Power Electronics

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Lecture - 5

Controlled Rectifier Part-4

(Three Phase)

Here, we will talk about the commutation process or the commutation over lap and due to commutation over lap, what happens to the output voltage repel. Here also, instead of going to the three phase fully controlled converter, we will take the semi converter or the three phase mid point configuration and we can explain the same thing for the three phase fully controlled converter also.

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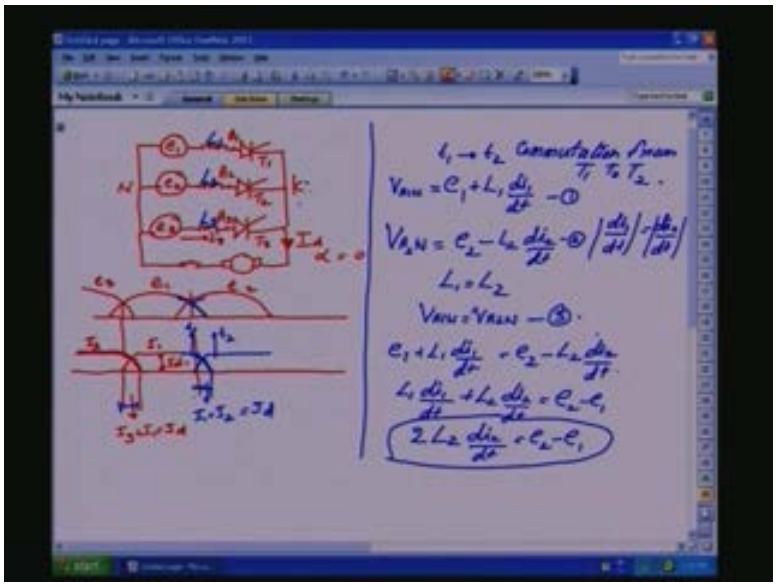

So, let us draw the schematic of the three phase fully controlled converter. This is my e_1 phase, this is my e_2 phase, this my e_3 phase, this is my neutral side phase, mains node. So, the finite inductance, it can be the line leakage inductance, transformer leakage inductance or we have deliberately introduced to avoid the short circuit between the phases during the commutation over lap. So, this is my thyristor, this is connected like this. I will mark these points for the analysis as A_1, this point as A_2, this point as A_3 and this is my point K. So, between K and N, we will be connecting the load. Here, we will represent it as a dc motor.

Now, how the commutation over lap? Let us draw the waveform. Let us draw for easy to understand, easy to explain. Let us assume alpha is equal to, firing angle alpha is equal to 0. So, let us draw the waveform. This is the half side of my e_1, half side of my e_2, this is my e_3; e_1 e_2 e_3, negative portion we have not drawn.

Now, let us see, this is alpha is equal to 0 starts from here. At this point, the T 3 that is 3, T 1, T 2 and T 3, at this point, till this point, T 3 was conducting, now T 1 will be turned on. So, what will happen and assuming load is highly inductive, we will assume the output current, the load current this one that we say as Id is clearly dc. So, we are not worried about the repel part. So, what will happen to the current? How the commutation, how the current transfers from one side to other? Let us see.

At this point that is here, I_1 will conduct, slowly conduct and I_3 will be I_3 is the current flowing through T_3 will be slowly coming to 0. So, I_3 will rise like this no sorry I_1 will rise like this and come to Id stay there and till now, the load current was supported by sore contrast flowing through T_3, so we will call this as I_3. So, I_3 the net value, this the this value is Id, the amplitude of this one is but this is the current, this portion of the current, this is the current, load current; this portion of this portion of the current, the load current flowing through I_3 T 3 and here, it is flowing through T 1.

Now, load is highly inductive so that as the current builds up along I_1 I_3 will decrease such that we can assume I_1 plus I_2 is equal to Id because load is highly inductive. During this portion, we can assume I_3 plus I_1 is equal to Id and finally, the current through I_3 decreases and fully after sometime, it will fully, the full load current will be taken over by I_1.

Now, again here, at this point, T 2 will be turned on. So, when T 2 will be turned on, we can use different color so that it will be here T 2 will be turned on. At this point, till this point, I_1 is equal to Id that is the current through T_1 will be Id and from here I_2 will slowly come into picture and thyristor T_1 will be switched off by T_2. So, current will slowly decrease like this and I_2 will slowly increase like this. So, this portion is the I_1 portion. Here also, during this period, we can assume I_1 plus I_2 is equal to Id. So, what happens?

Whenever there is a commutation, whenever we have initiated a turn on of the thyristor, momentarily both the thyristors will be turned out that is this portion during this period; this period T 1 and T 3, this period T 1 and T 2 and we can also from the voltage waveform here, the instantaneous values of the voltages are not the same in this portion and this portion during the commutation overlap. So, there is a difference in the voltage. This voltage has to be dropped across some element. For that purpose, we have put this inductance or many times the transformer leakage inductance may be sufficient.

Now, let us find out during this period, what will happen to the output dc voltage. The interval we will take it for T 1, the commutation from T 1 to T 2, we will take for the analysis. So, this period we will take as this is the period T 1, this period we will take it as T 2. So, during the current transfer from T 1 to T 2, from this figure; what is V_{A1N}? V_{A1N} is equal to e_1 plus let us for we will say the leakage inductance, this one we will make it as this is L_1, this is L_2, L_3. But now practical case, L_1 is equal to L_2 is equal to L_3; just for easy analysis, we will make it as L_1

into di 1 by dt and during the period that is period from T 1 to T 2 that is commutation from commutation from T 1 to T 2.

Now, during this period, during the commutation overlap; what is V_{A2N}? V_{A2N} is equal to e_2. See here, e_2 minus L_2 di by dt. See, here plus, here minus because in one case, e_1 current is decreasing. So, di by dt is negative, so polarity will be trying to aid the voltage here at the e_1 side and in the other case, current is increasing, so it will be trying to oppose L di_2 by dt. So, V_{A2N} will be e_2 minus L_2 di_2 by dt.

Now, for analysis, the assumptions, we can use some assumptions. One assumption what we made; we cannot take the all the practical, all the non idealities into concentration if you are try to solve the equation, it will be complicated. So, some engineering assumptions so that the final conclusion will not be not very far away from the reality. So, we will assume the current rise and fall is approximately linear. Assume we are neglecting the load repel current, we will assume current is highly inductive that means the load inductance is much much higher than the leakage inductance so that the change in the leakage inductance current we can assume approximately linear so that during this period, the magnitude of di_1 by dt is equal to di_2 by dt that is the magnitude and also I_1 plus I_2 is equal to Id.

Now, if you see here, the voltage drop across the thyristors or we can assume the voltage drop across the thyristors are negligible and we can also assume L_1 is equal to L2. So, what it shows? So, you see, if we assume that the voltage drop because both are conducting T1 and T2 are conducting, the voltage drop across T1 and T 2 are negligible; then e_1 and e_2 will be A_1 and A_2 will be shortened to K that is this point. So, V_{A1} during this portion, V_{A1N} is equal to V_{A2N} that is from equation 1 and this is 2, this is 3.

So, V_{A1} is equal to V_{A2N}, so from 1 and 2, e_1 plus L_1 di_1 by dt is equal to e_2 minus L_2 di_2 by dt. So, then bringing back e_1 e_2 one side and di_1 by dt terms on the other side, we can say we can write L_1 di_1 by dt plus L_2 di_2 by dt is equal to e_2 minus e_1 and also we said L_2 is equal to L_1 is equal to L, so we can say or L_2, we can say 2 into L_2 di_2 by dt is equal to e_2 minus e_1. What it shows? During commutation over lap when the both device are conducting, during commutation over lap when both device are conducting, the difference in voltage; here e_2 minus 1 will be dropped across the leakage inductor. So, your leakage inductance is very much for these type of converters.

Otherwise, let us let us assume that L_1 and L_2 are not there and both thyristors are conducting; this e_2 minus e_1 difference will heavy circulating current will flow, it can damage device or the transformer. So, this leakage inductance is required. Now, we have introduced the leakage inductance for one purpose. Now, this part, we have not, this commutation overlap, we have not taken into consideration while deriving the E_0 alpha that is output dc voltage with respect to the firing angle.

Now, what will happen to the terminal voltage or the output voltage due to these firing angle or during this commutation overlap, what is the nature of the voltage repel across the load; we will we will derive that one now. Let us go to the next page now.

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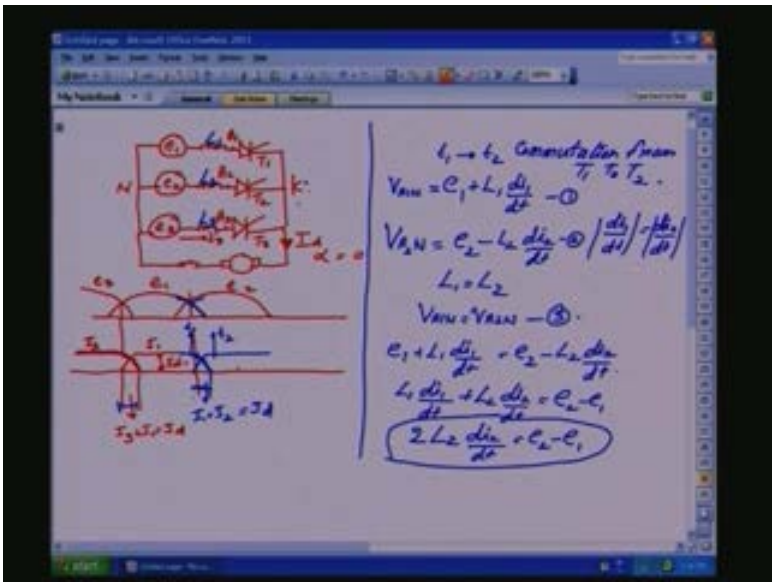

Clarity, quickly I will write this portion; e_1 e_2 e_3, this is N, this is the leakage inductance part, then T 1, T 2 and T 3. This is K, A_1 A_2 A_3 and our load. Now, during the commutation overlap, during the commutation overlap, during the commutation overlap, V_{A1N} is equal to e_1 plus L_1 di_1 by dt V_{A2N} is equal to e_1 minus L_2 di_2 by dt. Also, we said we are assuming the drop. These two thyristors are in the on condition, so the voltage drop across device is 0. So, V_{A1N} is equal to V_{A2N} will be equal to V_{KN}. So, this implies V_{A1N} is equal to V_{A2N} is equal to V_{KN}.

So, what will be V_{A1N} plus V_{A2N}? V_{A1N} plus V_{A2N}? If you see this equation, the rater change L_1 d i_1 by dt L_2 di_2 where the same but this one is positive and one is negative; so, this will cancel. So, V_{A1N} plus V_{A2N} will be equal to e_1 plus e_2 is equal to $2V_{KN}$. What is KN? KN is instantaneous repel voltage across the load. So, V_{KN} is equal to e_1 plus e_2 by 2.

So, during the commutation overlap, previously we assumed that the moment commutation started, the moment T 2 is turned on, the thyristor T 1 will immediately go, there after the voltage repel is the part of e_2. But during the commutation overlap during that small period; that depends on inductance we have produced, we have introduced and also depend on the maximum load current that period. This will be equal to e_1 plus e_2 by 2 that means during that period, the output repel is not T 2 but is e_1 plus e_2 by 2. So, what will happen if you plot the waveform?

So, let us again draw the output repel, output waveform, only the positive side. So, this is our positive side of e_1, after 120 degree we have e_2, then we have the e_3; e_3 e_1 e_2. So, during this commutation, let us say commutation overlap is from this to this one; during this period, it is e_1 plus e_2 by 2. So, if you see here, e_1 plus if the commutation is instantaneous, it would not started from here that is assuming, let us say the commutation is instantaneous, instantaneous means here T_3 will be off and T_1 will be on, immediately from this point, the commutation starts. So, let us highlight with a different color. So, it will be more clear.

So, instantaneous means it will start from here. But now, due to the commutation overlap, it will never start with the same point at this point. What will happen? During this point, it will be e_1 plus e_2 by 2. So, if you see, the net repel, it will be something like this; that means some portion some area is lost in the output voltage control. So, it will go like this. This is true in every cases. So, this much is lost. That means now, this much area is lost that means there is a reduction in the output voltage due to the commutation overlap. How to find out the reduction in the commutation overlap? This we can find out from the previous figure during which the current was, this figure, see assuming the current I_2 is slowly increasing and I_1 is decreasing.

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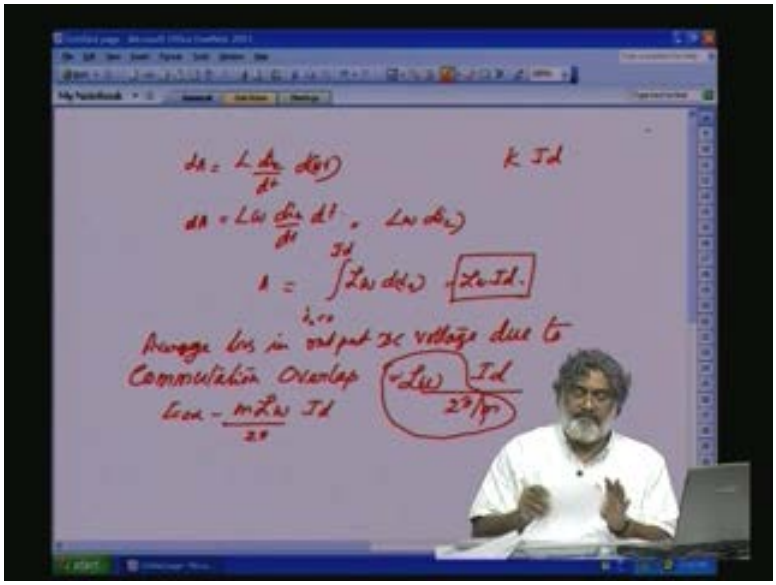

So, during this portion when the I_2 increases during this portion, the voltage drop, the net area of the voltage on the volt second if we take the voltage along the inductance, it will be equal to, we will go to the next page, when the current is slowly rising in the limp in the limp where the thyristor T 2 is connected, the volt second let us say the area dA is equal to L into di_2 by dt into d omega t or exactly d omega t; this much, so this will be equal to this d omega t, so omega is will not be, omega is constant, so we will bring it outside. It will be di_2 by dt into dt but if the commutation was instantaneous, immediately the limp 2 will have the load current dc current and there is no drop across the inductance L_2.

Now, because during the commutation overlap, there is a drop across the inductance that drop is equal to L into di_2 by dt and what is the volt second? That area L i_2 by di_2 that is the voltage and extacy d omega t. So, that will be equal to dA is equal to L omega di_2 by dt into dt. This is equal to L omega di_2. Now, this is an instantaneous that a small area loss, that is the small area loss during the commutation process. So, total area loss during the full commutation process is when i_2 start from 0 to Id so the area A lost is equal to integral I_2 is equal to 0 to Id L omega into di_2.

So, as the current increases from 0 to Id, this much area volt second is loss from the output, output from the output dc commutation. This will be equal to L omega into Id. This happens

during this much area lossed in the integration. Previously, we are integrating the voltage; now but from that total area this much will, area will be lost during every commutation.

Now, for a general m phase; what is the period for half bridge? 2 phi by m. So, the net voltage, so the average voltage drop lossed, this has to be subtracted from the output voltage. So, average average loss in output dc voltage due to due to commutation overlap is equal to L omega Id by 2 pi by m. So, this much has to be subtracted from our previous computed ideal conditions, computed output dc voltage that is E_0 alpha minus m into L omega Id by 2 pi. This much is lost.

This L omega, for a converter, this is a constant; L omega sorry L omega into the whole thing, L omega, let us clear it. So, I will rewrite it again; L omega divide by 2 phi. So, this portion, the whole L omega divided by 2 pi m is a constant for a particular converter and then if you see here, the dropping voltage that is the V_0 the dropping voltage is equal to some constant K into Id. Id is the maximum output load current. So, this can be assumed as a resistive drop because this constant into Id as an internal resistance of the converter and converter can be we can model like this; you have the…

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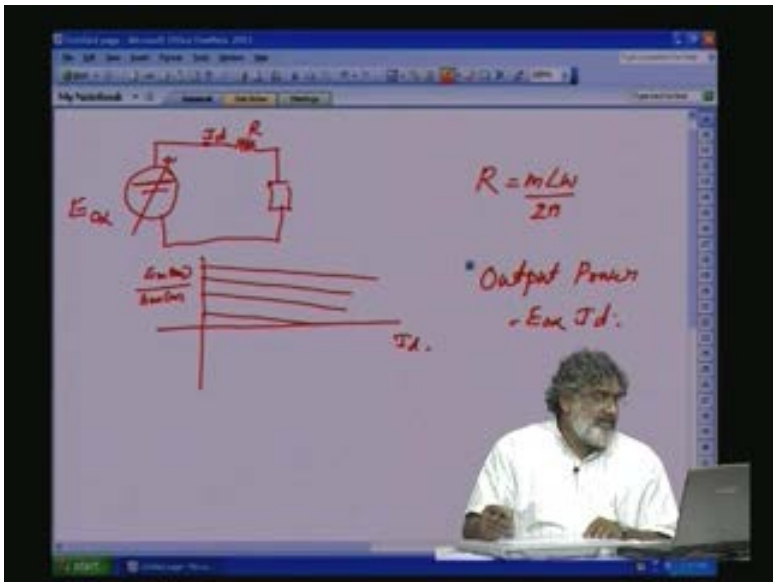

So, the converter will be this is variable dc voltage, that is our E_0 alpha that is why put variable here, then Id is going, then have an internal impedance that is equal to this value internal impedance R. R is equal to m L omega by 2 pi. m is the number of phases. For three phase, it is 3 L omega by 2 pi into R. Then you have the load here, this way. So here, if you see, the Id verses Id is the load current verses our E_0 alpha maximum divide by sorry E_0 alpha divide by E_0 alpha maximum just the Id varies, this is a drop happens like this.

So, as Id varies, sometimes the output voltage can vary and depending on the Id, sometimes it can be a 0 also. So, this we have to take into consider, this commutation overlap due to leakage inductance indusly we are putting or due to the circuit inductance, there was a drop in the voltage. For a three phase converter, it is L omega m by 2 pi; for three phase fully controlled, it

will be again multiplied by 2, 6 times it happens. So, this voltage drop you should take into consideration while designing your converter with load for control application. This is some of the some of the problem associated with non ideality of the phase controlled converter.
Now, so far we said, we start from single phase converter, then we are going through the we are going through the semi converter fully converter converter, then three phase mid point configuration, then we have come to the three phase fully controlled converter, we have derived the output dc voltage with respective to firing angle for semi converter as well as a fully controlled converter, then we have also did some more the typical output ripple for the and we have noted the ripple frequency for three phase as well as fully controlled converter.

Then we found commutation is not instantaneous, we introduced the commutation over lap and due to the commutation over lap, we found that there is an output voltage dc reduction. Even though with the same firing angle is used as the Id is increased, the output voltage is slowly drooped, there is a droop. That droop depends on the Id and the internal impedance. Internal inductance we are represent as 3 L omega by 2 pi.

Now, we are using the phase controlled converter for output voltage control. So, we are using the phase controlled converter with firing angle for output control. So, if you see, the output power will be equal to, output power power, assuming load is highly inductive, we will take the dc value of the current; output power from the converter output will be equal to E_0 alpha that is the dc with output dc with respectly firing angle and Id.

Now, what will happen to the input power? Input power, input is a sinusoidal voltage and what type of input current drawn from the converter? Let us see for a single phase fully controlled converter.

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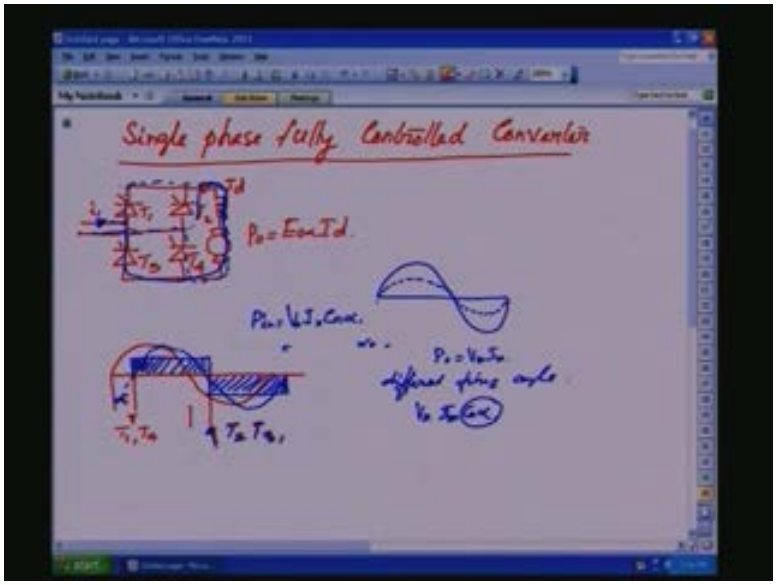

Let us take the single phase fully controlled converter, controlled converter. Now, let us draw the half circuit schematic thyristor. These are single phase, comes here. Let us see, this is our i_1, i_1

we represent as input and we will assume the load current is nearly sinusoidal, triple part we will neglect for analysis. This is our Id, load current, this our V phase waveform. So, let us draw for the V phase waveform; what will happen? Output power is equal to P_0 is equal to E_0 alpha into Id. The E_0 alpha we have derived for a single phase fully controlled converter.

Now, let us see what will happen to the input power that is AC side. If you see here, we will draw the mains waveform first. This is our input mains waveform. Now, let us mark the thyristors; this is T 1, this is T 2, this is T 3 and this is T 4. Now, let us say when the firing angle is equal to alpha, when firing angle is equal to alpha from here, this is alpha; from here onwards, we are turning on S_1 and T 1 and T 4 and for the negative side, firing angle alpha from here to here, we will be turning at this point, we will be turning on according to diagram T 1 and T 4 together and at this point, we will be turning on T 2 and T 3.

Now, when the T 1 and T 4 is turned on, the load current Id will pass through T 1, Id will pass through T 1 and Id will pass through T 1 that is through this way, come to the load and through T 4 and it will transfer. So, what will happen? Till the T 2, T 3 is fired, the load current Id is going through T 1 and T 3, this is the load current portion, this is Id, this height is Id. The moment at this point, when T 2 and T 3 are turned on because already the voltage has become negative, it will reverse bias T 1 and T 4 and T 2 and T 3 will conduct immediately. Here also, for easy analysis, commutation overlap, we will neglect; we are aware of the commutation overlap, with that we know there is a decrease in output voltage. But for easy analysis, we will assume that commutation this commutation is instantaneous.

Now, T 1 and T 2 T 4 will be conducting this during this portion. Now, I have taken the i_1 current direction like this, here. So, during this portion, i_1 will also have the same current. Now, when T 2 and T 3 is conducting; what will happen? The load current will be transferred to T 2 and T 4 but as far the load is concerned, till it will go from the same direction. Load current will be always in the same direction but if you see when T 2 and T 3 are conducting, the load current, the current I_1 will be suddenly reversed. During the tilt, the next thyristor is fired.

So, the load current is a stepped waveform with 180 degree for single phase. Assuming load is highly inductive, the load current is fully dc, regaining our ripple, we say waveform will be a square waveform and what is the input power? Input power if, this mains we will assume sinusoidal voltage, input power will be V rms into I rms into cos phi. That is the fundamental component of the voltage and the fundamental component of the current and the angle between the them. Now, the current is a alternating waveform with a square wave where the fundamental current will be fundamental current will be approximately here. The fundamental current will have the same phase relation which have the same phase relation with respect to the voltage waveform as the square wave has, the square wave pulse current has with the phase waveform.

So now, here, what is the phi? phi is the firing angle alpha. So here, the input power P_{in} is equal to V rms into I rms into cos alpha. So, what happens? As the output power increases or decreases or if we want to change the output dc voltage; let us assume Id is constant, we want to vary the output dc voltage. As the firing angle varies, the input power factor, the cos alpha as alpha varies it will get versant. So, what happens? It will affect the input power, the input power factor is not always constant.

So but ideal case, we want ideal case will be where cos alpha is equal to 1, alpha is equal to 0 that means voltage and current in the same phase, ideal case voltage. Then the output power P_0 will be V rms into I rms. Now, with different different firing angle that means output power will be with different firing angle, with different firing angle; what will be the input power and with constant load power constant load power, what will happen? Vr will be the same, Ir cos, cos as alpha increases, this cos alpha decreases.

Now, to make the power the same the Ir amplitude, the fundamental amplitude has to vary. So, this happen, so for ideal condition, we want cos alpha to be 0 and we want nearly, we want nearly cos alpha should be 1 so that alpha or the phi should be 0. So, this called unity power factor, this ideal condition to achieve. As the power factor increases, it is not a positive reflection on the input power side. This is so this the problem with the firing angle control. Now, let us take a semi converter.

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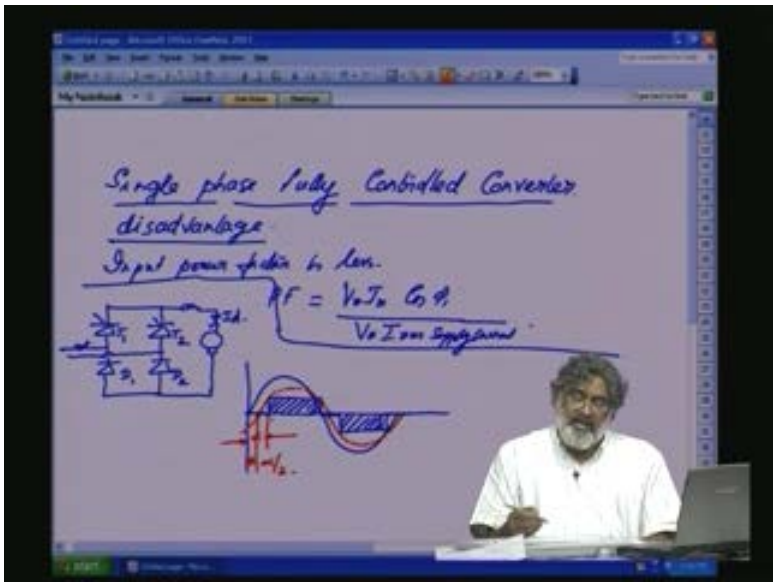

So, single phase fully controlled converter, disadvantage. What are the disadvantage? So, before coming to what are the advantage; simple power circuit, the device will be turned on, thyristor will be turned on the moment the gate pulse is given and you do not require extra commutation circuit to switch off, these are natural commutation, the incoming phase will switch off the thyristor in the already conducting phase. So, these are advantage.

What is the disadvantage here? The disadvantage here, input power factor is less as the firing angle increases. What is meant by power factor, the definition of the power factor? The input power factor is equal to definition we can say, power factor is equal to V rms into I fundamental rms into cos phi 1 alpha divide by the V rms that is sinusoidal and the total rms of the supply current, rms supply current not the fundamental. That is a square wave.

So, because input current as I told previously, it has a square wave content. In the square wave content, only the fundamental will generate the real power that is the required on the output. But the harmonics can also, it can cause heating causes - I square r losses. So, the total power taken from input side V rms into I rms, the supply current, the square wave pulse and the usual power is equal Vr into Ir into cos phi. So, this for a particular Id whether the firing angle is delayed or increased, only the square wave pulse with Id will shift left side to the right side so that the V V rms into I rms, the total supply current will be always the same. But the input real power Vr into Ir into cos phi that will keeps on reducing as the phi one increases. So, input power factor is less with power factor angle. So, this is a disadvantage with the phase controlled converter.

So, what will happen? So, it will drag as the power factor angle power factor or the displacement or the firing angle alpha increases, it will draw cos phi decreases and sin phi slowly increase. So, it will drag more amd more lagging power and decrease the power factor. So, this is one disadvantage. So, ideal case, we do not want any lagging current. The lagging current we do not want, that is reactive component. It is not generating any useful power. So, ideal case, we want to draw, to get the maximum efficiency or maximum input maximum power from the input, we require nearly unity power factor. Current and voltage should be it should not have any displacement angle phase angle.

So, let us talk about the semi converter. So, fully controlled converter; what is the disadvantage? Let us talk about the semi converter. What will happen for the semi converter? So, let us draw the semi converter waveform. I will draw the semi converter waveform; this is T 1, T 2, D 1, D 2, this is the load. Now, let us draw the current waveform that is input current, same like I_1 with respect to load current. Load current is Id, these are mains voltage waveform. So here, as I told previously when T 1 and D 1 are conducting, it is a free wheeling. So, there is a zero period. So, if you see, the current during the free wheeling time, free wheeling period; there is no power, there is no current and no power drawn from the mains.

So, typically for a firing angle, it will be like this, then the zero period, then it goes like this. So, this is the input total input current waveform, nature of the current wavefrom drawn from the mains. So, because of the part of the time, we are not drawing power from the mains that means we are not drawing reactive component power from the mains. So here, how the fundamental will be? Fundamental will be the zero crossing the nearly half of this one. So, the fundamental current waveform will be like this. So, what happens?

Eventhough firing angle is here, alpha is this much distance, the displacement angle, displacement or the phi is equal to alpha by that is the fundamental phase shift between the mains and the current is equal to alpha by 2. So, that means here there is an improvement in the power factor. So, for the same firing angle, the reactive power drawn from the mains for a semi converter is less but semi converter, it has its own advantages as well as disadvantage. As far as the power factor is concerned, it has a better power factor.

Now, the question is how to get improved power factor from the phase controlled converter? Then the question is with natural commutation, is it possible? Then we have to introduce these type of half period or force the free wheeling in a phase control by appropately turning on and turning off the devices. So, force commutation is required. So, if you see here, we require single

phase fully controlled converter. Let us take the single phase thyristor. Why we require? We require both positive dc and negative dc but the semi converter, semi converter will have only 0 to positive voltage but the advantage of semi converter is there is an improvement in the power factor that is the displacement angle between the fundamental voltage and fundamental input current is alpha by 2. So, the power factor, power factor increases compared to the single phase fully controlled converter.

Now, we want to in ideal case, we want to draw the input current, input power as close as to unity. The fundamental should be fundamental should be in phase with the as close as, as closely as possible in phase with the input mains so that we can have nearly unity power factor and the system will not draw any reactive component. So, the efficiency of the system can also be improved. In that case, what we require? We require a we require a full single phase fully controlled converter for both positive and negative output dc voltage. But to improve the power factor, we have to force the converter into semi converter operation both the positive cycle and negative cycle. That means we should have a situation like the single phase half bridge converter that is the free wheeling, free wheeling is happening.

During the free wheeling, there is a during a free wheeling period forcibly happening through the thyristors. In that case, we have to forcibly turn on the device. Not forcibly turn on, forcibly turn off the device. That means natural commutation is required. That means the thyristors should for some period it should act as diodes as for the conduction period with respect to the single phase semi controlled converter as concerned. But there are many commutations are available, many of these things are already used in some applications, its already available in text book. So, some of the semi converter operation of fully converter, I will be taking in the next class. Then the commutation circuit, one of the very popular commutation circuit and forced commutation circuit and how to design the components; we will study in the next class.