase configuration. How it is possible? Where is the firing range? How the repel comes? Most of the high power applications or drive applications, three phase will move or drive application, we will be drawing power from the three phase and the how the output voltage can be controlled with respect to firing angle for m inductive load?

Now, we have talked about we have not talked about the resistive load for the three phase as well as three phase case. That also we will cover in the next class. So, next class we will go for the three phase and first we will start with resistive load, then inductive load with firing angle; how the output repel will happen? We will conclude on the three phase controlled converters.

Then we will talk about the non-idealities. As I told, we will put the small leakage inductance small inductance across each thyristors. Why it is turned? To take care of the commutation, during the commutation period that means when thyristor is one thyristor is turned off and another thyristor is turned on during the delay period, final turn on and turn off time. So, the two phases can be short circuited. So, to avoid short circuit: why this is getting short circuited? The incoming phase and outgoing phase, the voltages are not equal. So, there is a difference in voltage. Because of the difference in voltage, heavy and the diodes are conducting simultaneously conducting that can be a short circuit.

So, to avoid the short circuit, avoid the heavy current; so the difference in voltage has to be for a momentarily for microsecond duration during the turn on and turn off period, it has to be across some impedance we have to provide. That is why we have to provide the leakage inductance and how to design? What are the effects of this one? Whether it is going to affect our output DC voltage or extra component we have put; we will study in the next classes.