Basic Electronics
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Module - 5
Power Circuits and System
Lecture - 8
SCR Applications

In the earlier classes we have seen how the current flows in a purely resistive load in an AC-AC converter. Now let us see what happens when instead of a purely resistive load we have a complex load having resistance and inductance in series. As there is inductance, the current through this load will not be immediately zero when the thyristor turns off. It will continue to flow for sometime even after the thyristor stops conducting. The voltage and current waveforms if we plot, then the current will start after firing angle alpha which is the angle at which the thyristor is fired and it will even continue after the thyristor turns OFF.

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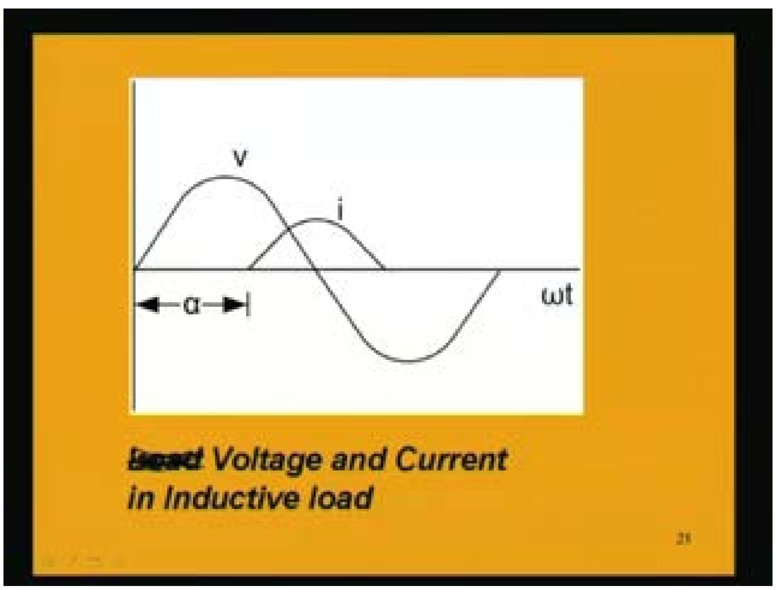

Let us find out what will be the current in such a load having inductance in series with the resistance.

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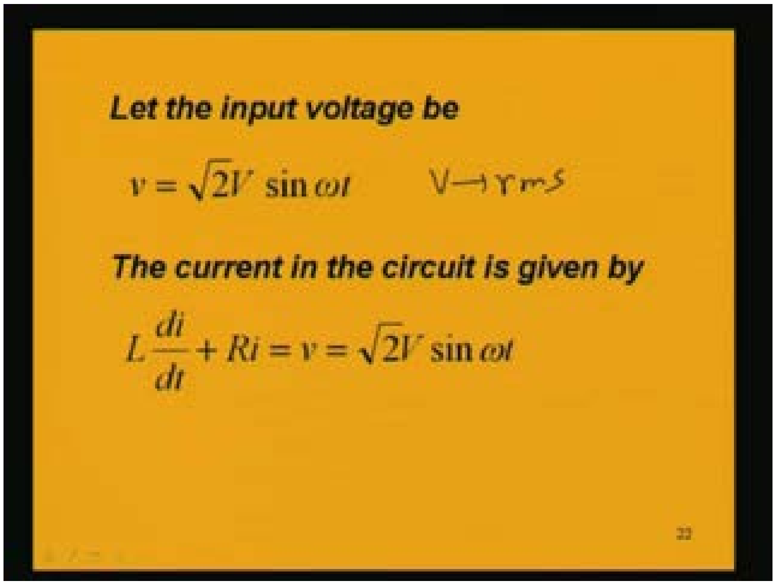

We will consider the input voltage to the converter as small v equal to root 2V sin omega t, where V is the RMS value. Here V is the RMS value of the voltage. So, root 2 into V means peak value is that much; it is V_m sin omega t, which is equal to root 2V sin omega t.

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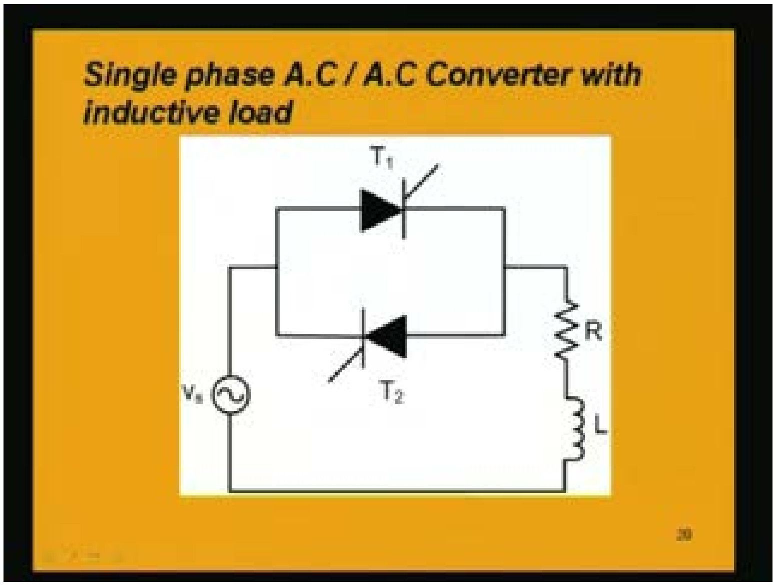

If we consider the current in the circuit, the current in the circuit when one turn thyristor is firing say thyristor T_1 fires in the positive half cycle at an angle of alpha, then what will be the current? That can be found out using Thevenin's voltage law, sorry Kirchhoff's voltage law in this circuit and the law will give us the equation which is L di dt, the drop in the resistance plus the drop in the inductance that will be equal to input voltage. Writing the Kirchhoff's voltage law, L di dt plus Ri equal to v, which is the input voltage and that is a sinusoidal voltage, so root 2V sin omega t.

We have to solve this equation. It is a first order differential equation.

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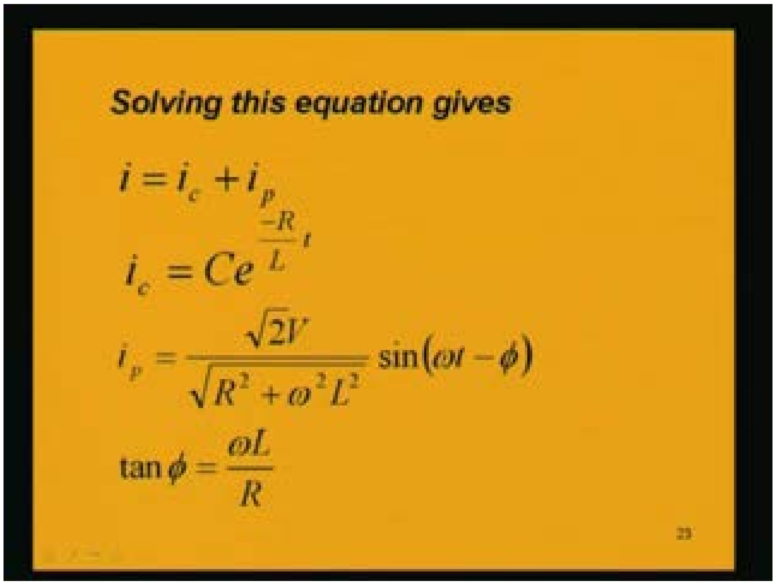

We know that solving this differential equation will lead to the current which is a summation of the complementary function of the particular integral. We have two portions in the solution. The complementary function will be given by Ce; C is a constant into e to the power minus R by L into t and the particular integral i_P is equal to root 2V by root over R square plus omega square L square into sin omega t minus phi. This is a standard solution I am using; instead of solving from the first principle, I am just writing down the equation's solution because it is first order differential equation. This phi is the phase angle which is given by tan phi equal to omega L by R. We need to know the constant C. So, we have to find out this constant C from the first principle. That is initial condition.

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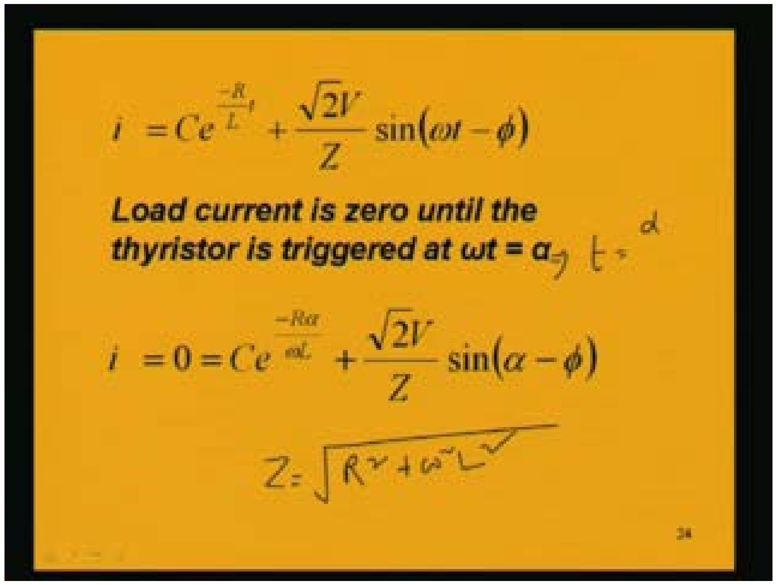

We will write the current equation i equal to C into e to the power minus R by L into t plus root 2V by Z. Z is nothing but root over R square plus omega square L square. This is the impendence of the load that is representing the Z and sin omega t minus phi term which is the steady state component, basically. Now we will apply the initial condition to find out the constant C. Applying initial condition means the current in the load will be zero till the thyristor is triggered and thyristor is triggered at omega T equal to alpha. We will use that condition to find out C. So, i will be equal to zero when omega t is equal to alpha. Putting here the value of omega t is equal to alpha gives us value of t equal to alpha by, if we replace here C into current, which is equal to zero and zero equal to root 2V by Z sin omega t equal to alpha; so, we will write omega t as alpha minus phi. The value of C can be found out.

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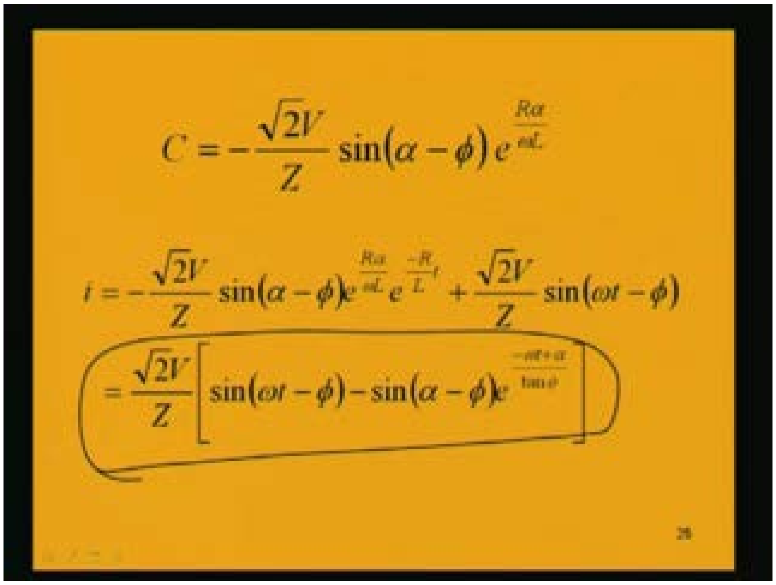

Here C is equal to minus root 2V by Z sin alpha minus phi. Now we can write down the value of i. So, i equal to C is root 2V by Z sin alpha minus phi into e to the power minus R by L t. So, e to the power minus R by L t plus the other term which is the stead state component. Now from this, we will get the equation for the this current i equal to minus root 2V by Z sin alpha minus phi e to the power minus R by L t plus root 2V by Z sin omega t minus phi. Finally we get an equation which gives the value of i and we can see that the exponential term is there and because of this exponential term the current in the inductance will fall very slowly.

It is not immediately falling to zero and depending upon the R and L, the time constant of the inductive circuit the falling of the current will take place. If time constant is high in comparison with the input cycle period, then there will be fall of this current very instantaneously. But if they are not comparable, if the time constant is not so high as compared to the period of the input voltage waveform then there will be significant lagging of the current and the current in the inductor will continue for considerable period. We have discussed about the AC to AC converter and we have seen how controlled power can be supplied to a load using the AC to AC converter which employs a thyristor.

Another application of thyristor is in rectification. Earlier we have seen rectification in diode circuits. The diodes were used for rectification and half wave rectifiers, full wave rectifiers we have discussed earlier; but thyristors can also be used for rectification. Here as it is dealing with high power, so sometimes it is easier and cheaper to use thyristors in rectification than using other metals. We will now discuss about some basic rectifier circuits using thyristor which will give the rectified output and using half wave rectifier and full wave rectifiers also we can get the rectified output, which basically employ thyristor in the circuit.

First of all let us take a simple half wave rectifier using resistive load.

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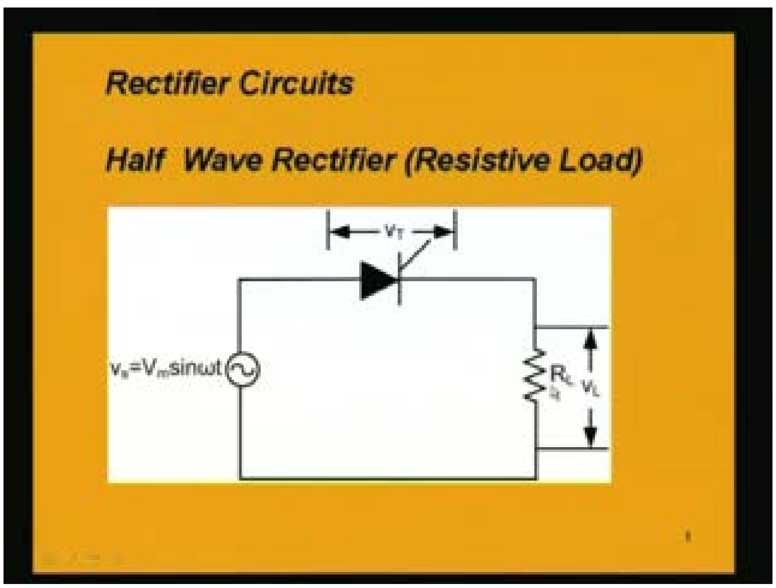

Here instead of the diode which we are using earlier in half wave rectification, we will have a thyristor and initially let us assume that the load is purely resistive. The input is sinusoidal V_m sin omega t which is given as the input. Let us take the voltage across the thyristor as V_T and the resistance has a voltage across it as V_L. We will try to find out the waveforms V_T and V_L also in this circuit.

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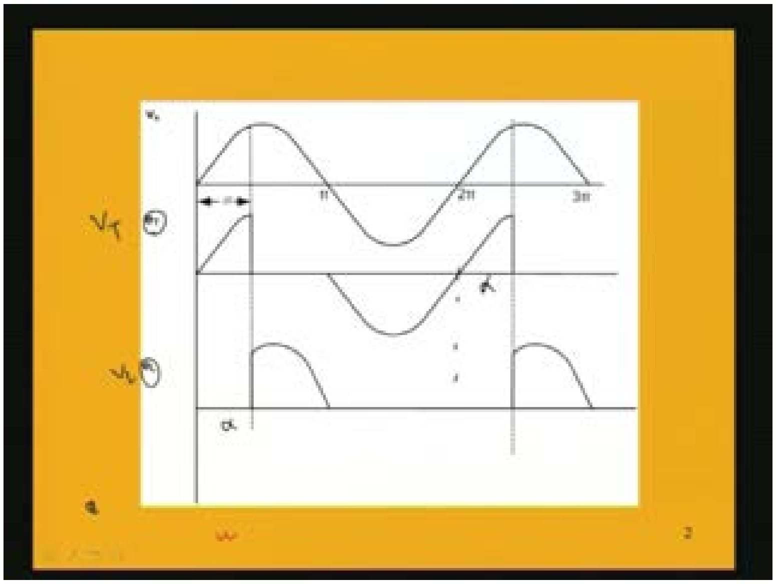

Input is sinusoidal V_S is equal to V_m sin omega t and we are having a single thyristor firing at an angle of alpha, say. When the thyristor fires at an angle of alpha, the voltage across the thyristor becomes zero. In comparison with the voltage at input, we can assume that the thyristor is having a voltage drop of zero because the voltage drop is very small and it can be neglected. Once it is ON or in conduction, the thyristor will have a voltage of zero across it. Up to the point of conduction the thyristor is not firing.

The voltage across the thyristor will be the equal to input voltage because we can see in this circuit (Refer Slide Time: 13:54) that the voltage across the thyristor when it is not conducting there is no current flow. So, voltage which is at the input will be equal to V_T. I am using symbol V_T and V_L here. What will be V_T? Initially it will be equal to the V_S. As soon as it starts conducting, it becomes zero. It will conduct till pi because after that the input voltage becomes negative. If the input voltage is negative that means there cannot be any conduction in the thyristor since the anode is now negative and cathode is positive.

This is reverse biased, so it will not conduct and that is why after this pi the thyristor is OFF and that is why the voltage across the thyristor is same as the input voltage. After this point again alpha angle is exceeded because alpha is the delay angle. After this point again it will have to wait for alpha and till then the input voltage will be equal to the voltage across the thyristor. Now what about the voltage across this load resistance? Up to the point of alpha that is till the thyristor conducts, the voltage across this resistance R_L will be equal to zero. Since no current flows, the thyristor is OFF. The voltage is zero because the voltage across the resistance equal to current into the resistance, so it will be zero till this point. As soon as the thyristor conducts or fires then what will happen? The voltage across this resistance will be equal to the voltage at the input because this drop equal to zero we are assuming; thyristor conduction voltage is zero. So, this voltage is equal to voltage across this resistance. It will follow this shape of the input voltage and after the pi, phase angle that will not conduct; the thyristor will not conduct. The current will be zero, so voltage will be also zero.

Again from this point till alpha angle is crossed the voltage will continue to be zero. Since there is no current flow in the resistance, the thyristor is not firing. The voltage is zero and once the thyristor fires again in the positive half cycle after this angle alpha is crossed, then the voltage across the resistance will be again equal to input voltage. These are the waveforms of the voltage across the thyristor and the voltage across the load.

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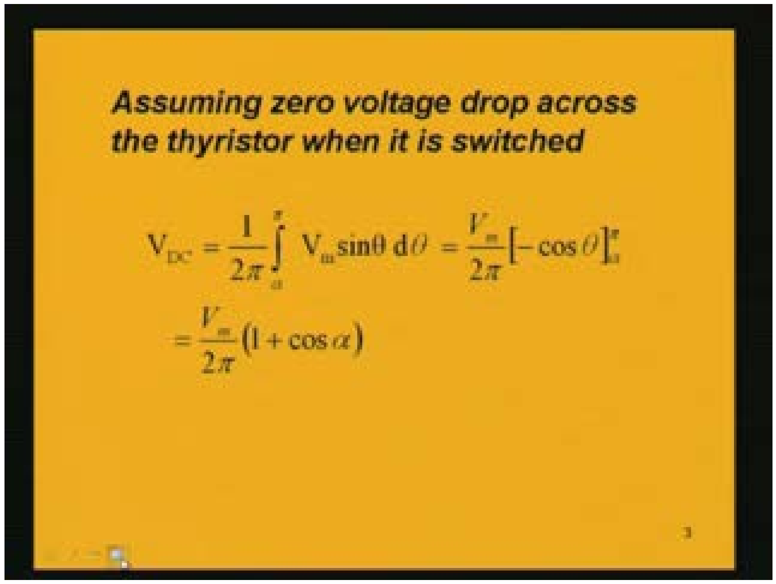

We can find out the voltage values. Assuming zero voltage drop across the thyristor when it is switched or fired we can find out the DC value of the voltage, DC value or average value because we are having a rectifier. It is a half wave rectifier.

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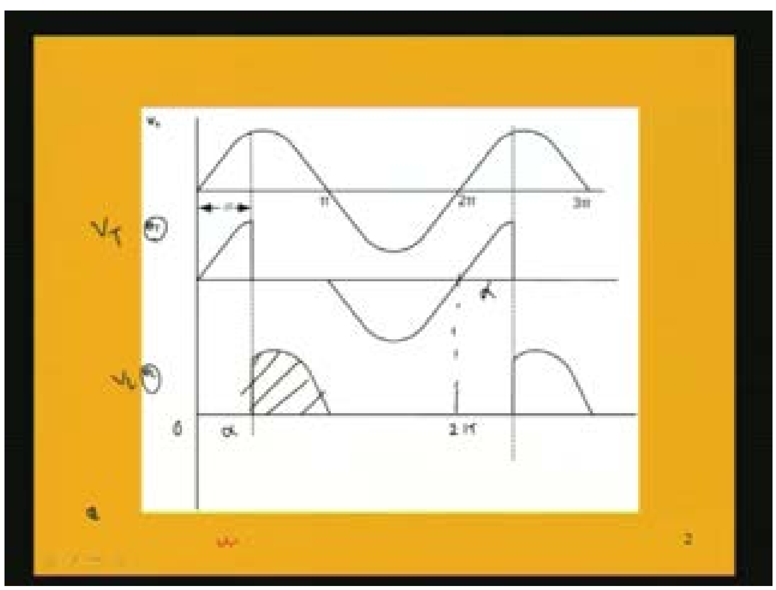

Using the expression for finding out the mean value or the DC value over the whole period 2 pi, we are getting the output voltage V_L within this region only. This is the region where we are having an output voltage in between from zero to 2 pi. From alpha to pi we are having an output voltage. The integration in the expression from alpha to pi will be. It is V_m sin theta because the output waveform is exactly following the input waveform V_m sin theta.

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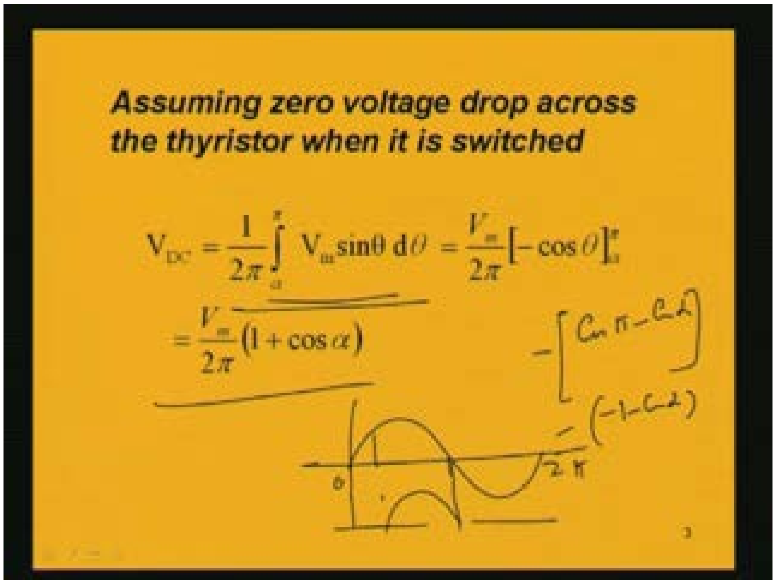

This integration V_m sin theta d theta between alpha to pi has to be done but multiplied by 1 by 2 pi because we are having the input voltage between zero to 2 pi if we consider output voltage will be between this portion only and the rest is zero in the whole period. In order to find out the DC value or mean value, we will use this expression and that is equal to, V_m by 2 pi constant part can be taken out; integration sin theta d theta will be give minus cos theta between the limits alpha and pi which is equal to V_m by 2 pi minus cos theta. If we put the limit it will be, minus cos phi minus cos alpha; cos phi is minus 1, minus 1 minus cos alpha so, 1 plus cos alpha. So, V_m by 2 pi 1 plus cos alpha. This is the DC value of the voltage for this resistive load.

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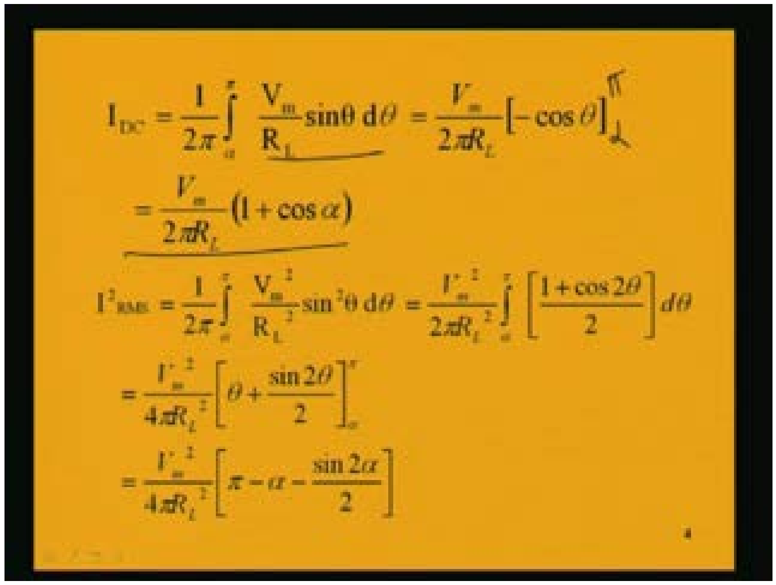

Similarly if we want to find out the current I_{DC}, by dividing the V_{DC} by R_L we will easily get the DC value of the current. That is what is done here. I_{DC} equal to 1 by 2 pi integration alpha to pi V_m sin theta d theta by R_L; R_L is the load resistance and it can be written as V_m by 2 pi R_L; integration sin theta is minus cos theta within the limits alpha to pi. Putting the limits we get V_m by 2 pi R_L 1 plus cos alpha. This is just a follow up of the DC value of the voltage. Dividing this DC value of the voltage by R_L, we get the DC value of the current and if we want to find out the RMS value of the current, then we have to do it according to the way RMS value is found out.

Square of the RMS value if we take, it will be 1 by 2 pi integration alpha to pi square of this expression V_m square by R_L square sin square theta d theta. In this integration, replacing this sin square theta in terms of cos twice theta, we will get finally the value of RMS square equal to V_m square by 4 pi R_L square; putting the limit we get pi minus alpha minus sin twice alpha by 2.

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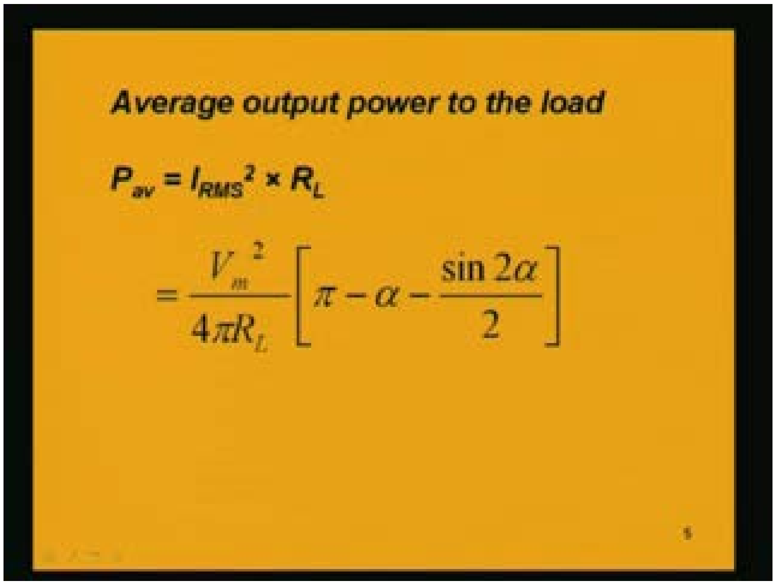

If we want to find out the average output power to the load, output power is nothing is I_{RMS} square into R_L; average output power to the load that is obtained as I_{RMS} square we have found out. Replacing this expression here and multiplying by R_L will cause the square in the denominator of R_L to vanish. What will be here is V_m square by 4 pi R_L into pi minus alpha minus sin twice alpha by 2.

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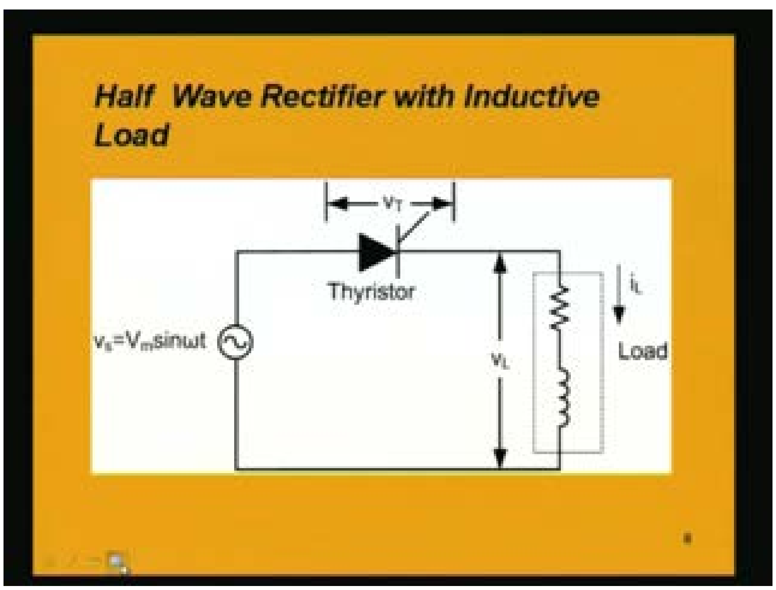

This example was using a resistive load. If the load is an inductive one that means instead of having a pure resistance we are having an inductance in series with the resistance as the load. What will happen to the half wave rectifier? What will happen here is that this inductance will not let the current to stop immediately to zero once the thyristor turns OFF. But it will allow the current to continue for some more time because the current cannot immediately become zero in an inductance. It will follow exponential curve.

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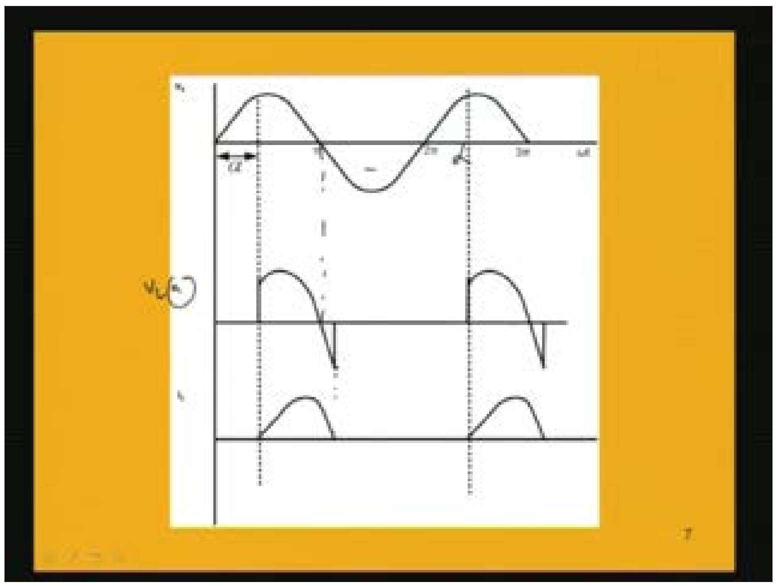

If we plot these waveforms in this circuit again this V_T and V_L and V_S, V_S is the same sinusoidal waveform, then the output voltage across this inductive load is equal to the voltage at input. But here after the thyristor stops conducting what will be this voltage? After the thyristor stops conducting, still there will be current flow for sometime. 2519 The thyristor stops conducting after pi, from alpha to pi it will conduct. But after pi also, if we project this point, after pi also, there will be a current flow due to which there will be a voltage available across the load and that voltage is equal to the input voltage. If we look into this waveform of the input voltage, from alpha to pi the thyristor is conducting. It is fired at an angle of alpha, it will conduct till pi. After pi, the input voltage waveform becomes negative that is why the thyristor will be turned OFF.

It should have current zero, but it will not have current zero. There will be current flowing in the circuit. That is why there will be voltage available across the load which is equal to the supply voltage. This is the supply voltage. It will follow the supply voltage and then only it will become zero. Till when the current flow will continue that will be decided by the load. The current waveform if we see from this point, there will be conduction of current. Current will start flowing and then after this point till this point also current will be flowing and it will become zero at this point. After this becoming zero, it will continue to be zero again till alpha is crossed. Again the current will start to flow and it will continue beyond zero value of the input voltage and after sometime only the current will become zero.

We have seen that there is voltage available across the load even after the zero of the input voltage is crossed to the negative side. This is a disadvantage or actually this should not happen because we are having a controlled half wave rectifier. But here in the negative half also there is voltage available across the load. In order to get rid of this negative voltage in the output what we can do is that, we can use a diode which is known as flywheel diode which will prevent the voltage across the load becoming negative. How it does that? Let us consider the circuit.

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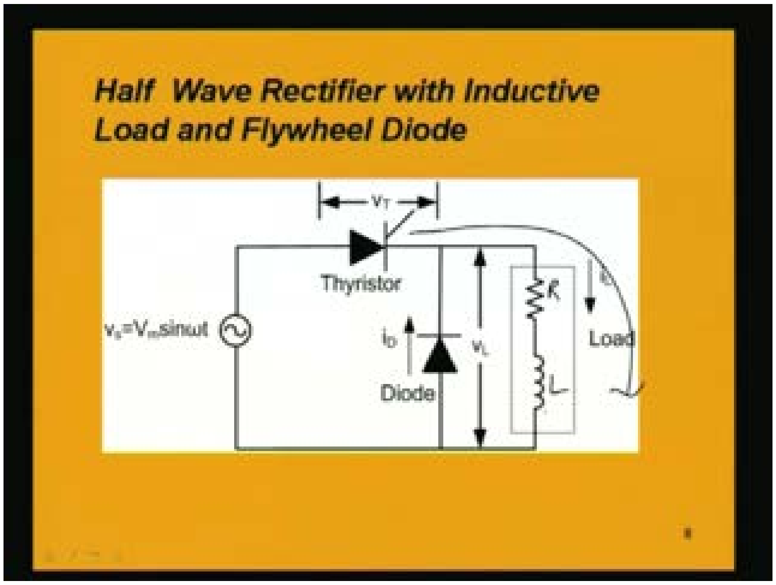

Here in addition to the thyristor which we were having in the half wave rectifier circuit, we are also having a diode. This is a normal or ordinary diode connected in the circuit. Basically what does this diode do? Let us see and try to understand the behavior of the circuit. We are having an inductive load as it is; a resistance and an inductance in series is the load. The current through this circuit is i_L say, voltage across this load is V_L. Now the thyristor fires at angle of alpha that is the delay angle. What will happen in the positive half cycle? After the alpha angle is crossed the thyristor will fire and it will cause the current flow through the load in this direction. The diode is reverse biased. It will not conduct in the positive half cycle anyway and we will get an output voltage across this resistance and inductance in series which is the load, which is V_L that is equal to the supply voltage.

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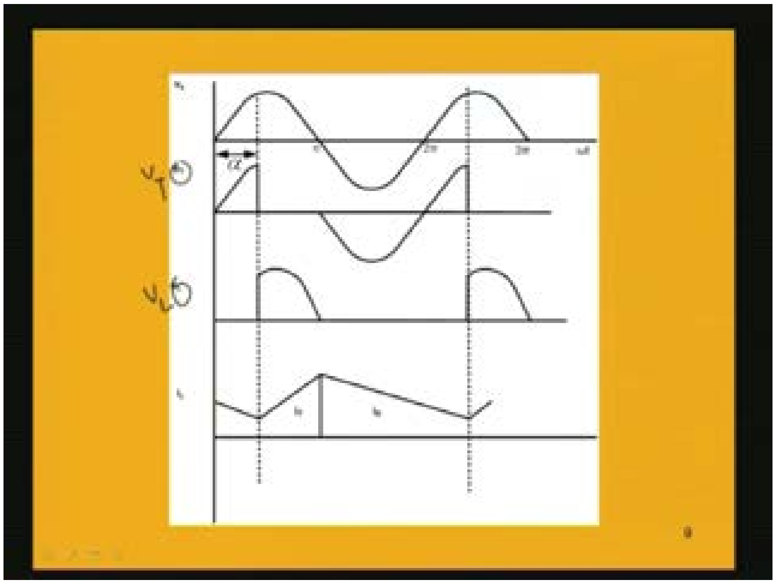

This is the input voltage waveform V_S, it is V_T, this is V_L. When we have non conduction of the thyristor, input voltage and thyristor voltage are same because it is not conducting. At this point it starts to conduct. It conducts or fires at this point. By using triggering voltage we are firing the thyristor and then it turns ON. Thyristor voltage becomes zero and that is the reason why in this region the thyristor is conducting. The voltage across the resistance will be now equal to the supply voltage, so V_L and V_S are same.

What will happen when the supply voltage crosses into the negative half cycle? When it enters the negative half cycle, then in the negative half cycle what will happen is that this anode is negative. But what will happen to the current through the load? Because we see that when the thyristor conducts, the load current is the thyristor current.

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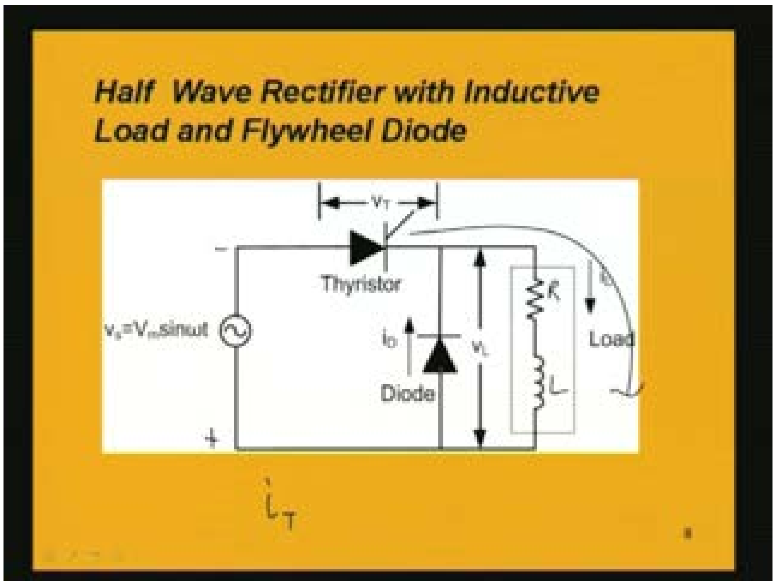

Thyristor has a current flow through it that is say i_T. We are naming this current as i_T; i_T is the current in the thyristor. When it is in the negative half let us consider this negative half; in the negative half cycle this diode is now forward biased. The current will be bypassed through this diode. The diode is conducting. The voltage across this diode is zero. This also we are assuming zero because it is very small 0.7 volt; it is almost zero. The voltage across the load is the voltage across this diode which is zero.

When it is in the negative half cycle, the voltage across this load is zero. Mind it the current flows, but that current will be now bypassed by this diode in this circuit consisting of load and the diode and the supply will not allow any current. We do not get the supply current through the thyristor but we are having a current in the load due to the diode current. That is the difference that the flywheel diode is making.

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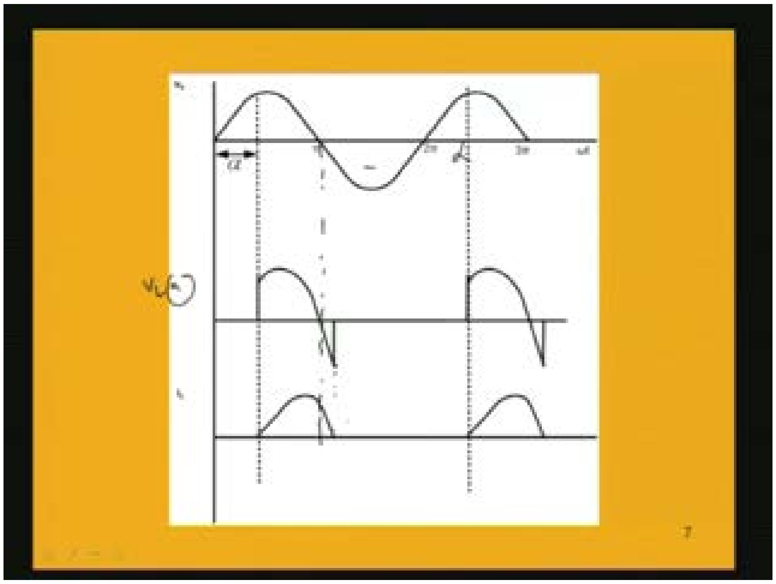

Earlier what we have seen is that in the inductive load, even when it was in the negative half cycle, the supply was in the negative half cycle at that time we were getting a voltage across the load which was negative. The supply voltage and load voltage were same and the current was flowing. In the negative half cycle also there was current in the load but here what we are getting is that there is current flowing in the load but that current is bypassed by this diode. It will not flow through the thyristor; earlier it was flowing through the thyristor. The current in the load was drawn from the supply. It was flowing through the thyristor in the load even when the voltage was in the negative. It was going into the negative half cycle because of the current in the inductor not becoming zero immediately; it was following an exponential behavior. That was the difference.

But here we have seen in this case, use of flywheel diode has stopped the voltage across the load becoming negative as was the earlier case. Now the voltage is zero but the current flows in the load. We are getting the current in the load. But that current is not through the thyristor, it is bypassed by this diode.

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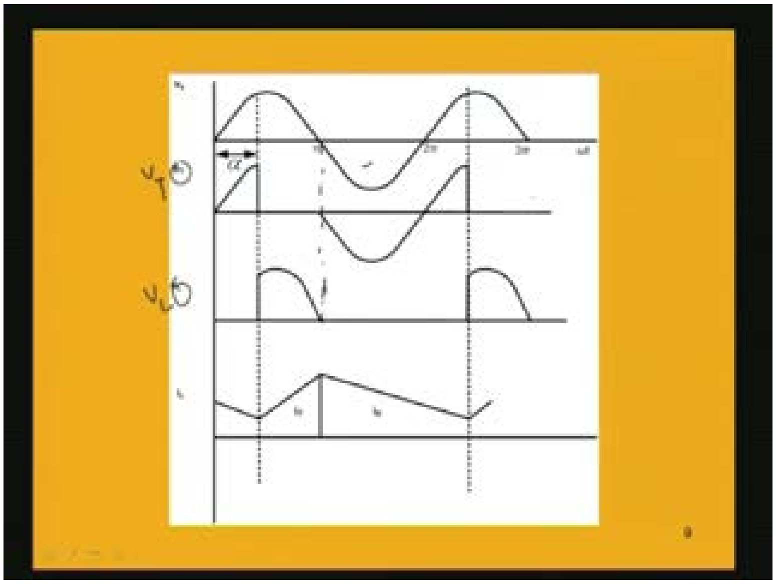

Here what is happening is that if we consider the load voltage or the voltage across this load, when the thyristor was not conducting it was zero. When it starts conducting it becomes equal to the supply voltage. But as soon as the supply voltage enters the negative region, then the thyristor stops conducting. Why the thyristor stops conducting is because this anode is positive and in the negative half cycle the anode is negative. So, it will stop to conduct and the voltage which we will obtain across this thyristor will be the voltage across this supply because if we apply the voltage law here, then the voltage across this is equal to the voltage across this, because this diode drop is zero. We get the voltage across the thyristor as the supply voltage; when again it starts conducting then again it will be zero and the voltage across the load will be zero. When the thyristor fires, then it will be equal to the supply voltage. As soon as the supply voltage becomes negative this voltage across the load will become zero because it is the diode drop, diode drop is zero. Again it will be equal to the supply voltage after the thyristor fires.

Now what about the load current? Load current is flowing throughout the period but this is contributed by two different parts. One is the diode current which flows when you have the negative half cycle. In the negative half cycle, as we know the current is bypassed through the diode and load current flows due to the current in the diode only and that is the current here, the diode current and it is exponentially decaying because it is flowing through the resistance and inductance in series. Because of this time constant of this load, the current which is contributed by the diode in the negative half cycle will fall exponentially and in the positive half cycle this is due to the thyristor current which is drawn from the supply but in this portion the current is due to the bypassing of the current by the diode. We will have a current which will rise and fall like this. The rising means it is because thyristor is conducting. When conducting, it is flowing through the load and thyristor only and that is why it will rise from zero onwards. Exactly this value is not going to become zero because it will fall exponentially.

We have assumed that the time constant of the load is sufficiently high as compared to the time period of the input voltage. Under that assumption it will not fall down to zero and it will fall and again it will rise like this. This rectified output is half wave rectified output and it is not present during the negative half cycle. That has been achieved by using a flywheel diode which is bypassing the load current in the negative half cycle.

We consider now a full wave rectifier using a center tap transformer. We were discussing earlier using diodes we were using a center tap transformer. Here also similarly we are using that type of circuit using a center tap transformer and two thyristors.

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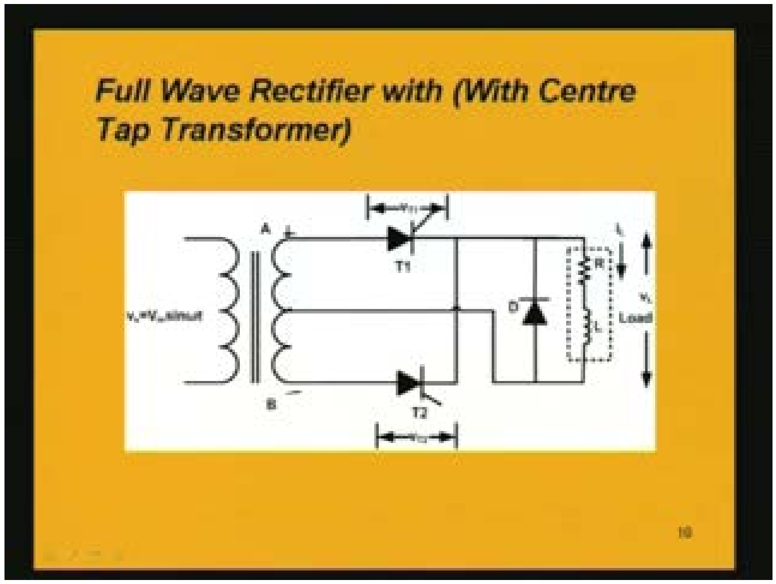

When we have two thyristors what will happen is alternately the conduction will take place; also we are having a flywheel diode. Here we are connecting the diode; as we have connected in the half wave rectifier, here also there is a flywheel diode and the load is an inductive load or a complex load R and L in series. The voltages across these thyristors are assumed to be V_{T1} and V_{T2}. We are applying sinusoidal voltage V_m sin omega t. In the positive half cycle of the input signal, the thyristor which will conduct is the upper one because in the positive half cycle of AB we are considering this secondary side of the transformer and we will analyze the waveform.

Let us consider the voltage across AB. The point A when it is positive with respect to B, it is a center tap transformer. It will be like plus and it will be minus, this point is the ground or center point is the ground. In this situation, the upper one thyristor that is T_1 will be forward biased or anode will be positive and it will conduct at angle of alpha, say. Both are identical thyristors, we are assuming. Conduction angle or delay angle is alpha. When it conducts after an angle of alpha this current will flow through the load and the voltage across this load, this voltage will be equal to this. This point is ground.

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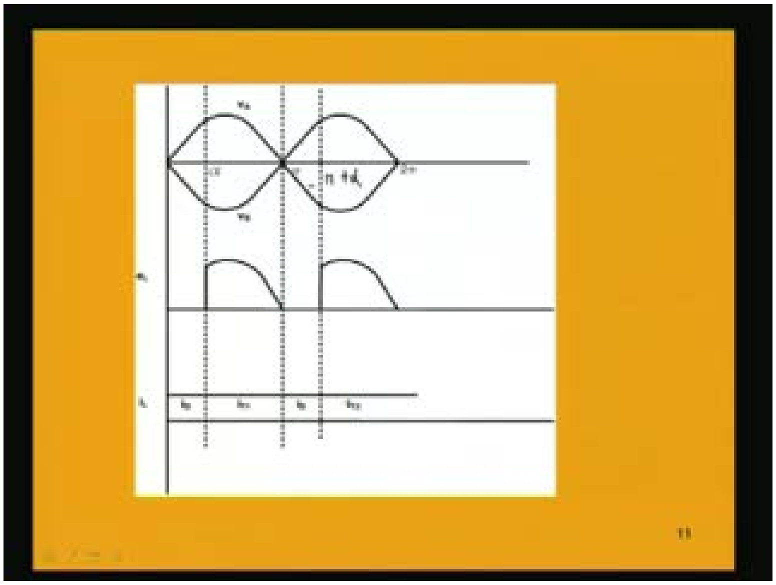

We are getting the voltage across this load following the voltage at the input that means at the secondary side.

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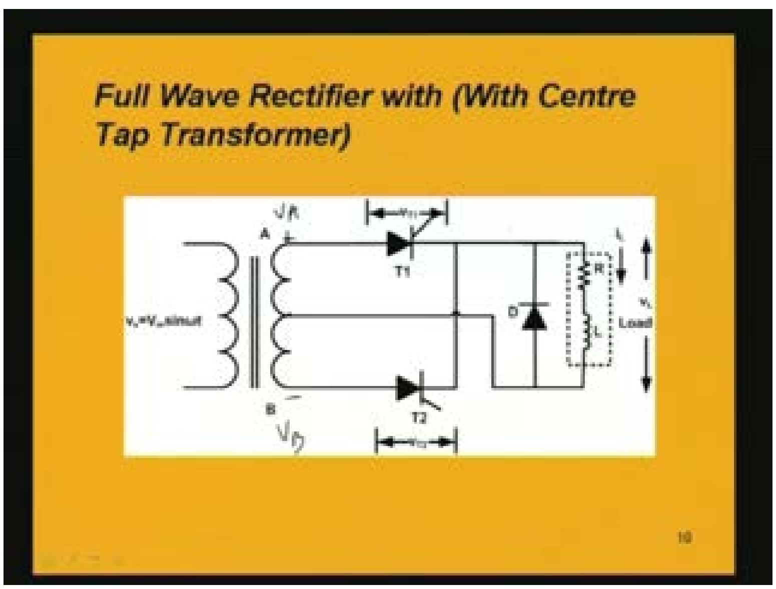

If we consider the voltage V_A here and V_B here, V_A and V_B will be just out of phase by 180 degree and so V_A will be like this and V_B will be like this. They are out of phase by 180 degree. Now what will be the output voltage? That will depend upon the current flowing through it. When the current flows through this load, the voltage across this load will be equal to this V_A when this T_1 conducts. That is happening here. When this T_1 conducts after angle of alpha, the voltage across the load will follow this V_m.

In the negative half cycle when the V_A enters negative half cycle, V_B becomes positive. But the conduction will not take place in the lower one thyristor T_2 till another angle alpha beyond pi. That is it will conduct at pi plus alpha only. Within this region that is from pi to pi plus alpha V_A enters negative half cycle. What will happen when V_A enters negative half cycle.

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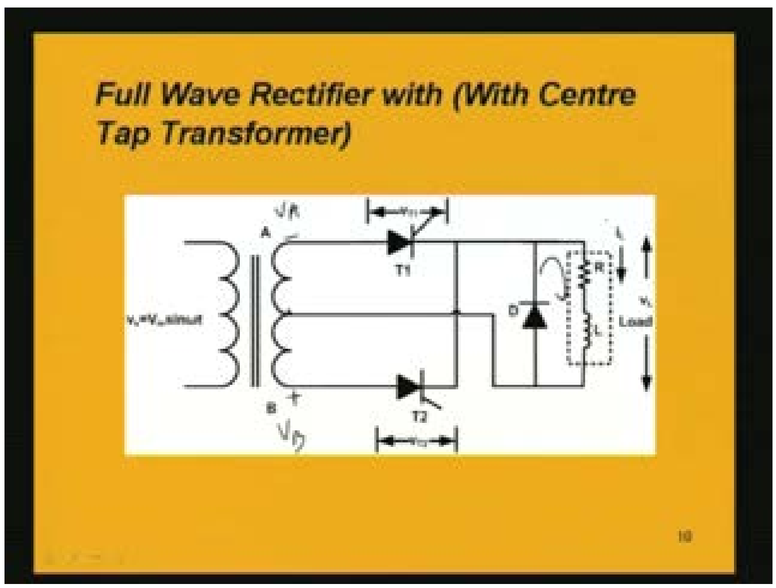

Now this becomes negative with respect to B. This is ground. What will happen is that if we look into the diode D, then this n is negative; that means the n is negative with respect to this p and this means it is forward biased. As soon as this V_A enters the negative half cycle, then the diode D will be forward biased. The load current which is flowing, I_L is the load current, will be contributed by the diode current only. The current will not flow through this transistor but we will have a load current which is contributed because of the diode. Since the diode is forward biased it will bypass that load current in this way, in this fashion and what will be output voltage across this load? This voltage will be equal to the diode voltage and which is equal to zero; this voltage equal to zero.

In the full wave rectifier here we have seen that during the portion when the V_A goes into negative half cycle before pi plus alpha angle, this is pi plus alpha, we have the voltage across this load zero, but the current which is flowing in the load that is almost constant because here the current which is flowing is the diode current. When the thyristor T_1 was conducting, the current was due to this i_{T1}; i_{T1} means the thyristor current which was drawn from the supply because the current flow was from the point A through this load to this point, center or ground and that current we are denoting by i_{T1}. But when V_A enters into the negative half cycle the diode conducts. The thyristor T_1 is now turned OFF since anode is negative and the load current is due to the diode current. If the R and L, the time constant of this circuit is properly chosen then we will have almost a constant current like this although contributed by two different components. Each time we are not getting the same contribution from the same component but here it is the diode current, here it is the thyristor current but we will have almost a constant current.

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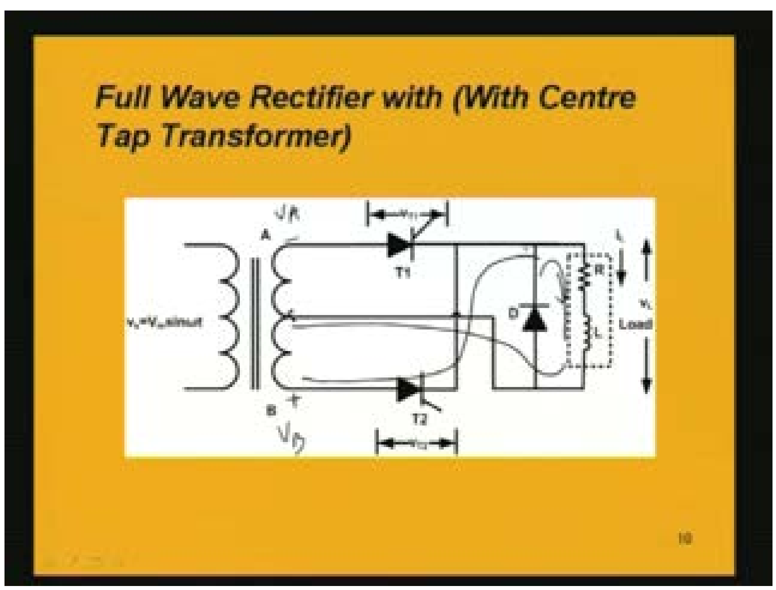

In the other half cycle, that means when V_B is in the positive half cycle and after pi plus alpha then the thyristor T_2 will fire. The thyristor T_2 will conduct now because it is positive, anode is positive. When this thyristor T_2 is conducting, then the load current will flow from positive like this and it will conduct and current will flow through the load and it will enter the ground. Through the load, the current enters or flows in the same direction in the both the cases. The current in the load is due to the thyristor T_2 that is iT_2 and again when it will be entering the negative half cycle then your V_A will enter the positive half cycle. When V_A is entering positive half cycle, then the diode current will flow.

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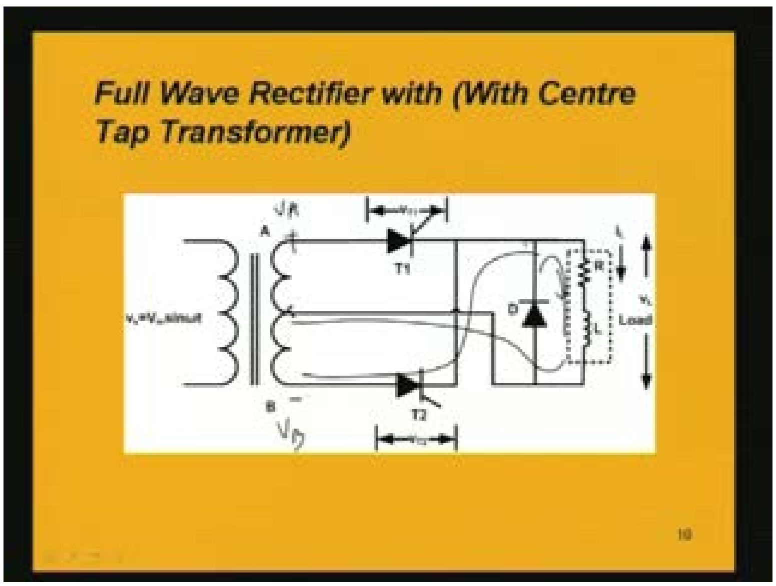

If we consider now positive half cycle, and it is below this alpha. That means it is below the firing angle. Then also the diode current will flow and so, it will continue.

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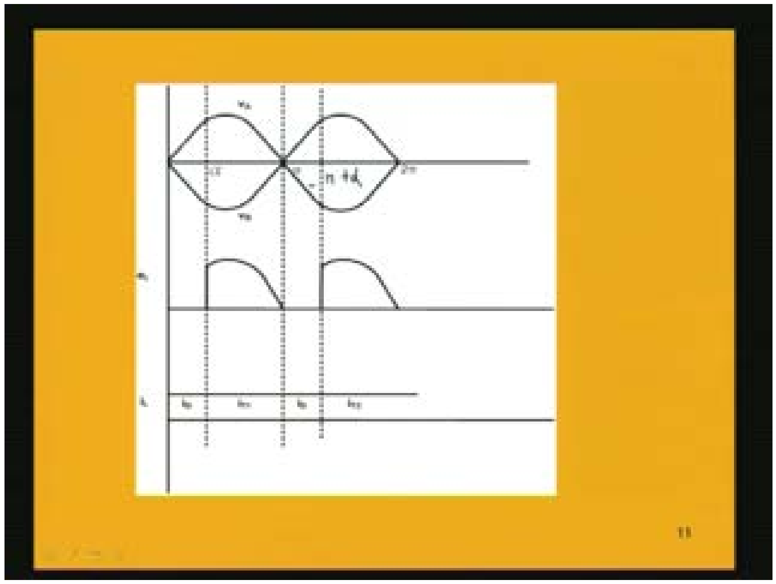

What is important here is that it is full wave rectifier. We are not getting a negative voltage across the load as we were getting without the flywheel diode. But here during the positive as well as negative half cycle of each signal we are getting output waveform across this load. That means we are getting the output voltage across load and in between the conduction by the two thyristors the voltage is zero. When the diode is conducting, the diode voltage is zero. This is typically the output voltage waveform for a full wave rectifier using center tap transformer and flywheel diode. Here we have seen that the rectification using this thyristor will have output waveform across the load with no negative portion. Similarly there are also circuits for full wave rectifier using bridge.

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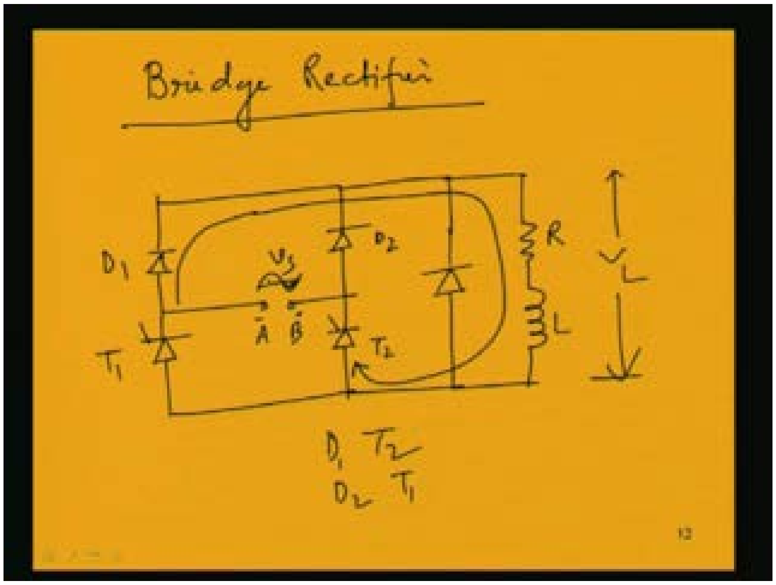

If we consider a bridge rectifier bridge type rectifier using the thyristors, we will have thyristors. In addition to those thyristors we will also use diodes - the circuit for a bridge rectifier. We are using single phase bridge rectifier, we are till now considering single phase only but it can be extended to three phase also. What will be the shape of the bridge rectifier? It is having diode and thyristor in series like this. We will have pairs of diode and thyristors; they will conduct in pairs. Here this is say D_1, this is say T_1; this is D_2, T_2 and the supply is given between A and B which is a sinusoidal supply V_S. Apart from this diode thyristor pairs, we will have a single diode connected in this way across this load R and L. This is a single phase bridge rectifier circuit. The voltage across this load is V_L say.

Here what will happen? This v_S when it is in the positive half cycle we can see that the diode D_1 and the transistor T_2 will conduct. In the positive half cycle, this diode D_1 and T_2 will conduct. These pair will conduct and in the negative half cycle, when this is negative, in the negative half cycle it is like this. We are having the diode D_2 and T_1 conduct. In pairs they will conduct and the current will flow through the load after firing of the thyristor. Because only after firing of this thyristor T_2 this loop will be complete and the current flow through this load will occur.

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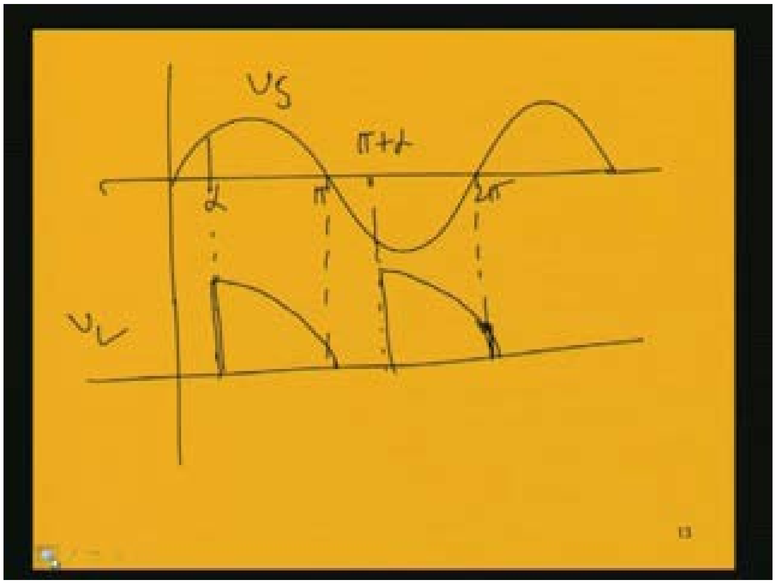

When this thyristor say T_2 is conducting in the positive half cycle, the voltage across this load V_L if we consider, if this is the input voltage v_S, then if we draw the voltage V_L that is the voltage across this load, here say alpha is the angle and pi; this is again pi plus alpha and this is 2 pi like this. So, the V_L will follow the input voltage like this and from here to here, the other pair will conduct and we will get the voltage like this. We will get this output voltage, the rectified output voltage but the difference between the earlier rectifier using center tap transformer and this bridge rectifier is that we are having pair of diode and thyristor which will conduct one pair in one half cycle and this is the diode which is there to prevent the output voltage to become negative.

Today we have seen the application of the thyristor in rectification. We have studied about the half wave and full wave rectifier and we have also seen for an inductive load how the flow of current in the load takes place for the presence of a diode and how the voltage across the load which goes negative when the thyristor does not stop conduction can be prevented by using a flywheel diode. Using a flywheel diode we have seen that the voltage across the load is stopped from going down to negative values and we get proper rectified output across the load. The thyristor in this way is used in many of the applications which are useful in power control.