Power Electronics

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Lecture - 6

Controlled Rectifier Part - 5

In the last class, we just introduced the concept of the input power factor that is the fundamental power factor and how it affects due to the firing angle. So, fully control converter we said as the firing angle increase, the power factor will decrease and for the semi converter, it is half of the firing angle. So, it is an improvement in the power factor. So, what I want to mean say that in all phase control converter, the input ac current is non-sinusoidal. So, this will affect the performance of the system.

So now, there is a way for accessing the performance. This is from the input power factor and input total power factor and the input displacement factor and the for fundamental power factor based on that one, the fundamental power factor. So, let us talk about the input power factor, input power factor.

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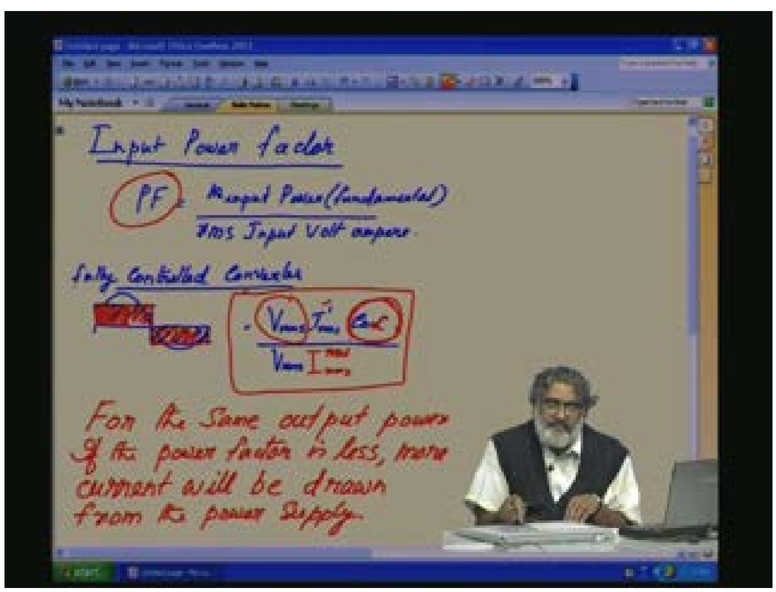

Input power factor that is PF is defined as mean input power or the power due to the fundamental component that is the mains is fundamental and from the non-sinusoidal current, the fundamental current which is and the fundamental voltage and the power factor which that contribute to the input power. So, we will say input fundamental power, mean power, input power, fundamental component divided by input rms input volt ampere.

What is the mean input power? We know, the input current is nearly for a phase control converter, fully controlled converter. For fully controlled converter, we approximated the input current nearly a square wave pulse like this, equal positive and equal negative. The fundamental component will be something like this. And reverse of the firing angle, this fundamental will be displaced or not in not in the same phase with the input, mains voltage. So, what is the input power factor that is input V rms into I_1 fundamental rms into cos of phi, phi is the alpha firing angle, divided by input is the total input volt ampere.

So, input is voltage is fundamental, so rms. What is the total rms? What is meant by total of rms? Because of this, because of this square wave, this is an ac wave form. What is the rms or what is the equivalent dc so that the same square wave and the dc when passing through the same resistance, it will produce the same heat. So in this case, if this is the value, Id is the peak value, the rms value will be Id. So, the total rms of the system, total rms of the input waveform, not the fundamental: that we represented as I, not the fundamental, total rms.

Now, as the displacement or the firing angle increases; what will happen? This value will decrease, the cos alpha decreases. So, for the same power but the power is demanded by the load but we require voltage control; for voltage control, we are using the firing angle that is the alpha. So suppose, we are controlling the voltage and the load requires same power as the firing angle varies, this will this factor will slowly decrease and then what happens? V rms is fixed. The mains voltage is fixed. So, this part, it will draw large and large fundamental current.

So, this input power factor, this is the input power factor which is defined by this one, it is the measure of the quality of the system, power supply system. So, what we can say? For the same power, for the same output power, same output power, for the same output power, if the power factor is more sorry the power factor is poor that means this is less. As the firing angle increases, the power factor is less that is this portion is less or the alpha is more; if the power factor ideal power factor, we require cos alpha should be 1. So, power factor decrease cos power factor is less. Hence, more current will be… for the same current power, output power, more current will be drawn from the power supply. So, more current means more heating losses; efficiency will come down.

So, even though we can control voltage through firing angle, we want to improve the power factor. The next step is improved. Ideally we want cos power factor should be always unity. That means alpha should be 90, cos 90 should be sorry alpha should be 0 sorry 0; so cos 0 will be 1. That means there should not be any displacement between the fundamental mains voltage and the fundamental current. Here, we said the semi converter we can use. Semi converter; what is the advantage? We cannot have the full output dc control; from negative to positive is not possible, 0 to positive is possible.

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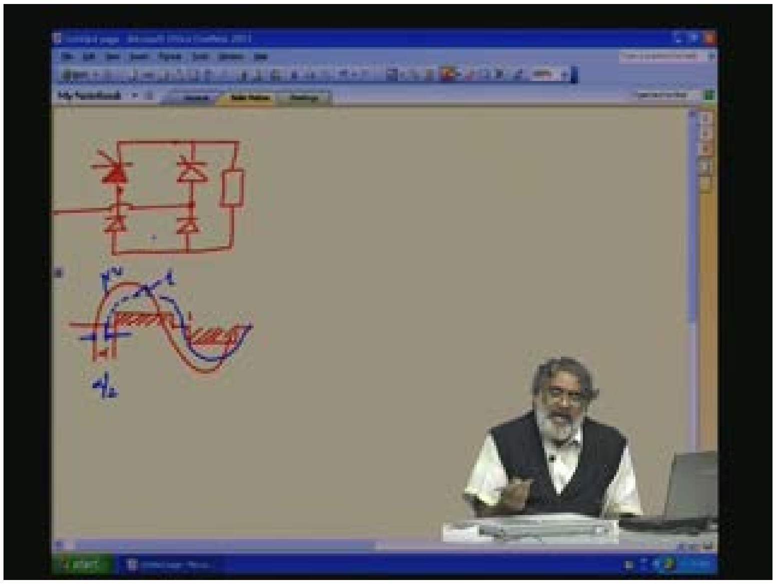

And, last class we said, for the semi converters, then we have like sorry we will sorry I will redraw again. We have upper thyristors and the bottom devices are diode. So, our V_{ab} and the load here. So here, if we draw the mains like this, we found; depending on the firing angle, it is a zero period happening. The current waveform input current waveform is something like this; this is the firing angle alpha, this one, I will draw.

So, this zero period happens when it freewheels through the thyristors and the diodes. So, the thyristors is not switched off; might happen the moment, any point, this point or this point goes negative, this diode will conduct immediately. But for the thyristors to conduct, we have to give the turn on pulse. So, the moment diode compass, suppose this thyristors is conducting, now the voltage goes negative; this diode will immediately conduct, this diode if this point goes negative that is V_{ab} goes negative, in this portion zero portion.

Then there is a free wheel happens. So, during the freewheeling operation during the freewheeling operation, this zero period will happen. Now, here the next thyristors is fired. So, what happens? The fundamental current, if you see here, the fundamental current is here; so the phi, the displacement between the fundamental voltage that is V and the fundamental current I is alpha by 2. So, alpha reduces or phi reduces, let us say our power factor improving the power factors is there. But ideally, we want the phase control converter, fully control converter to get both positive as well as the negative voltage. At the same time, we want improved power factor. So, how is it possible?

Now, the question is can we run the fully three phase fully control converter or semi converter in the positive direction as well as the negative direction? What do you mean by positive direction as well as the negative direction? Let us take the positive case. Positive case; bottom, we want to work as diode. To work as diode means thyristors, we should fire alpha is equal to 0. The moment we turn on the thyristors, it will automatically turn on. So, for the bottom thyristors, the firing angle is alpha.

Let us see, how we can work as the three phase fully control converter as semi converter in the forward as well as in the reverse direction. So, with the firing angle alpha, the power factor is not cos alpha, cos alpha by 2. So, it has an improvement. So, let us study that one.

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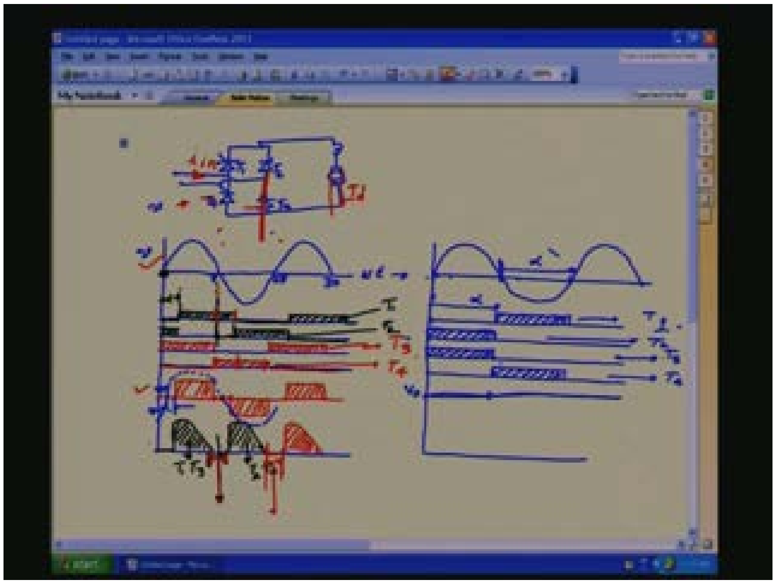

This is my thyristor one - T 1, this is my thyristor T 2; then T 1, T 2, this is T 3 and T 4 and it is my input voltage, now our load, goes like that. Now, during the positive period that means when the output voltage varies from 0 to positive with the firing angle control, we want T 4 and T 3 to act as diode so that we can give so that the firing to act as diode, we want to give firing angle alpha is equal to 0 for T 4 and T 3.

So, let us draw the sequence of operation. Now, this is our x axis and this is our y axis. Now, let us draw the mains voltage; this is our mains voltage nearly sinusoidal. By practice it is possible. This is our main; this is 0, this is phi, 2 phi and 3 phi, this goes, this is our omega t, this direction. Now, let us draw the gate pulses, gate pulses for the G 1, G 2, G 3; so probably we will use, this is for 1, this device is for 2, this is for 3 and this is for 4. So, 2 and 4, we want to work as diode. So we will be turning on. So, firing angle alpha is equal to 0. When this is positive, when this is positive which one we should be turning on?

T 3 should be turning on. That means when the input is positive, T 1 and T 3 should be conducting. So, T 3 should be firing angle alpha is equal to 0, full positive side, this should be turned on. So, this is G 3. So, we will use another color so that clarity will be better. So, this is G 3. This is with respect to the speed, G three is turned on. Negative side is not turned on. Again, positive side G 3 is turned on. This is our gate pulse for thyristors 3, T 3.

Now, from the negative side when the voltage wave goes negative, we want T 2 and T 4 to conduct. But we want T 4 to act as a diode. So, that means the moment the voltage wave form, this side it goes negative, this side, T 4 should conduct. That means at the zero crossing, we have to turn on T 4 that is full negative side T 4 will be turned on. So, this is T 4. Now, T 4 is turned on but we want voltage control. So, voltage control is done by varying the firing angle for T 1 and T 2. So, let us take a typical case of firing angle alpha. So, the T 1 pulse. Probably here, we will use a different color so that clarity will be better. We will use we will go back to black.

So, this is the firing angle; the firing angle for a single phase converter alpha zero starts from omega t is equal to 0 that is this point. So, this is our alpha region, from here to here, alpha. T 1 is fired with respect to alpha; positive side, the firing angle control is for T 1 and for the negative side, the firing angle is for T 2. So, the negative side, it starts from here. So, alpha is same alpha if you want use, this alpha region.

Here, we will assume the computations are instantaneous that is why at this period, the one is turned on immediately, other one is turned off for making the analysis simple; this is for T 1 and this is for T 2. Now, for a firing angle, we are controlling the firing angle; so for this firing angle, what will be the input current shape? What will be the input voltage wave shape, volt voltage wave shape? Let us see, when T 1 is fired when T 1 is fired and when T 3 is fired that time the input phase voltage will appear across the load. So, T 1 is fired here and T 3 is fired here; so this is the only period during which T 1 and T 3 is fired that is here. If you see here, during this period T 1 and T 3 is fired part of the input phase voltage waveform appear across the load. So, this is T 1 and T 3 conduct.

Now, during the negative portion, negative portion, the input, part of the input voltage wave form will appear across the load when T 2 and T 4 are conducting. So here, which are the periods, durations? T 2 and T 4 are conducting that is from here to here. So, if you see here, that time, since it is a rectifier, even the input is negative, this will form and come like this. Here, we have T 2 and T 4. Now, if you see here, part of the wave form only coming in, there is no negative. Will there be a negative part as before phase control converter? It will not be there.

Let us take this portion that is this portion; what happens here? During this portion, during this region that is this region, we will mark it with a different color, so its clarity will be better. So, during this region, the output ripple is 0. Why? If you go to the waveform during this period that is from here to here and here to here, T 1 and T 4 are conducting. T 1 and T 4 are conducting, load is freewheeling. So, output voltage will be 0.

Same way, in this period; what is happening? If you so here T 2 and T 3 are conducting, T 2 and T 3 conducting. This is the portion; it is freewheeling through this part. So, 0 will be there. So, this way, the output ripple will go. The firing angle, the part of the wave form as the firing angle increases, the width of the waveform in part or part of the input mains wave form appearing across the load will slowly reduce and voltage will come to 0. When firing angle is 0; what happen? This portion will go here, finally it is named three phase three phase control, it will act as a three phase, single phase diode sorry single phase diode rectifier with alpha is equal to 0. So, as far the voltage waveform is concerned, we have main the converter during the positive side half circle, we have made the converter to work as a semi converter.

So, let us see the current wave form. Assume the load is highly inductive. We will say dc current is flowing through the load. So, load will always see the dc current and pause of the dc current will be to get on the positive side, positive side, it will be shifted to T 1 and T 3 and negative cycle T 2 and T 4; for freewheeling, it will go through T 2 T 3 or T 1 and T 4.

So, when T 1 and T 3 are turned on, T 1 and T 3, then it is portion; this is the input current that is this current. Current if you measure, if current, we connect it here, this point, the current I, input current. If you connect it here, the current wave form will be like this. During the freewheeling that is this portion, current will be 0. Again, when T 2 and T 4 goes, the current direction at input side, it goes in the reverse direction. Even though current is coming like this; now what will happen? T 2 and T 4, see it will go like this, come back like this. So, it will reverse. So, this is the current wave form.

Now, if you see here, this wave form, input current and input voltage; where is the fundamental component? So, why we are taking the fundamental component? Input main sees fundamental voltage and fundamental current can only be real, useful power to the load. Harmonics with the fundamental voltage will not give any useful power but harmonics current, it can create losses - I square r losses in the device, it can reduce the efficiency.

So, fundamental power is always fundamental rms voltage input rms voltage, fundamental input ah current and the power factor cos phi. So, if you see, what is the power factor here? So, fundamental will be symmetric about this one. So, we will draw with a different color. So, fundamental current will be approximately this way, the shape. So, if you see here, the displacement that is this one, the displacement is if this is firing angle alpha, the displacement is alpha by 2, alpha by 2.

So this shows, during this period, during the full 0 to positive period, there is an improvement in the power factor. Even though the firing angle is controlled by alpha or a three phase for a single phase fully control converter; as alpha varies, the power factor or the displacement factor is alpha. So, the power factor will be the fundamental power factor will be cos alpha. Now, we have reduced, we have reduced the alpha and improved the power factor. That is improved the power factor cos alpha by 2. So, there is a power factor improvement.

So, quality of the power supply, we have improved. It will draw less reactive power. If cos alpha by 2, there is a sin alpha by 2 is there; V rms I rms sin alpha that is that shows the indication of the reactive power down from the thing. So, that is reduced here. Now, as alpha varies, when alpha becomes alpha becomes phi by, when alpha becomes phi; what will happen? Let us show that waveform when alpha is equal to phi. Again here, alpha is equal to phi; we can draw with respect to the input sine wave. Again, we will draw; I will approximately draw the input sine wave here. This is my input sine wave. Let us draw the axis so that it will be clear. This is our x axis for the gate 1, this is for gate 2, this is for gate 3 and this is for gate 4.

Now, we are increasing the firing angle alpha to control the output voltage. So, as the firing voltage increases, the output voltage will come down. We have derived the equation previously, it is the function of cos alpha. Now, alpha is equal to see here, during the full positive half cycle, we are not disserving the function of T 4 and T 3. T 4 and T 3 is fully fixed. So, this is the T 3 waveform. T 3 waveform will be positive side, it is fully fixed; then T 3 is fixed, T 4 is also fixed. So, during the full negative proportion, T 4 is conductive. So, this is gate pulse of T 3, this is the gate pulse of T 4.

So T 1, sorry this T 1, I will just, so this is T 1. So, if you see here, during the positive half cycle T 2 and T 3 are conducting. The moment T 2 and T 3 are conducting means what will happen? T 2 and T 3 conduct means this is freewheeling. So, if you see here, during the freewheeling operation, output voltage will be 0 during the freewheeling operation. So, this is the V_0 path, output volt that is the path of the voltage coming across the load will be 0. Again, the next half cycle you can see, T 1 and T 4 are conductive. So, load is freewheeling. So, here also output voltage is 0. So, output voltage ripple will not come across the load. So, what it shows? What it shows?

When the firing angle is equal to 0, alpha is equal to phi, the output voltage is equal to 0. So, we brought, by varying the firing angle, we brought the output voltage waveform from positive high value to the 0 value and every time if you see here, based on the current direction here, the displacement angle is equal to alpha by 2 corresponding to the power factor will be cos alpha by 2. That is an improvement in the power factor.

Now, let us take the case when the negative half cycle; negative half cycle if you go with the symmetrical circuit, now what we have to do? We have to fix the T 1 and T 3 waveform sorry T 1 and T 2 waveform, we have to fix it and only control T 4 and T 3. So, let us draw the waveform during the negative half cycle. Let us go to the, lets draw it; negative half cycle.

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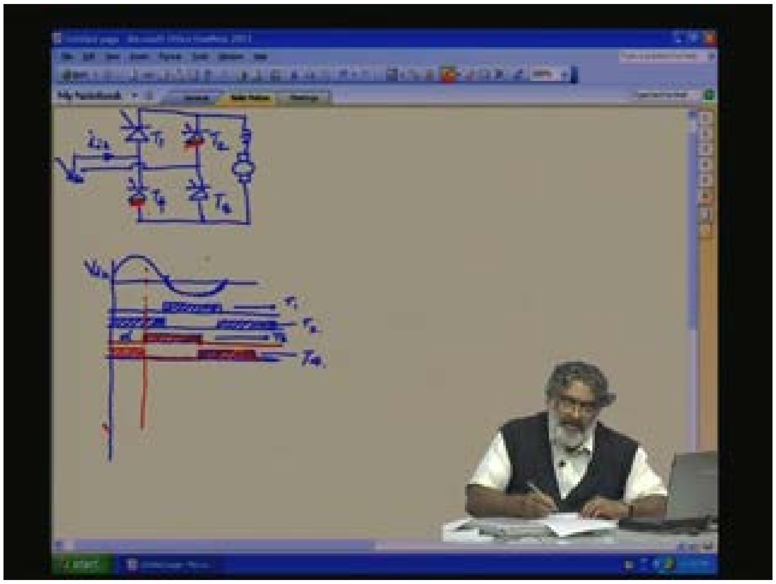

So, let us draw the converter waveform, converter fast again. This is T 1, then this is T 4. Let us mark T 1, this is T 4, this is T 2 and this is T 3 and the load. So, we always represent load as motor. So, all these explanation is for drive applications. So, variable voltages for DC motor drive application. This is our I input, I Input, this is our new input dc wave. This is our new input, new input waveform.

Now, let us draw the positive and negative half cycle. So, let us first draw the sinusoidal input voltage wave form assuming the input is always good sine wave but mains will not be always a same perfect sine wave but for our analysis, we will assume it is sinusoidal. This is our V input. Now, we want to vary the firing angle such that the output voltage will go from go towards the negative side. So here, how it is done and as I told, here we will fix the firing angle of T 1 and T 2 fixed. So, let us say T 1 and T 2 fixed. Previously, at alpha is equal to phi, there was a freewheeling. Now, T 1 and T 2 is fixed. So, T 1 is during the 90 half cycle, T 1 and T 2 will act as, T 1 will act as a diode. So, this is the T 1 pulse. This is our T 1 pulse and the positive cycle will make T 2 fixed, this is T 2.

Now, we are varying; which are the pulses? T 3 and T 4 pulses: T 3 and T 4 pulses, with firing angle so that the output dc shall go from 0 to minus negative. Let us take one firing angle firing angle let us say this one, this is the alpha. Here, after alpha we are firing T 3, this is T 3 with gate pulse. The moment T 3 is switched off, we will be turning on T 4, we are assuming for instantaneous. So, with the moment T 3 is turned on turned off, T 4 is turned on. So, this is T 3 and this is T 4. Probably, we can T 3 and T 4, we can go with different color, so the clarity will be better. So, I will mark it with different color. This is T 3 and this is T 4.

Now, how the output voltage will be? If you see here, when T 2 and T 4 are turned on, T 2 and T 4 are turned on, that these are these are the when T 2 and T 4 are turned on that is this one; this is T 4, T 2. Thus part of the input voltage will be appearing across the load. So, which are the, which part is appearing across the load? T 2 and T 4 that is this this much portion, this much portion. So, what is that part that is appearing across the load? So, if you see, during the negative portions, T 2 is turned on. When the input is negative, T 2 is, input is, when input is positive, if you see here, T 2 is turned on during this portion. Sorry, I made a mistake in drawing the input waveform during the negative side. So, this is wrong. It has to be input waveform has to be on the other side. So, let us, let me remove that one.

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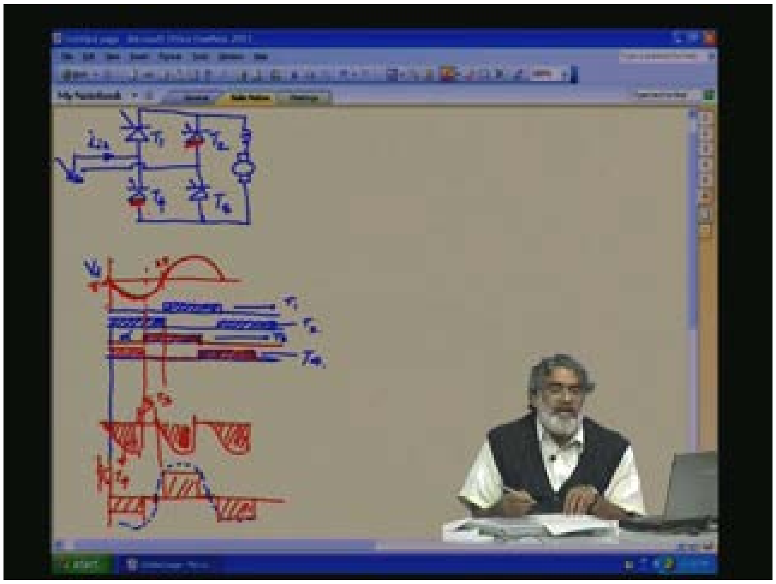

So, I will again draw the correct input waveform for the negative side. This is the axis, so it will be this is the waveform sorry because we are going to the negative direction, so the firing angle is this way. Already, we have come to the negative side, from the positive 0 side, from the positive side. Now, it has to go from the negative side. Previously, what we have come? We have come up to this point, negative side, alpha, firing angle is phi. But from here, we have to continue that is a continuation, a continuation.

So, if you see here, during this portion T 2 and T 4 are conducting T 2 and T 4 are conducting; that part of the waveform, that waveform is already negative. So, why negative? So, there was a drawing in my mistake. This is a continuation from the previous case where we are going from positive voltage come to 0. When it comes to 0, the firing angle was phi and from there onwards the waveform has going towards negative side. So, that is why returned. This is the waveform.

Now, we are varying slowly firing angle of 3 and 4. Now, during this period, start from here, from pi, starting from pi; this is pi, this point pi, this is 2 pi. So, we have to start from 0 to pi. Now, firing angle here is only varied. So, if you see here, T 2 and T 4 are conducting. During T 2and T 4are conducting, the negative portion that is this portion will appear across the load, this ripple. So, the ripple voltage if you see here, it will be here.

Now again, as you see here, T 2 and T 3 are conducting, so it is freewheeling that is from here to here. So, this time, what will be the output voltage? Output voltage will be 0 here. So, output voltage here; this is T 2 and T 4 are conducting, here it is freewheeling, so T 2 and T 3 conducts. Now again, from here to here, this portion T 1 and T 3 is conducting, T 1 and T 3 conducts means again that part of the waveform will appear across the load. But here what are the T 1 and T 3 are conducting. So, again the voltage get T 1 and T 3 voltage waveform comes in the negative direction.

So, during this portion which are T 2 conduct T 1 and, T 1 and T 3 are conducting. This is during this portion; T 1 and T 3 are conducting. So, T 1 and T 3, again it will go negative. So, this way, it will go. So, negative side voltage will come across the waveform. Now, how the current waveform will be? Current waveform will be we can draw it here sorry we will draw from this point. Current waveform will be during this portion, negative portion upto this point, it will be here, like this. Then 0 from here to here and positive from here to here and again 0, then negative; it will go like this. So, this is the waveform.

So, here also the fundamental, fundamental will be I will draw with different color, the fundamental will be like this. So, here also the firing alpha the improvement in the fundamental component is here. This way we can, by appropriately giving the gate pulse, alpha is 0 to thyristors, we can drive the converter as a semi converter in the positive as well as negative side.

Now, we will study about the converter that single phase fully controlled converter working as a semi converter in the negative voltage region that means 0 to negative. So again, for clarity, let me draw the phase control wave form, the phase control converter waveform will be here.

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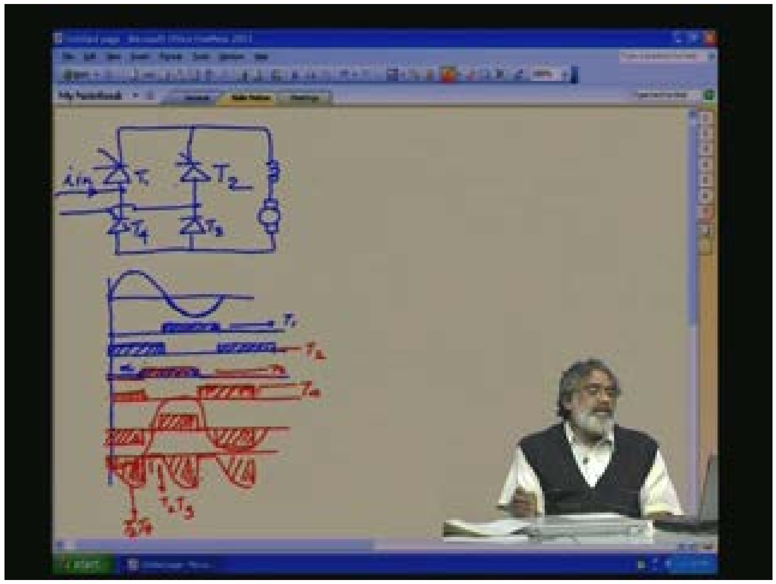

This is again T 1, this is T 2, this is T 1, T 2, this is T 4 and this is T 3 and then comes the load. This is our input waveforms, this is our input current direction I_{in}; T 1, T 2, T 3, T 4. Let us draw the corresponding waveform during the negative period. So, let us draw the mains waveform again from 0 to phi. This is our input mains waveform, this is axis we will draw and let us draw the gate pulse for one. So here, the negative side that is the output voltage going negative; so here T 1 and T 2 will act as diode. So, during the negative half cycle we will be fully turning on the T 1. So, this is our T 1, and then next is T 2. During the full positive half cycle that is here, we will be turning on T 2. Then here, we will assume the moment T 2 is turned on, T 1 will goes off and when the moment T 1 is turned out, T 2 will go off.

Now, firing angle control is given to T 4 and T 3. Previously, the firing angle control was given to T 1 and T 2. Now, let us take a general alpha firing angle. Let us draw the wave form of gate pulse T 3. The firing angle alpha that is from here to here, the firing angle alpha; this is the pulse value, this is for… Let us draw different colour, so its clarity will be better. This is our T 3, T 3 is here.

Now, the moment T 3 is turned on, we have to turn on T 4. So, where is the T 4 wave form? T 4 wave form will be somewhere here. This is T 4, again when T 3, this is T 3 and this is T 4. Whenever T 3 is turned on, T 4 will be turning off. So T 4, here it will be turning off. So, these are the T 4 T 3 waveforms. Now, with respect to this one, how the output repel will be, voltage repel will be? Let us draw the output voltage repel. Output voltage repel from here if you see, here during the when T 2 and T 3 are turned on, this is T 2. When T 2 and T 4 are turned on, what will happen? The input repel will come across the load.

But if you see, during the positive cycle, T 2 and T 4 are turned on. So, the waveform will be like it is inverter, it will happen like this. Again when both the switches are conducting that is from here to here, there is a 0; again, it goes like this. So, this a negative repel will come across the load. So, this will continue like this. So, firing angle can be varied from alpha 0 to pi. When it comes to pi, again it will go to 0.

So, how the input current will be here? Input current, we can draw it like this, we can draw it like this. When this is there, till this period, if you see this is the current waveform that is when T 2 and T 4 are turned on, this is T 2 and T 4 are turned on; the current, input current is in the negative direction. Then freewheeling? There is no current. During this freewheeling period, this period? T 2 and T 3 are conducting, so freewheeling. So, during that portion, there is no current. After that current will again change. So, it will go like this, again it will come like this. So, this way, we can go from negative side also. Previously, what we are varying the firing angle, varying from zero to pi.

Now, during the negative half cycle, after that we will be fixing T 1 and T 2 permanently that is it is working as a diode by turning the, keeping the firing angle alpha is equal to 0, then or to get the negative dc voltage, we are varying the firing angel of T 3 and T 4 with respect to the mains. So, we will get slowly, firing angle when it comes to 0 to phi, the moment here phi comes, output voltage will be 0 and from there again when it increases, the output voltage going to the negative mode; so you get the output dc voltage like this and we are making the converter, positive and negative half cycle work as a semi converter.

So, here the power factor improvement is there. If you see here, this is even though there is an alpha by 2, there is an improvement in the power factor angel is there as before the semi converter with respect to the firing angle. Even though the alpha, firing angle is alpha, the change in the firing angle, there is if you see here, the improvement in the current input power factor is here; in same like in the semi converter.

So, this way, this is with respect to the mains; this way, we can have there is a the firing angle the output power factor is not proportional to not decide by the alpha, it is an improvement in the power factor is possible. This way, I explained in the previous class for the positive side; now it is for the negative side. See here, this is for the positive side. So, if you see the power factor angle that is this is not alpha, cos alpha by 2 here. So, there is an improvement in the power factor.

The same thing is achieved for negative side also that negative side, it is here. So, this way, by controlling the firing angle for making the devices, the fully controlled converters working as positive and negative side to devices are thyristors that means the full period, we will make it on; alpha is equal to 0 for T 4 and T 3 in the positive and for negative, it is T 1 and T 2. So, we can have output dc control both positive and negative side and improve in the power factor is possible.

Now, an ideal case, ideal is the power factor, the respective of the firing angle. Firing angle is only for the controlling output voltage. But as far as the input is concerned if you want to have efficiency good efficiency of the system, we want we should draw the input main current that is the fundamental current in the same phase with the phase. That is with unity power factor that means the displacement angle alpha should be 0. That is the best way that is the most efficient way of drawing power from the mains. At the same time, we require firing angle; we require a firing angle control. So, this we will study in the next class using PWM operation during the control or force computation technique. We will then after that we will come to PWM; we will study in the next class.