Power Electronics

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Lecture – 16

In my last class I had discussed the operation of a dual converter, there are 2 single phase fully controlled bridges are connected back to back.

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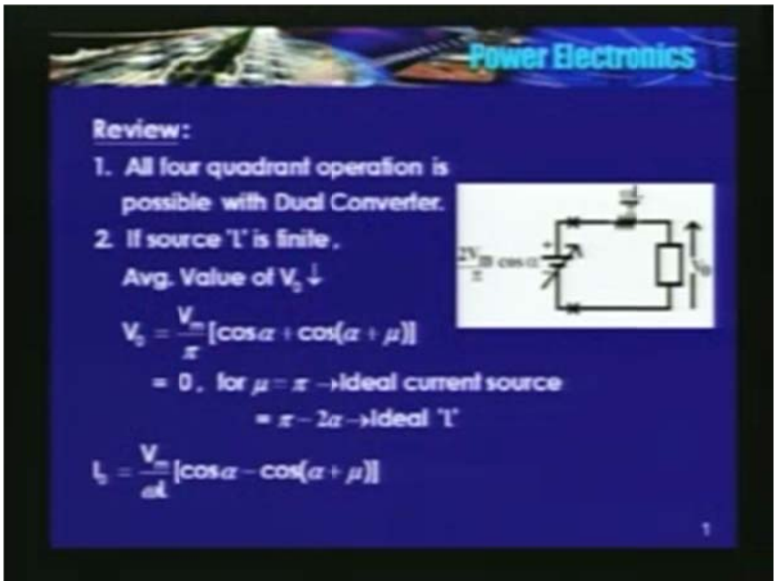

So therefore, the polarities of both voltage and current can reverse. So, if I use a dual converter to control a DC motor, all 4 quadrant operation is possible. In 2 quadrant, the machine is working like a motor. The difference is the direction of rotation is opposite. In the first quadrant if it is running in the clock wise direction, in the third quadrant it is running in the anti clock wise direction and in during regenerative breaking, it goes either to quadrant 2 or quadrant 4.

The other important application of a dual converter, I will discuss some time later after doing 3 phase bridge. That is an very important application. There are 2 types of operations; one is a circulating current type, another one is a non circulating current type. In the circulating current type, both the bridges are triggered simultaneously. If $alpha_1$ is a trigger angle for bridge 1, the bridge 2 is triggered at pi minus alpha 1. Mind you, this condition, we have derived assuming the DC link inductor is an ideal one. There is no internal resistance in the inductor, remember. Things do change if there is the finite resistance in the inductor.

The second point that we discussed was the effect of source inductance. When the source inductance is 0, the moment the incoming thyristor is turned on, the outgoing thyristor turns off, whereas, due to the source inductance for a finite duration, both thyristors conduct. Therefore, during this period, voltage applied to the load is 0 in a single phase.

So, I will repeat; during the commutation over lap period, wherein, both the thyristors are conducting, incoming as well as outgoing, the voltage applied to the load is 0. So therefore, there is a net reduction in the voltage applied to the load. The expression for the average value of the output voltage for finite mu is given by this equation; V_m by pi into cos alpha plus cos alpha plus mu and here is an equivalent circuit.

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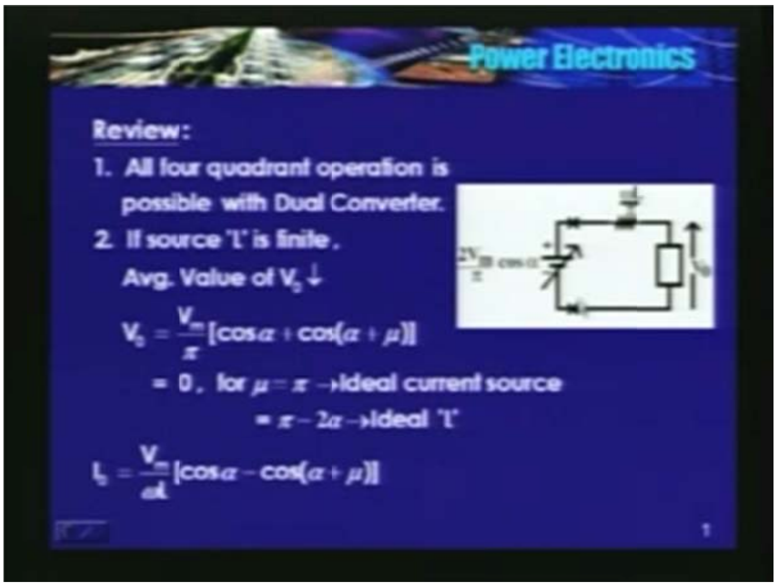

This is the average value of the output voltage. Voltage drop due to the source inductance, the node voltage V_0 and then here there are 2 thyristors because in a single phase bridge, 2 devices are conducted at a time and we found that V_0 is 0 for mu is equal to pi. It is possible only if the load is an ideal current source and it is also 0 for mu is equal to pi minus 2 alpha and we found that this is the case when load is an ideal inductor.

Now, value of I_0 is given by this equation; V_m by omega L into cos alpha minus cos alpha plus mu. This expression, we derived yesterday. Now, let we solve the problem in commutation over lap.

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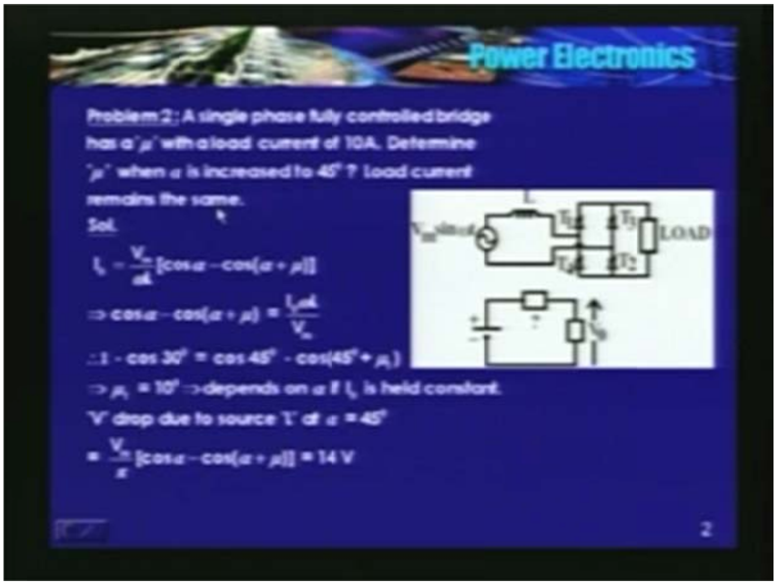

A very simple problem, very interesting problem also: a single phase bridge, a finite source inductance, the load. Problem says that load current is constant at 10 amperes. Initially, alpha is 0 and after wards alpha is increased to 45 degrees. Determine the overlap angle that is mu as well as voltage drop due to the commutation overlap. Input voltage is the same, source inductance is the same and load current is the same except alpha is changed. Initially, it is 0, now it is changed to 45 degrees. What happens?

Remember, all parameters; input voltage, source inductance, load current, magnitude of load current, this is a constant. So, in this expression we will see that all parameters are constant. Therefore, cos alpha minus cos alpha plus mu is I_0 omega L divided by V_m. So, for alpha is equal to 0, 1 minus cos 30 is equal to? Now, alpha is 45 degrees, cos 45 minus cos … mu1 because it is said that for alpha is equal to 0, overlap angle is 30 degrees. When alpha is 0, overlap angle is found to be 30 degrees. So, alpha is 0, cos 0 plus 30 is this, 45 degrees, 45 plus mu1.

So if you solve this equation, we will find that mu1 is 10 degrees. So therefore, do not assume that just because V_m is held constant, load source inductance is the same and even if I keep load current is constant, mu - the overlap angle will remain constant, no, it depends on alpha. A very important point to be noted, see, it is when alpha is equal to 0, when it is triggered at 0, commutation overlap angle is 30 degrees. Now, when it is triggered at 45, it reduces to 10 degrees.

Now, voltage drop due to source inductance at alpha is equal to 45 degrees, you just substitute here, it is found to be 14 volts, it is quite substantial. Again, we this is only due to source inductance. If I had, say, a 2 volts each, the total voltage drop due to load inductance as well as the voltage drop due to the devices, it comes to around 18 volts. More on dual converter, more on effect of source conductance, we will see after doing 3 phase circuits.

So far we have studied half wave rectification. I told you that half wave rectification is used only for small power application because the source supply, the finite DC current, average value of source current is finite in half wave rectification. When we discussed half controlled bridge which is also known as 1 quadrant converter, a fully controlled bridge also known as 2 quadrant converter then we connected 2 fully control bridge back to back and we called it is as dual converter, wherein, all 4 quadrant operation is possible.

I think our machine, in a machine course, our teacher might have told, in low power application fractional Hp motors are used, effective motors in low power application. For example fan. It is again fed from a single phase supply, single phase motor. So, as the power rating increases, the trend is to go towards a 3 phase motors. So, same thing is true even in power conversion. For low power application, you use single phase bridge. As the power rating increases, you go for a 3 phase. So, we will study first, 3 phase half wave rectification.

So, all the single phase bridges, there are 2 pulses per cycle. They are also known as 2 pulse converter and we will find that in 3 phase half wave rectification, there are 3 pulses. Hence, the name 3 pulse converter.

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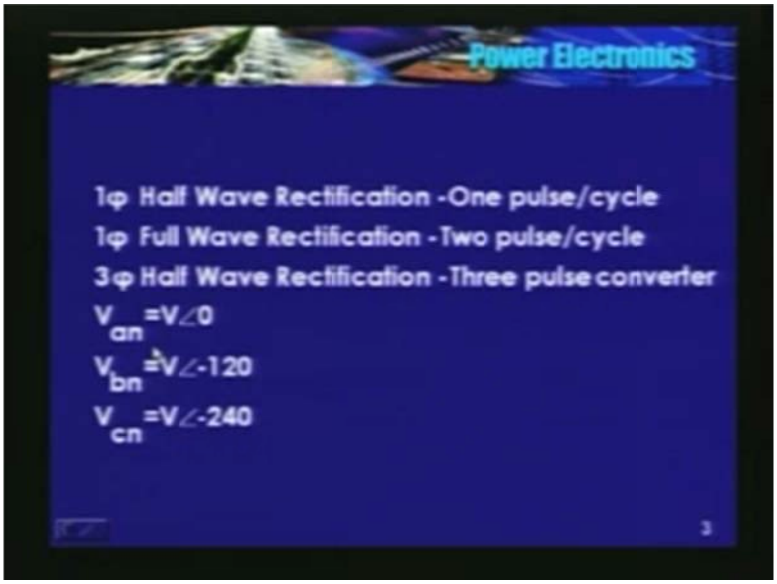

So again, things are bit difficult. You need to understand because so far there was only single phase voltage, V_{an} V_m sin omega t. Now, there are 3 voltages which are displaced by 120 degrees. Magnitude may be the same.

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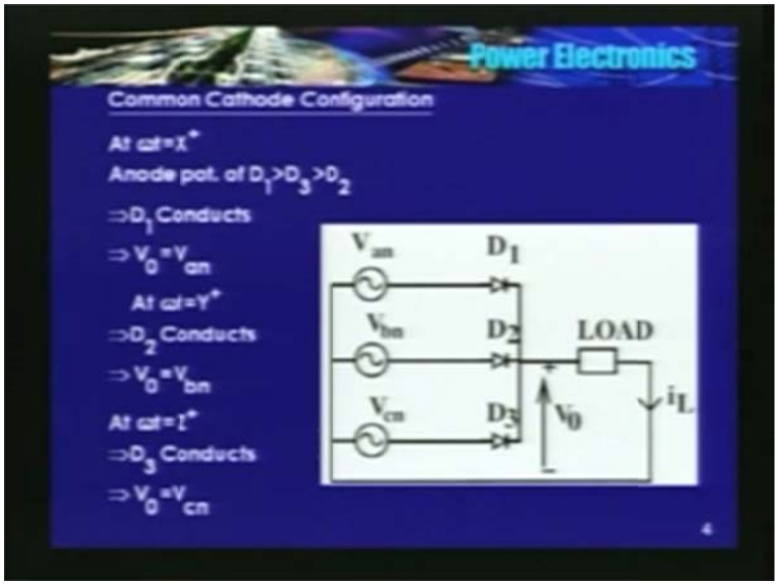

So, here is a bridge, the 3 diodes, first we will do uncontrolled, they form a common cathode configuration and load is connected between the common cathode and the start point. 3 diodes, D_1 D_2 D_3, they form a common cathode configuration. Therefore, the diode whose anode potential is at rest will start conducting.

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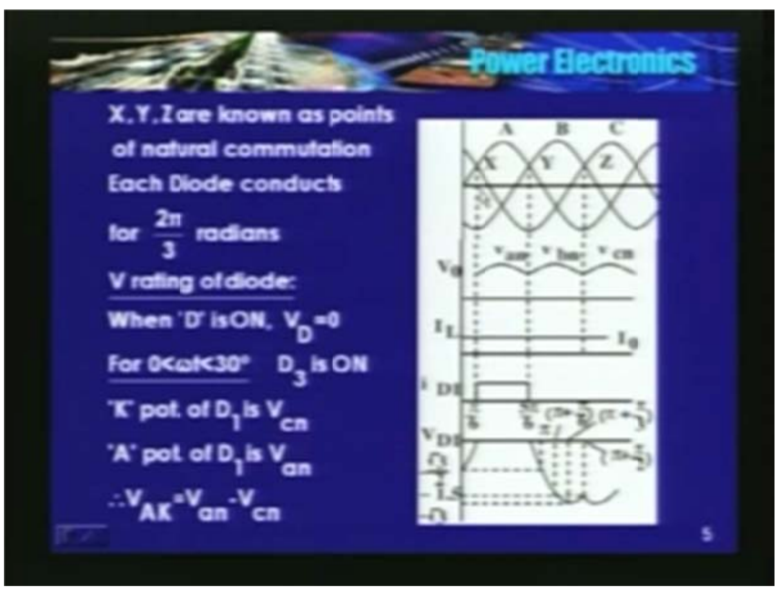

So, here is the 3 phase sinusoidal voltage, mind you, now you need to learn to draw a 3 phase sinusoid. Now, you need to draw a clean 3 phase sinusoid voltage, they are very important. If you make a mistake there, it is going to be difficult to draw the output voltage wave form. So, first exercise should be a drawing, a good, a neat, 3 phase sinusoid.

So, here there are 3 sinusoids. At point X, you will find that phase A becomes more positive than phase C. So, this is phase C, this is phase A and this is phase B. So, phase A becomes, see cuts 0 and becomes positive. After 120 degrees, phase B becomes and after 120 degrees, phase C, so this is phase C.

So at point X, phase C, instantaneous value of phase C voltage is same as the instantaneous value of phase A voltage and beyond point X, phase A becomes more positive. Similarly at Y plus, phase B becomes more positive than phase A. Similarly at Z, phase C becomes more positive than phase B. So, common cathode configuration, so diode whose anode potential higher will starts conducting. So, change over from 1 device to another device will take place at X or Y or at Z.

So, the diode which is connected to phase C will turn off at this instant, at X and diode connected to phase A, it starts conducting at X plus. Similarly at Y plus, the diode which is connected to phase B, starts conducting and the diode which is connected to phase A turns off. Similarly at Z, the diode which is connected to phase C starts conducting and that connected to phase B turns off.

So, you will find that this duration, the duration for which each device conducts is 120 degrees. See, I will tell you, 0, this intersection is 30 degrees, this is 60, this is 90, this is 120, this is 150, this is 180. So remember, there is an intersection at every 30 degrees; 30 degrees, 60, 90, 120, 150, 180, so, similarly in the negative half.

So, diode starts conducting from 30 degrees to 150 degrees. So, diode conducts between 30 and 150. So, duration is 2 pi by 3 radiance. So, when the diode is conducting, the load voltage is same as the phase voltage. So, if D_1 is conducting, load voltage is same as V_{an}, $V_{an,}$ potential, this potential is same as this, V_{an}. When D_2 is conducting, load potential is V_{bn} and when D_3 is conducting, load potential is V_{cn}. So, V_{an}, V_{bn}, V_{cn}.

As I said earlier, there are 3 pulses per cycle, hence the name 3 pulse converter. I will assume constant load current of magnitude $I_{0.}$ So, load current is constant and ripple free and I will assume source inductance is 0. So, change over from 1 device to another device takes place instantaneously. So, each device conducts for 120 degrees. If the magnitude is same as that of the load current, source here supplies power from pi by 6 radiance to 5 pi by 6 and it is 0. So, if I find the average value of this, it is finite. So, source supplies a DC component of current to the load. The effect, I have already discussed in the single phase.

Now, how do I draw the voltage across when the diode is not conducting? In a single phase case, it was straight forward. In the 3 phase case, it is not very straight forward, try to understand. When the diode is on, fine, voltage across it is 0, all of us know and when the diode is off, you will see here, cathode potential is it is the supply phase voltage, sorry, the anode potential is its phase voltage, whereas, cathode potential depends on the conducting diode because for some time the cathode potential is V_{bn} and for some time the cathode potential of D_1 is V_{cn}.

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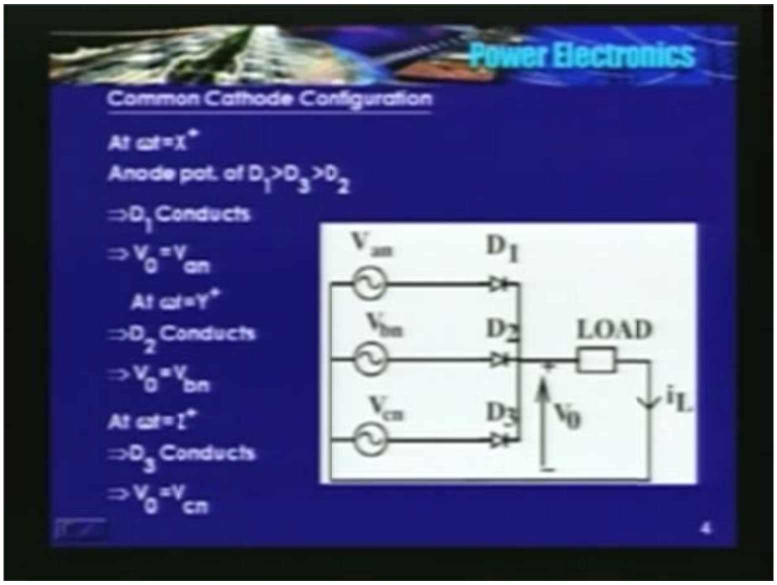

So, voltage across the diode for some time for 120 degrees is V_{an} minus V_{bn} and for remaining 120 degrees, it is V_{an} minus $V_{cn.}$ So, how does the wave form look like? At point X, so X minus, C was conducting, the diode which is connected to phase C that is D_3 is conducting. So, voltage across diode D_1 is V_{an} minus V_{cn}. So, if I take magnitude of each sinusoid is 1 that is 1 per unit, at omega t is equal to 0, phase A is 0. But then phase C is 120 degrees. The instantaneous value is sin 120 that is nothing but root 3 by 2.

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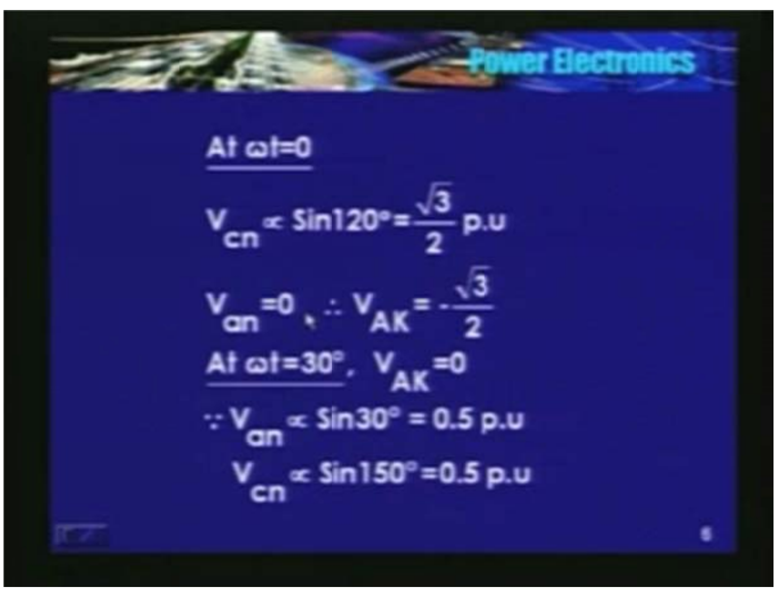

So say, here is that sin is V_{cn} is proportional to sin 120 is root 3 by 2 per unit. V_{an} is 0. Therefore, V_{AK} is minus root 3 by 2. So, I have shown it here. At that, at this instant, voltage across the diode connected to phase A is root 3 by 2, minus, it is blocking.

Now, what happens is beyond the 0 crossing potential of A is increasing, whereas, potential sorry potential of phase A that is V_{an} increasing, whereas, V_{cn} is decreasing and at X, both are same. Instantaneous value of V_{an} is same as instantaneous value of C phase. So, V_{AK} is 0, at that instant diodes starts conducting. It takes over, if I consider ideal diode because beyond point X, phase A becomes positive. A positive voltage, it starts appearing crossing at the diode, so it starts conducting.

So, from 0 to 30 degrees, this is the variation. So, from pi by 6 to 5 pi by 6, voltage is 0. Now, how does the wave form look beyond a pi by 6? Beyond 5 pi by 6, diode which is connected to phase B, starts conducting. Now, it is going to be V_{an} minus V_{bn} is the voltage appearing across the diode, same procedure.

At this instant that is at omega t is equal to pi, instantaneous value of V_{an} is 0. Whereas, instantaneous value of phase B is proportional to sin 60, this is 60. I will repeat, say, 0, 30, 60, 90, 120, 150, 180. So, this is instantaneous value of phase B is proportional to sin 60 that is root 3 by 2. So, V_{an} is 0. So, voltage across the diode D_1 is V_{an} minus V_{bn} is minus root 3 by 2.

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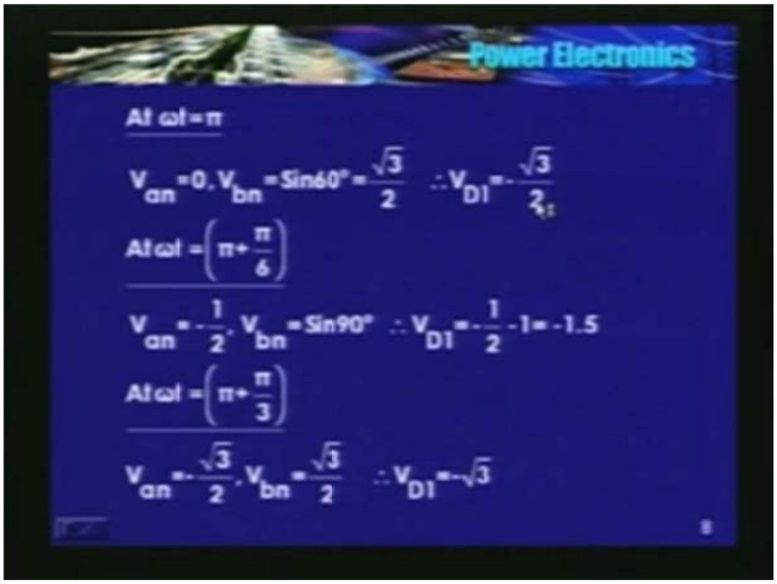

So what happens? At pi plus pi by 6 that is somewhere at this instant, instantaneous value of sin, phase A is now sin 210, this is 210 and whereas, this is sin 90. So, sin 210 minus sin 90. So, sin 210 is nothing but minus half sin 90 is 1, so, minus 1.5. So, see here, at pi it is root 3 by 2, at pi plus pi by 6 that is corresponding to this instant, it is minus 1.5 per unit.

What happens after 30 degrees that is 240 that is at this instant? At this instant, instantaneous value of V_{an} is proportional to sin 240, this is sin 240. Remember, you have to start, for a phase A, this is the 0 crossing. So, this value is sin 240, whereas, for phase B it is sin 120, this is sin 120 and for phase A, it is sin 240. What does that value comes out to be? Sin 240 is minus root 3 by 2 and sin 120 is root 3 by 2. If I add both of them, voltage across the diode comes to minus root 3 per unit. See, I have shown you here, this is root 3 per unit.

Now, what happens beyond 30 degrees that is at 270? This is 270 now or 270 minus because at 270 plus, D_3 starts conducting. At 270 minus, D_2 is conducting. So, at that instant, V_{an} is again 270 that is approximately 1. B is sin 150 minus, this is for phase B, this is 150, 150 minus.

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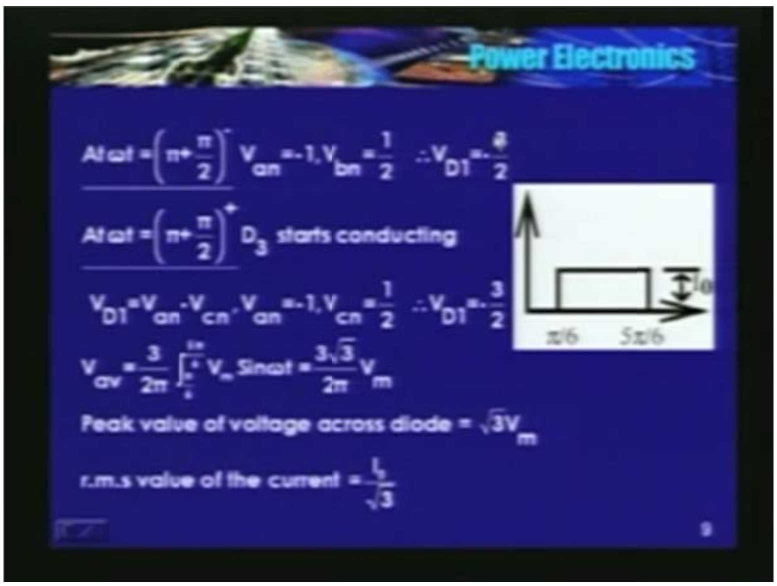

So, value is see, 270 is approximately minus 1, bn is half, so voltage is that minus 3 by 2 because at pi plus pi by 2 plus, D_3 starts conducting. The moment D_3 starts conducting, the voltage is now V_{an} minus $V_{cn.}$ So, prior to this instant, phase B was conducting. The voltage is V_{an} minus V_{bn}. So, I have drawn it here, at this instant, pi plus pi by 2 minus, it is actually minus 1.5 per unit.

So remember, in the sense, it is not very straight forward to draw, not very difficult either. So, what you need to do is you need to find out the instantaneous value of each phase value. At this instant, for phase A and phase B you add them up, you will get it. So, voltage across the peak value of the diode, peak value of the voltage appearing across the diode is root 3 per unit. If it is, V_m is 100, it comes to be, this comes out to be root 3 into 100 is of the order of 172 volts or so.

So, at pi plus pi by 2 plus, V_{cn} takes over sorry D_3 takes over, now voltage is V_{an} minus V_{cn}, you use the same procedure, the procedure which we used to draw the voltage wave form across the diode 1, D 2 was conducting and you will get the same wave form. So, what conclusions that we can draw now? Conclusions are each diode conducts for 120 degrees, peak value of the voltage appearing across the diode is root 3 times the peak value of the phase voltage or root 3 times the root 3 per minute and if I assume load current to be constant and ripple free, RMS value is I_0 into I_0 by root 3.

Now, how do I determine the average value of the output voltage? There are 3 pulses in 1 cycle and each pulse, the duration of each pulse is 120 degrees. So, phase A starts conducting at pi by 6 and it stops conducting at 5 pi by 6, output voltage is V_m sin omega t. So, average value is found to be 3 root 3 by 2 pi into V_m where V_m is the peak value of the phase voltage.

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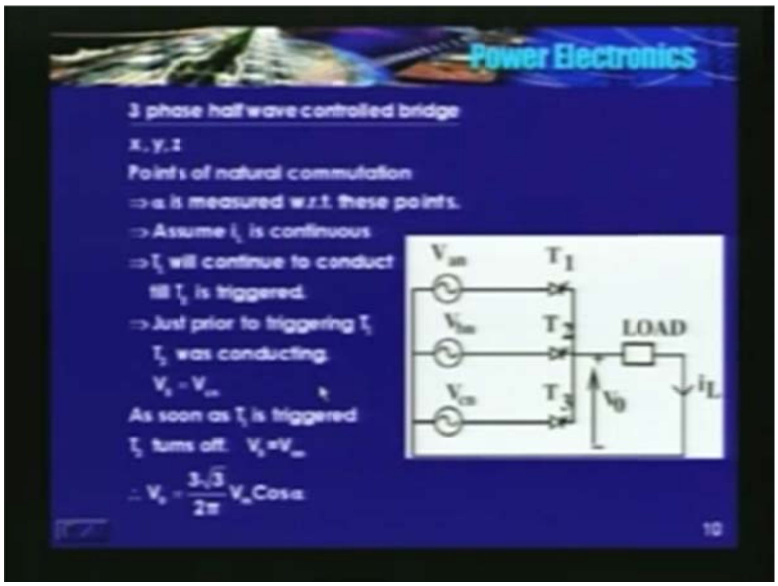

So, that is about half wave uncontrolled bridge. Change over from 1 device to another device takes place at X, Y and Z. At point X, point Y, and point Z, instantaneous value of 2 phases is the same. Since, change over from 1 diode to another diode takes place at these points, they are known as point of natural commutation.

Remember, in a single phase case, single phase uncontrolled bridge, change over takes place at the positive 0 crossing for 1 and D_1 and D_2 and change over from D_1 to D_2 to D_3 to D_4, it takes place at the negative 0 crossing. So, positive 0 crossing and a negative 0 crossing, they can be known as the point of natural commutation, whereas, in a 3 phase circuit change over from 1 device to another device takes place at point X or Y or Z. So, these points are known as point of natural commutation.

Therefore, alpha, the trigger angle alpha for SCR is measured with respect to point of natural commutation. Remember, not with respect to the positive 0 crossing or phase A, no, it is point of natural commutation. Alpha is measured with respect to point of natural commutation. The principle of operation of this bridge, a half wave controlled bridge is same as that an uncontrolled bridge. The only difference is the outgoing thyristor continues to conduct till the incoming thyristors is triggered. T_1 continues to conduct till T_2 is triggered. In this bridge, T_1 continues to conduct till T_2 is triggered. If the diodes takes over it, change over takes place at X, Y or Z. The only difference is T_1 continues to conduct till T_2 is triggered.

So therefore, there is going to be an instantaneous change or jump in the output voltage because when T_1 is conducting, output voltage was V_{in}, when T_2 is conducting, output voltage jumps to V_{bn}. So, it all depends on alpha. So, the average value of the output voltage, the expression is same as that of the half wave uncontrolled bridge. The only term that will come is cos alpha that is all. Rest all remain the same, each device conducts for 120 degrees.

Now, let me draw the output voltage wave form. Let me see how does it look like? I triggered T_1, T_2, T_3 at alpha is equal to 30 degrees.

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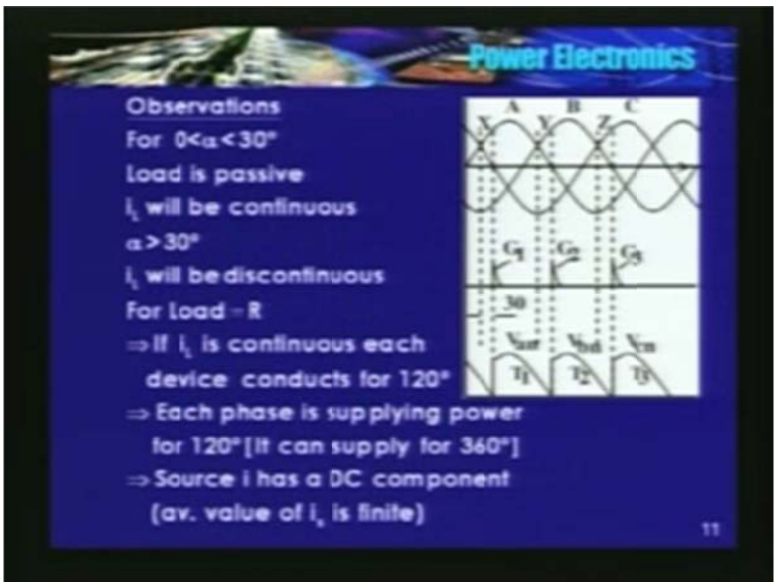

So, where is alpha is equal to 30 degrees? Because, any angle which is integral multiple of 30 degrees, I can determine on this wave form because I said at every 30 degrees either it will cut the X axis or there is going to be intersection. This is alpha is equal to 0 that is the point of natural commutation. Mind you, at this point, it is instantaneous value of A is proportional to sin 30. This is proportional to sin 30 but alpha is 0 at this 45, trigger T_1, the corresponding value of alpha is 0.

So, 30 is here. So, I will trigger T_1 at 30 degrees, the point of natural commutation or a point of reference point for T_2 is Y. So, this is 30, T_2 is triggered at this point, similarly, T_3 is triggered at this point. Reference point for the diode which is connected or SCR connected to phase B is Y. The reference point for the thyristors connected to phase C is Z, alpha is 30 degrees. Prior to triggering T_1, prior to conduct T_1, in uncontrolled bridge, the diode which was connected to phase C was conducting, remember, phase C was conducting.

So, if diode which is connected to phase C is conducting, prior to T_1 or prior to the diode D_1, in a 3 phase half controlled bridge, prior to triggering the thyristors which is connected to phase A, the thyristors which was connected to phase C was conducting, remember. So, prior to triggering

$T_{1,}$ T_3 was conducting. So, in this region, T_3 was conducting. It continues to conduct beyond X because we have not triggered $T_{1.}$

So, till you trigger $T_{1,}$ T_3 continues to conduct. Remember, till you trigger T_1, T_3 continues to conduct, till you trigger T_2, T_1 continues to conduct. So, instantaneous value or a load voltage is V_{cn}, see V_{cn}, this is V_{cn}. At alpha is equal to 30 degrees plus, T_1 is triggered. Instantaneously, output voltage jumps to the value proportional to V_{an}. So, this is the value, V_{an}. So, it will jump to V_{an}, it will continue in this fashion or 120 degrees, provided, the current is continuous, remember, provided, current is continuous.

So, T_1 conducts from this instant till you trigger T_2. At this instant, T_2 is triggered, instantaneous value of V_{an} become 0 that is why it touches the x axis. Immediately, T_2 is triggered, at that point instantaneous value of phase B is sin 60, remember. See, this is 0 for phase B, 30, 60. So, instantaneously it will jump to root 3 by 2 per unit, root 3 by 2 per unit, follows phase B, again. At this instant, instantaneous value of phase B becomes 0, T_3 is triggered, output voltage jumps to V_{cn}, follows V_{cn} and the cycle continues.

So, each device conducts even in this case for 120 degrees, provided, current is continuous. Mind you, if I have to increase alpha greater than 60 degrees sorry greater than 30 degrees, what would happen? See, for phase A, alpha is 60 degree somewhere here, 30, 60. So, prior to triggering $T_{1,}$ T_3 was conducting. So, output voltage is V_{cn} and you will find that V_{cn} becomes 0 beyond this point. Beyond this point, V_{cn} becomes 0.

At alpha is equal to 30, it just becomes 0. Beyond 30 degree, it becomes negative. So, if I had a load which is purely resistive, current cannot flow beyond this point. So, thyristor turn off of its own because current as become 0 and till you trigger the next thyristor, load voltage is 0 because none other thyristors are conducting. So, you would have had a finite 0 period if the load is purely resistive and alpha greater than 30 degrees, remember.

So, if the load is purely resistive, current is just continuous. I will remember, current is just continuous for alpha is equal to 30 degrees. Beyond 30 degrees, current will become discontinuous because beyond 30, the instantaneous value of the outgoing phase goes negative and you cannot have a situation, wherein, voltage across the register becoming negative in a AC to DC power conversion.

Now, I am not going to draw the voltage across the blocking thyristor. Procedure is the same. The only difference is now you can have a positive voltage across a blocking thyristor. You just cannot have a positive voltage across a diode because it is an uncontrolled device, whereas, you can have a positive voltage appearing across the thyristor.

So, I just tell you, I encourage you people to go back to your room and draw the voltage wave form across the blocking thyristor. See, at point X, instantaneous value of V_{an} is same as V_{cn}. So, voltage across the thyristor is 0. Beyond X, V_{cn} is less than V_{an}. So, voltage across the thyristor is V_{an} minus V_{cn} and V_{an} is magnitude of V_{an} is higher than V_{cn}. So therefore, a positive voltage appears across V_{an}. It is possible, fine. Till you trigger or get gate of $T_{1,}$ it is blocking.

So only difference is you can have a positive voltage appearing across a blocking thyristor. So, beyond X, till you trigger T_1, a positive voltage appears across it. The variation is the same procedure, V_{an} minus V_{cn}.

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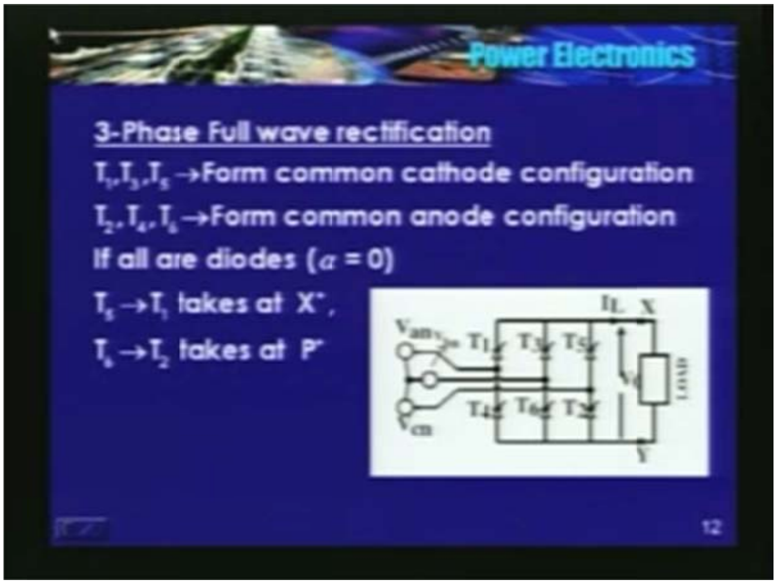

Again, 3 phase half wave rectification has a DC component. In the single phase case, from half wave rectification we went to full wave rectification. Same thing we will do in a 3 phase, full 3 phase circuits. Remember, it is going to be a bit more difficult. Here is the bridge, T_1, T_3, T_5 form a common cathode configuration, T_4, T_6, T_2 form a common anode configuration. V_{an}, V_{bn} and V_{cn} are the input voltages.

As of now, I will assume 0 source inductance. No source inductance, load current is constant and repel free whenever the conducting thyristor in the upper half, the load voltage is same as that of the conducting phase. In the lower half, potential of Y is same as the potential of the conducting phase.

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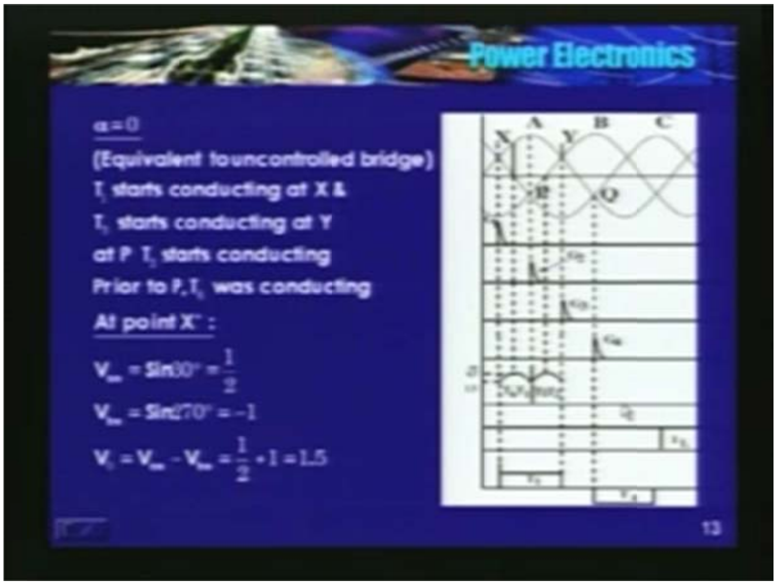

Common anode configuration diode or device whose anode potential is least will start conducting or can be triggered. Similarly, common cathode configuration; diode whose anode potential is maximum will start conducting. I will repeat, in a common anode configuration or in the lower half of the bridge, change over takes place at P, Q and at this point, may be, R.

So, if I added the if I have an uncontrolled bridge, all 6 layer, all 6 elements are diodes, at the upper half, change over from 1 diode to another diode takes place at X, Y and Z, whereas, in the lower half it takes place at P, Q and R. They do not takes place at the same time, remember, they do not takes place at the same time. So, things are bit difficult now.

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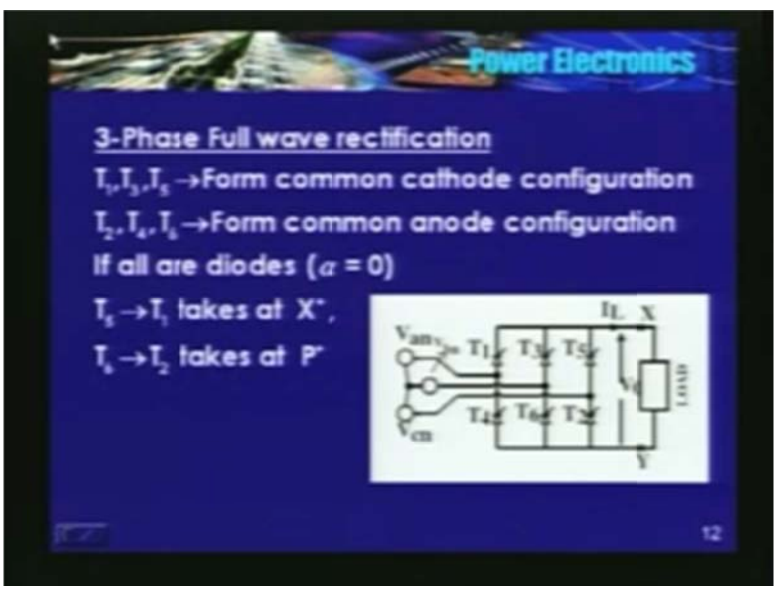

Prior to triggering T_1, T_5 - the device which is connected to C phase is conducting. Remember, when I had D_1, D_2, D_3 prior to D_1, D_3 which is connected to C phase was conducting. Now, remember, I have changed the number, suffix. I am calling 1, 3, 5, 4, 6, 2 because this is particular reason. It becomes very obvious as we proceed, as we go along. So, prior to T_1, T_5 was conducting. Similarly, in the lower half if you see here, see, this is the C phase, this is C and this is B.

So, diode which is connected to phase C starts conducting at P plus and prior to C phase, B phase diode should conduct. So, what is the number? So, prior to C phase, the diode which is connected to B phase is conducting. In other words, 6 was conducting prior to 2. See, 2 is connected to C, 6 is connected to B. So remember, B 6 is see here, B phase is more negative, so 6, 2 and this is for phase A. You will find that number is 4, this is for phase A, whereas, this is for phase again A, upper half, 1.

This is for phase B, we have numbered it as 3 and this is for phase C, we have numbered it as 5. So, this point is same as this. I will, first I will draw the output voltage waveform for alpha is equal to 0. Alpha is equal to 0 is same as an uncontrolled bridge. Let us see, how does the waveform look like?

At this instant, point X, T_1 is triggered. At point P plus or at point P, T_2 is triggered. The diode or device which is connected to phase C that is 2 is triggered. At Y, device which is connected to B phase in the upper half is triggered that is T_3 and at point Q, see, phase A becoming more negative. So, the device which is connected to phase A, lower half that is 4 is triggered. So, you will find that see, there is a sequence 1, 2, 3, 4. So, that is why I have numbered the upper half as 1, 3, 5, lower as 4, 6, 2.

Now, let us draw the output voltage waveform. Try to understand now. I said, alpha may be measured with respect to the point of natural commutation. While drawing the output voltage waveform, you need to find out the instantaneous value of the phase voltages measured from the positive 0 crossing, remember. Alpha is measured with respect to the point of natural commutation that is all, nothing else.

So, at alpha is equal to 0, what is the instantaneous value of phase A? It is proportional to sin 30. So, in the upper half, T_1 starts conducting. At X plus, instantaneous value instantaneous value of phase A at that point is sin 30, remember, this is sin 30.

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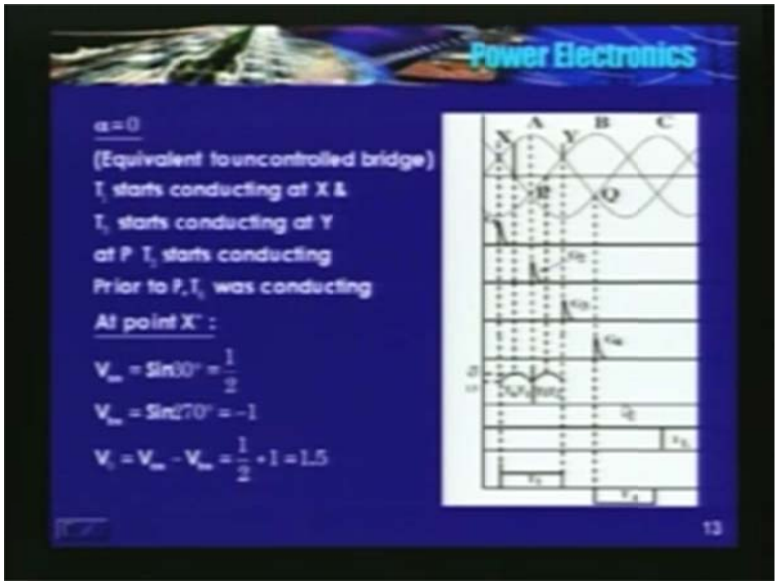

In the lower half, see, this is phase B, at this instant, phase C or a device which is connected to phase C is triggered. So, phase B was conducting at in this beyond this, sorry before. Before this point, before, prior to this point, phase or the device which was connected to phase B was conducting. So, potential of bus Y is B and potential of X is V_{an}.

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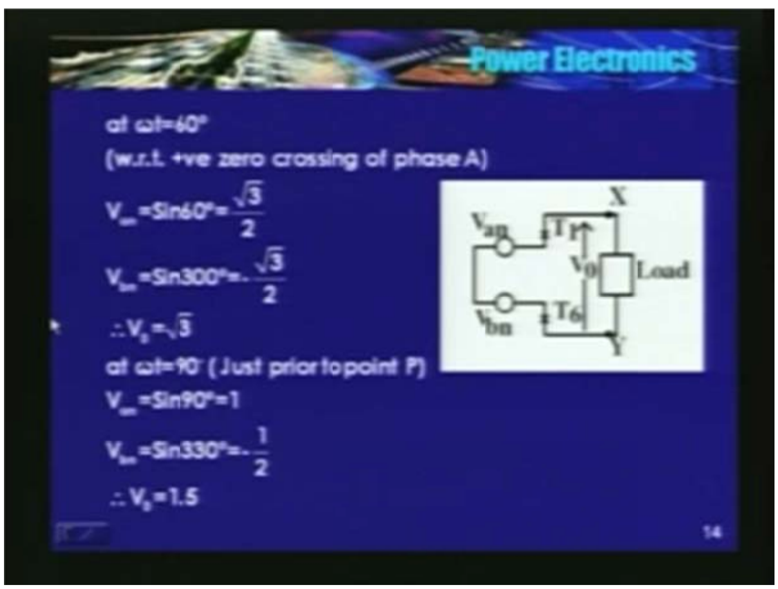

So, the equivalent circuit is see, V_{an}, $T_{1,}$ X, load, Y, $T_{6,}$ V_{bn} and the load. This is the equivalent circuit. So, at alpha is equal to 30, at the instant when you have triggered the thyristor, it is sin 30 for phase A and sin 270 for phase B. See, this is 270, sin 270, phase B is at the negative peak. So, that is the minus 1. So, output voltage is V_{an} minus V_{bn}. You will find to be 1.5 per unit. I am taking the magnitude to be1. So, at this instant, it is 1.5 per unit.

Now, let us see after 30 degrees what happens? At this point, V_{an} is sin 60. V_{an} is sin 60 and V_{bn} is sin 300.

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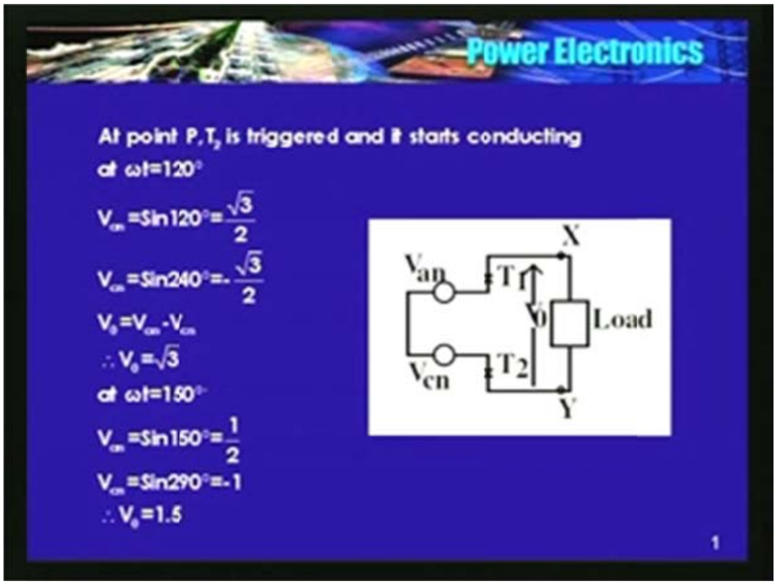

So, what is the value? It is, sin 60 is root 3 by 2, sin 300 is minus root 3 by 2. The load voltage is V_{an} minus V_{bn}. It is root 3 times the peak of the input voltage or root 3 per unit. So, if you see here, it is root 3. It was 1.5 that is at alpha is equal to 0 or omega t is equal to 30 degrees with respect to the positive 0 crossing of phase A, after 30 degrees, the peak value of the output voltage becomes 1.73 times.

Now, let us see what happens after 30 degrees, in the sense, just prior to triggering T_2? See after, at this instant, T_2 is triggered. What is the output voltage just prior to triggering T_2? Still, output voltage is V_{an} and V_{bn}. Immediately after P or at P plus, output voltage is V_{an} minus V_{cn}. Till P, P minus, output voltage is V_{an} minus V_{bn}.

So, just prior to P, V_{an} is at the peak, it is approximately sin 89 or so that is approximately equal to 1, whereas, phase B is 330 minus that is again half, minus half. So, V_{an} is 1, V_{bn} is minus half, so output voltage is V_{an} minus V_{bn}, it is again 1.5. So, during this instant, T_1 and T_6 were conducting. At this instant, T_2 is triggered, now voltage is V_{an} minus V_{cn}. It continuous for another 60 degrees, this is 60 degrees, mind you. See, this is 30, this period is 30 degrees and here is again 30 degrees.

So, in this instant, T_1 and T_2 are conducting. Procedure is the same to determine this output voltage. See, here is it. This is the procedure, V_{an}, now we need to consider … T_2 … Now, you will find that if I assume the current to be constant and repel free at I_L, T_1 conducts from this point till you trigger T_3 at Y. So, this is 120 degree duration. So, T_1 conducts for 120 degree duration, same as half wave rectification, 3 phase half wave rectification. Similarly, we have a common anode configuration, 3 devices forming a common anode configuration, again fed from an ABC system.

Now, each device in the lower half also conducts for 120 degrees. So, T_4 takes over at this point. Mind you, T_4 takes over at this point, alpha is equal to 0. So, this is the point of natural commutation for the lower devices. So in this period, T_4 conducts, direction of current is now reversed, just opposite to that of T_1 and it continues for 120 degrees. So, what observations can we make now? Each device conducts for 120 degrees but then each phase conducts power for 240 degrees. Each phase conducts power for 240 degrees. You just see, each phase conducts for 240 degrees, 120 here, 120 there.

At any given time, only 2 devices are conducting. At any given time, 2 devices are conducting. Just see here, T_1 and $T_{6.}$ T_6 is connected to phase B, T_1 is connected to phase A, phase C is open. In other words, phase C does not supply power in this period. At any given time, only 2 phases are on, third phase is open. How many pulses are there in 1 cycle? There are totally 6 pulses in 1 cycle.

I have just drawn 2 pulses and we found that each pulse is of 60 degree duration. Each pulse is of 60 degree duration, remember. There are 6 pulses per cycle and each pulse is of 60 degree duration. Each device conducts for 120 degrees. Each phase supplies power for 240 degrees. See here, T_6 $T_{1,}$ T_1 T_2.

Now see, there is a sequence T_6 $T_{1,}T_1T_2$ and in this region you will find that it is T_2 T_3 because T_2 is conducting, T_3 gets triggered here is T_2 T_3 and from here T_3 $T_{4.}$ That is why we have numbered as 1, 3, 5 in the upper half and 4, 6, 2 in the lower half. More, we will see in the next class.

Thank you.