Power Electronics

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Lecture - 18

Last lecture I discussed the operation of a 6 pulse converter for various trigger angles. We found that the peak value of the output voltage is root 3 times the peak of the input phase voltage for alpha varying from 0 to 30 degrees. For peak, in other words, peak value of the output voltage is same for alpha, 0 to 30 degrees and second observation is for alpha less than or equal to 60 degrees, V_0 is always positive. Instantaneous value is always positive. When it is 60 degrees, it just touches the x axis.

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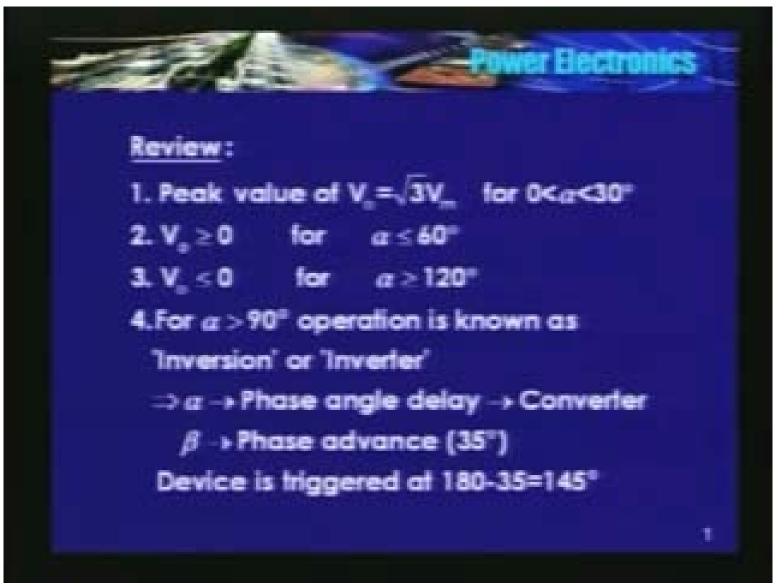

Instantaneous value of output voltage is either 0 or negative for alpha greater than 120. For 120 degrees, it just becomes 0 and it becomes negative. Therefore, to start the bridge or to energize the bridge, alpha should be less than 120 degrees. You can establish a current in the bridge only if alpha is less than 120 degrees, remember this.

Similar to single phase case, average value of the output voltage is negative for alpha greater than 90 degrees. This process is known as inversion or the power electronic equipment is working as an inverter. For 0 to 90, we call it as converter. So, 90 to 180, we call it as inverter. So, we called alpha as a phase angle delay to the converter. Generally, alpha is known as the phase angle delay because we are delaying the current flowing in the phase. Of course, we can use the same terminology even for the inverter also. So generally, for inverter we say that it is the phase advance, not phase angle delay.

Suppose, if it says that phase angle, advance is 35 degrees, what it implies is SCR is triggered at alpha is equal to 180 minus 35, remember. So, if someone says that bridge is triggered with the phase advance of 35 degrees, it is nothing but triggering the bridge at 180 minus 35 that is equal to 145 degrees.

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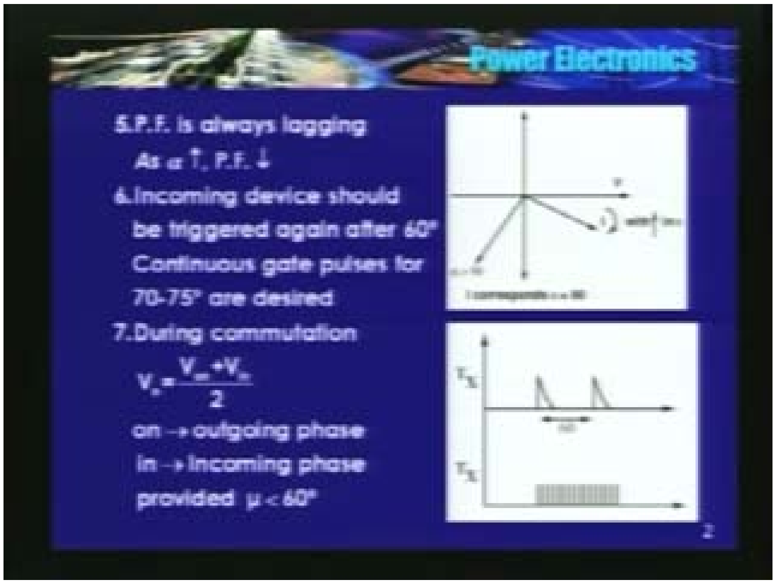

We found that power factor in a line commutated bridge is always lagging. So, see in this figure, angle between V and I increases with increase in alpha.

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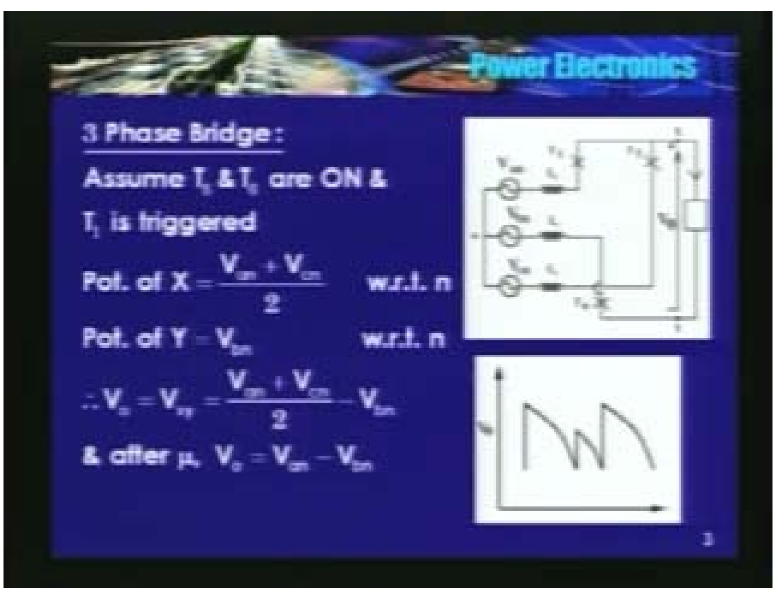

So, when alpha is equal to 90 degrees and if the current is continuous, average value of the output voltage is 0. I said that I can, you can have this situation only if the load is pure inductor. So, power transfer to the load is 0 if I neglect the inverter losses or in other words, if the inverter if the power electronic converter efficiency is 1, power input is also 0. It can happen only if power factor is power factor angle is 90 degrees and it is lagging.

Beyond 90 degrees, what happens? Power factor is still lagging. See, if I resolve V, I along V, this is VI cos theta, positive, VI sin theta, I can say, it is lagging. In the third quadrant, for alpha greater than 90, VI sin theta is still lagging, whereas, I cos theta has change its direction. So, V and Icos theta are in phase. So, in other words, VI cos theta is negative, source is absorbing power. You can have this situation only if the load is of RLE type, I have told you.

What is our next observation? At any given time, 2 devices should be triggered in a 6 pulse converter, why? One is to start the bridge, 1 from the upper half and 1 from the lower half should conduct. So, 2 of them should be triggered simultaneously or in case the current has become 0 and you have to establish it again, if only 1 device get a pulse at a time, so we will not be able to reestablish the current again. Therefore, 2 devices should be triggered simultaneously. In other words having triggered the device once, it should be triggered again after 60 degrees. See in this figure, it should be triggered again after 60 degrees, for any thyristor.

So, instead of having 2 sharp pulses which are separated at an angle 60 degrees, a good engineering practice is to have a large number of pulses of around say, 70 to 75 degrees. Instead of having just 2 sharp pulses, have a series of high frequency pulses of 70 to 75 degrees. The next point that we discussed was effect of source inductance. Similar to single phase case, even in 3 phase, during commutation there is going to be that is the 2 thyristors are conducting at a time. As a result, there is going to be a reduction in the output voltage.

In the single phase case, during commutation, voltage applied to the load is 0, whereas, in a 3 phase case it is the average of the 2 phase voltages. It is, if the A and B are conducting, V_{an} plus V_{bn} by 2. The procedure that we followed for the single phase case is same here. The only difference is in a single phase case, we took V_{an} is equal to minus of V_{bn} because we used a centre tap transformer, whereas here, V_{an} and V_{bn}, the angle between them is 120 degrees. So, remaining procedure is the same. So, if I write a generalized expression during commutation is V_0 is V_{on} minus V_{in} divided by 2. O is for outgoing phase, i is for incoming phase.

Of course, provided, remember, mu is less than 60 degrees because having triggered a thyristor or each pair conducts for just 60 degrees. I am assuming that source inductance is very small so that mu is much less than 60 degrees because if it exceeds 60 degrees, operation is going to be different. Let us not discuss the operation of the bridge with mu greater than 60 degrees. Basically, this is the first course in power electronics. May be, these topics can be covered in the second topic, second course on power electronics or the course on high voltage DC transmission, HVDC. I will discuss this sometimes later.

Now let us see, let us derive an expression for the voltage drop due to the effect of source inductance for a 6 pulse converter. See, it is the bridge configuration; T_5 and T_6 were conducting, so in the upper half, T_1 is triggered, in the lower half, 6 continues to conduct. So, there is V_{an} and V_{cn}, there is going to be a short circuit, current decreases here, current increases and this is the circuit.

So, potential of X during the commutation or during mu is V_{an} plus V_{cn} by 2, V_{an} plus V_{cn} by 2 with respect to n. So, potential of X with respect to n is V_{an} plus V_{cn} by 2, whereas, potential of Y is V_{bn} with respect to n. So, output voltage V_0 is V_{an} plus V_{cn} by 2 minus $V_{bn.}$

So, this waveform, this is the output voltage for 5 and 6 or when T_5 and T_6 were conducting. This is during the commutation overlap or during mu is given by this expression. After completion of mu, it is going to be V_{an} and V_{bn}, minus Vbn because after completion, pi turns off, T_1 starts conducting, it is V_{an}, T_6 continues to conduct here till T_2 is triggered. So, it is V_{an} minus $V_{bn.}$

So, this is during the commutation overlap period. Mind you, this all depends on, the magnitude of this depends on alpha, remember. What you need to do is you need to find the instantaneous values of those 2 phases, find an approximate average, subtract with V_{bn}, you draw. I would encourage you all to draw this waveform for other values of alpha.

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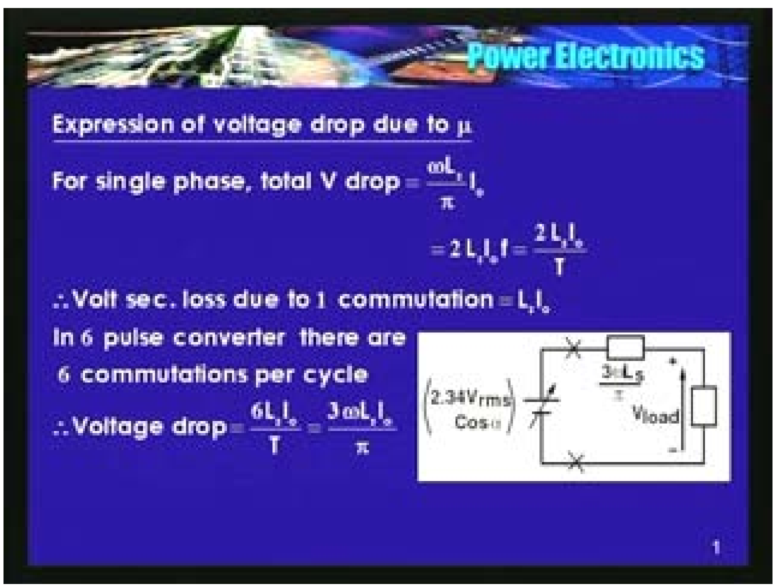

So, what is the expression now? For a single phase case, we found that voltage drop due to commutation overlap is omega Ls divided by pi into I_0 that is equal to 2 Ls into I_0 by f or 2 Ls I_0 divided by T. So, volt second loss due to 1 commutation is Ls into I_0 because there are 2 commutations, there are 2 commutations in a single phase. So, expression is 2 Ls I_0 divided by T. So, volt second is Ls into I_0 per commutation, whereas, in 6 pulse converter there are 6 commutation per cycle. So, if I have to draw the analogy, the voltage drop due to commutation overlap is 6 times the voltage drop due to 1 commutation. So, that is equal to 3 Ls omega I_0 divided by pi, a very simple way to derive an expression.

There are other ways also. By integrating the output voltage waveform and getting the equivalent, this is the easier method. So, the equivalent circuit of the 6 pulse converter taking into account the effect of source inductance can be drawn in this manner. So, 2.34 V_{rms} into cos alpha is output voltage of the bridge neglecting the effect of source inductance. At any given time, 2 thyristors are conducting. 3 omega Ls by pi is the voltage drop due to the effect of voltage drop due to the source inductance and this is the load voltage. So, 3.V4 V_{rms} cos alpha minus 2 device drop minus 3 omega Ls into pi divided by pi into I_0 is the voltage across the load.

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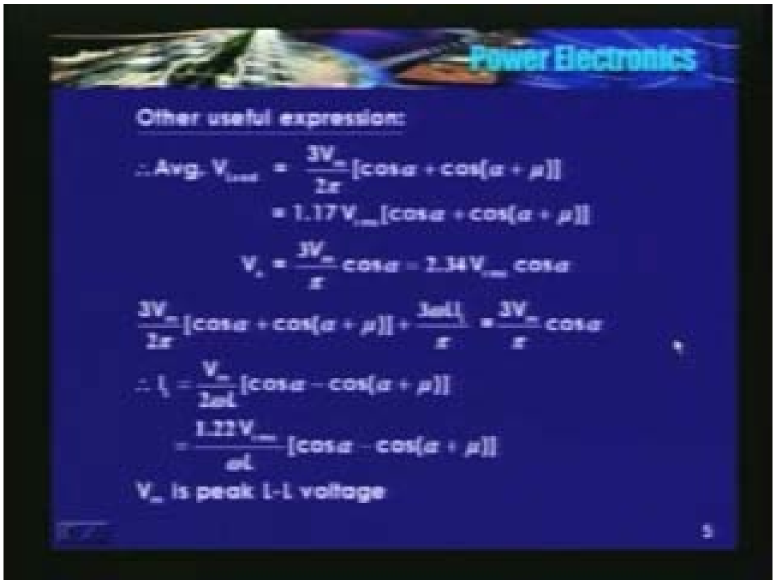

There are other useful expressions also. They are derived in the same manner in the way we derived for the single phase case. Go back and refer your previous notes. The other useful expression for a 3 phase case are here, 3 V_m by 2 pi into cos alpha plus cos alpha plus mu. So, it is 1.17 into V_{rms} cos alpha plus cos alpha plus mu. So, if mu becomes 0, it is 2.34 V_{rms} into cos alpha. If mu becomes 0, it is same as the ideal voltage. Here is it, 2.34 into cos alpha.

So, this is the load voltage plus voltage drop due to the source inductance is the output voltage of the bridge. I am neglecting the device drop here. So, if I solve for I_L, so, this is the equation for I_L in terms of the voltage, source inductance, alpha and mu where V_m is peak of line to line voltage or 1.22 into V_{rms} omega L into this. These are the based useful expressions, not very difficult to remember. So, 2.34 V_{rms} cos alpha, so it is 1.17 V_{rms} cos alpha plus alpha plus mu that is the voltage across the load.

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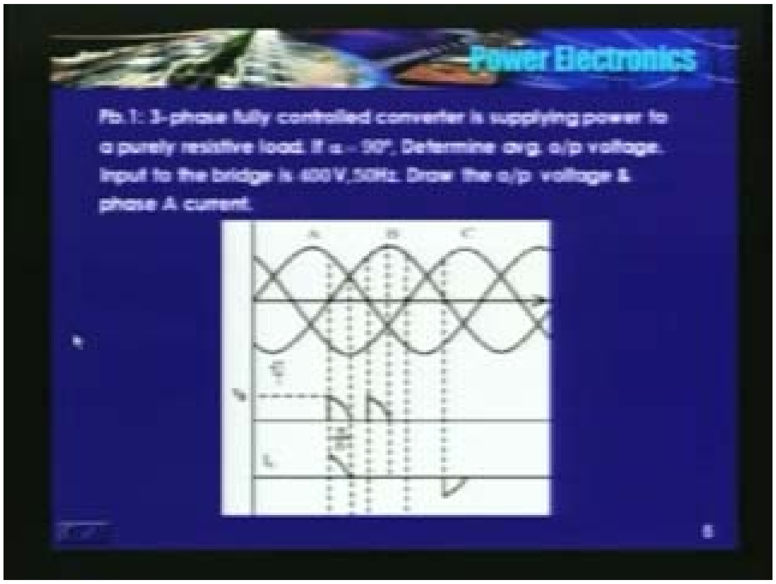

So, having done the theory, I will solve a problem. The problem says, a 3 phase fully controlled converter is supplying power to a purely resistive load. Life is bit difficult now. Alpha is equal to 90 degrees. Determine the average output voltage. Input to the bridge is 400 volts, 50 hertz. Draw the output voltage and phase A current.

Read the problem again, said, alpha is equal to 90 degrees. Straight away do not use expression, 2. 34 V_{rms} cos alpha is the output voltage, that is true only if the current is continuous. You can use it for a resistive load also, if alpha is less than or equal to 60 degrees, remember. For alpha less than or equal to 60 degrees, purely resistive load, current is continuous because at alpha is equal to 60, minimum value of V_0 is 0. At that time current also becomes 0. If I increase alpha beyond 60 degrees, current is going to be discontinuous and not purely resistive load.

Now, let us draw the wave output voltage wave form first. Point of natural commutation, for $T_{1,}$ this is the reference point, 30, 60, 90. See, at this instant, T_1 is triggered, at remember, current is discontinuous. None of the devices are conducting. So, if I apply a trigger pulse only to $T_{1,}$ you cannot establish the current, remember. So, you have to trigger the lower device also. You have to trigger 1 more device in the lower half. So, that is the reason, even having established the current, if it is continuous, you can do with theoretically, you can do with only 1 pulse or triggering. But then, if the current is going, if the current is discontinuous, 2 devices should be triggered at a time.

Alpha is equal to 90 degrees, T_1 is triggered. Assuming that one more device in the lower half is also triggered, that is 6 because reference point for 2 is here. So, at this point, output voltage is V_{an} minus V_{bn} that is root 3 by 2. So, at this point, current becomes 0. So, till I trigger again the next pair, current is 0. So, I need to find out the average value of this waveform. So, 30 degrees only, there is output voltage. For remaining 30, output voltage is 0 and I have again, I have a pulse.

The source current, since the load is purely resistive, it follows its output voltage, same and after 180 degrees, this is due to T_4 conducting. So, there is 1 pulse here, again there is 1 more pulse here, phase A, 1 more pulse here and again. So, source current is also discontinuous. It does not supply power for 120 degrees in the positive half. It is less because source current is load current is discontinuous. Therefore, source current is also discontinuous.

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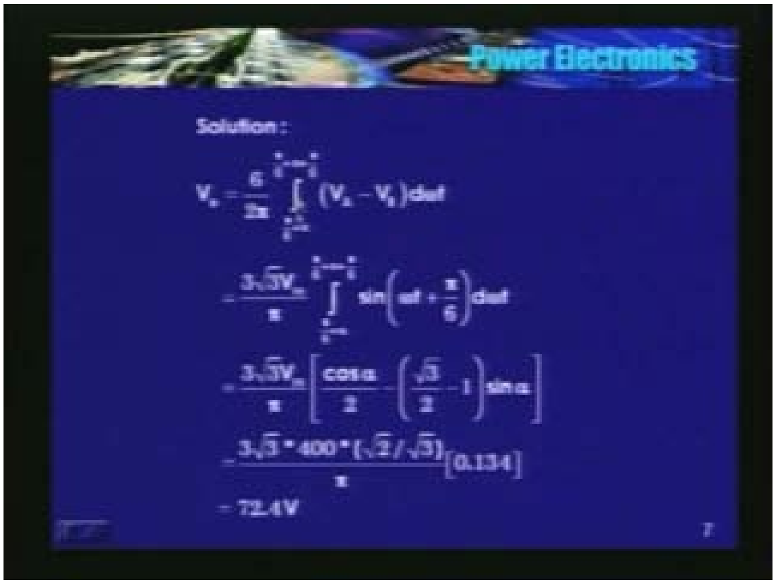

So, average value of this is simple, 6 by 2 pi. You integrate it, V_a minus V_b into d omega t. V_a minus V_b is sin omega t plus pi by 6 into d omega t. Solve it, you will get it as 72.4 volts.

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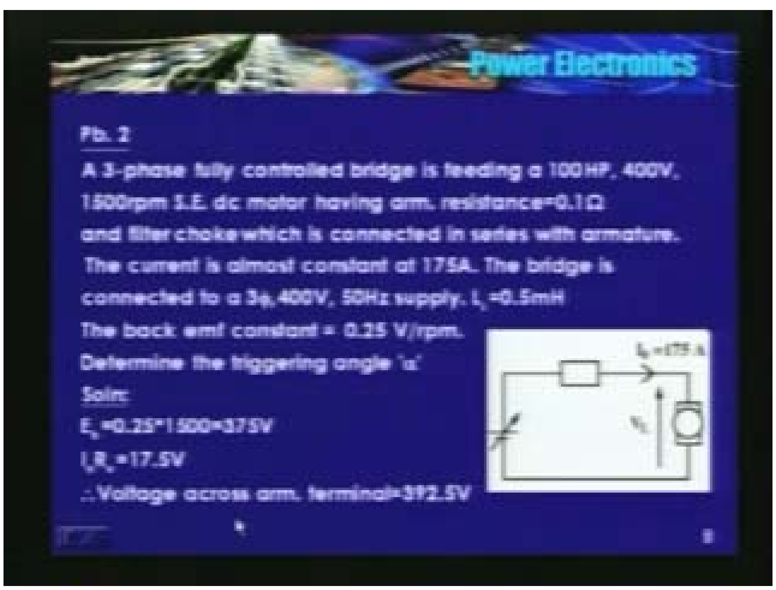

So, let me solve 1 more problem. It says, a 3 phase, a fully controlled bridge feeding a 1000 HP, 400 volts, 1500 rpm separately excited DC motor having armature resistance of 0.1 ohms and filter choke which is connected in series with the armature. A filter choke is connected in series with the armature, you can safely assume that current may be continuous and you can assume that it is constant. So, current is almost constant at 175 amperes, the bridge is connected to a 3 phase 400 volts, 50 hertz supply. Ls is equal to 0.5 million henries, back EMF constant is 0.25 volts per rpm. Determine alpha.

Back EMF constant is 0.25 volts per rpm, motor is running at 1500 rpm. So, E_b is 375 volts. Now, you may say that it is not mentioned it is 1500 rpm. So, you can assume that motor is running at 1500 rpm. I_aR_a is 17.5 volts. So, voltage drop across the armature terminals is 392.5 volts. Source inductance is 0.5 milli Henry per phase.

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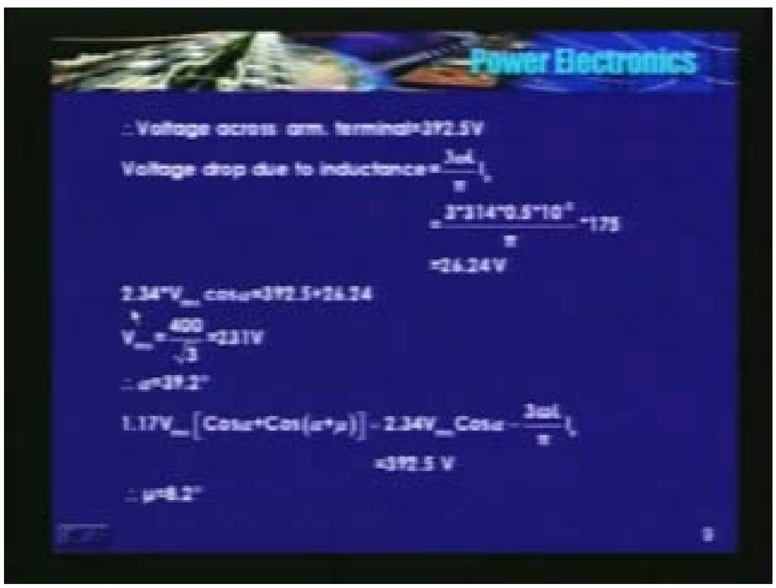

So, what is this voltage drop? Voltage drop due to the source inductance. It is 3 omega L divided by pi into I_L, the load current. So, it comes to be 26.4 volts. So, this should be equal to 2.34 V_{rms} into cos alpha. What is rms, V_{rms}? 400 by root 3, V_{rms} is rms value for the phase voltage is 231 volts. So therefore, for alpha, you will find it as 39.2 degrees or so.

So, how do I determine mu, the overlap angle? So, there is an expression gives 1.17 V_{rms} cos alpha plus cos alpha plus mu is equal to output voltage of the bridge minus voltage drop due to the source inductance. So, this is the voltage applied across the load. So, this is nothing but 392.5 volts, it is known, we calculated. So, mu is 8.2 degrees.

I will solve 1 more problem. In a single phase dual convertor, I said, we connected an inductor in the DC link and we derived a relationship between the trigger angle for bridge 1 and bridge 2. That is alpha 1 plus alpha 2 is equal to 180 degrees. How did we derive this expression? I said that voltage across, average value of the voltage across inductor is 0 and we assumed that inductor is ideal.

If the inductor has some internal resistance, invariably, it has. What is going to happen to alpha 1 plus alpha 2, will it be 180? No, because there has to be a difference between average value of V_{01} and average value of V_{02} because average voltage average value of the voltage across register is finite. It is I into R, I average into R.

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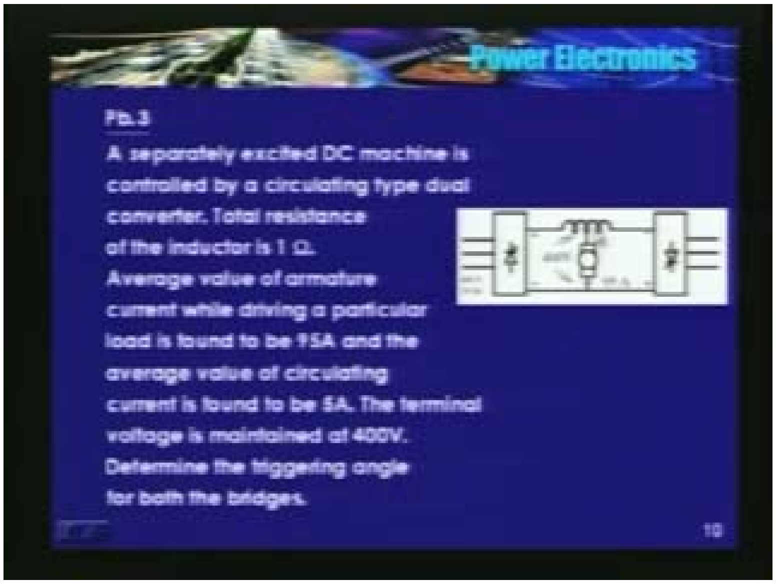

So, here is another very educative problem, 3 phase dual converter feeding a high HP motor. May be, a HP rating may be of the order of 100 HP, 400 volts. Total resistance of the inductor is 1 ohm. So, you have 0.5 ohms this side and 0.5 ohms this side. At a particular load current, this current is found to be 95 amperes and the circulating current, average value of the circulating current is 5 amperes.

So, this current is 95 and 5 amperes is circulating between the 2 bridges. That does not flow through the load current. What is the trigger angle for the bridge 1 and bridge 2? See, here is the equivalent circuit, 2.34 V_{rms} into cos alpha 1. 2.3 V into cos alpha 2, half of the filter inductance, the resistance of the filter inductance and here is the load.

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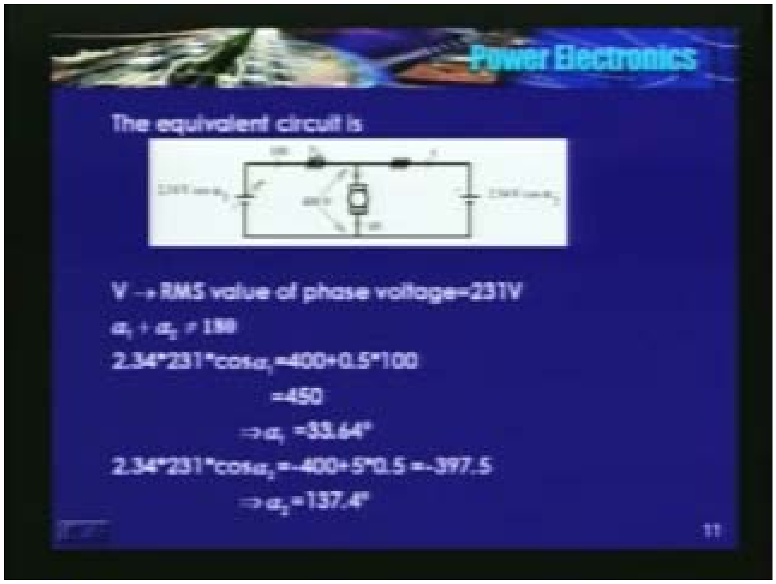

95 amperes current that is flowing here, 400 volts is the drop, 5 amperes is the circulating. If I apply KCL here, this current has to be 100 amperes. So, what is output voltage? This is 400 volts. Voltage drop across the resister is going to be 50. So, this voltage has to be 450. So, 450 is equal to 2.34 into 231 into cos alpha where 231 is the rms value of the phase voltage.

So, alpha 1 is 33.64. So, do not write alpha 2 is 180 minus 33. 64, no. So, you calculate. Now, for the bridge 2, it is 400 volts. Current that is flowing, 5 amperes here, so if I apply KVL here, what you will get? 2.34 into V_{rms} into cos alpha should be equal to V_L equal to 397.5 minus. So, alpha 2 is 137.4 degrees.

Now, you may say that alpha 1 plus alpha 2 is approximately 180 degrees. That is not what I am going to or that is not what I intend to convey. What I intend to convey is if there are resistances in the DC link, you need to take into account, you cannot ignore. So, this is a very educative problem. What is another application of a dual convertor, another application? One is in drives. Using a dual convertor, I can have all 4 quadrant operation. Another application is high voltage DC transmission.

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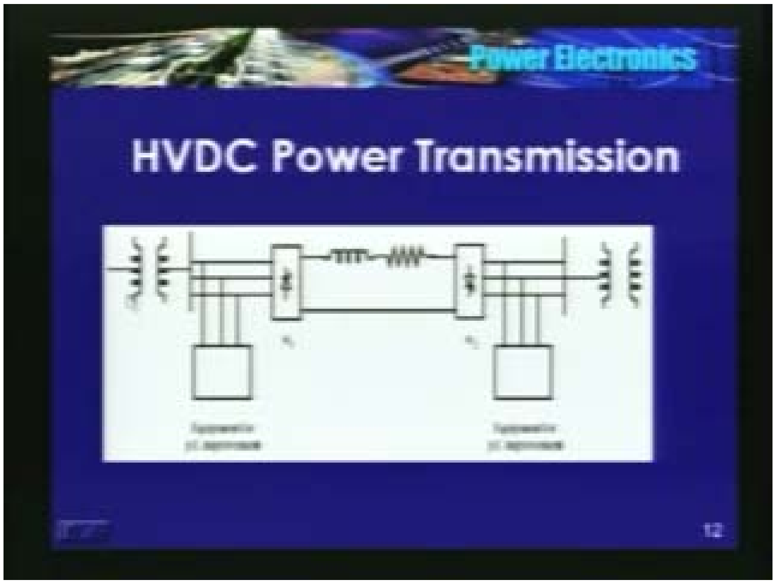

Power, AC power that is generated, it is converted into DC using a bridge and connect a large inductor in series to filter the current or make this current constant. So, you converted AC power into DC, you transmit it. At the receiving station, you use 1 more bridge. So, now you need to invert it, DC to AC, step it up. So, AC power is converted into DC and again DC to AC. Now, you may say, why are we doing this? After all AC that has to be, AC is generated, now it is again, it is consumed all the loads are AC in nature. Why do all this? Of course, you will study in detail in a separate course that is high voltage DC transmission or HVDC course.

One obvious advantage that you can see here is AC power transmission is 3 lines, whereas, here I have only 2 lines - a positive and DC, a ground. Whether you need to have this ground, again you will study this in HVDC. I am not going to discuss all that. What is another obvious advantage of HVDC system? The effect of a voltage drop due to line inductance becomes 0 because current is DC. Basically, I am discussing only the obvious advantages. HVDC is a course by itself. There are other major advantages those will be discussed in detail in that particular course.

By the way, in AC power transmission, all the generators are located in remote corner of the country are connected in parallel. Bulk of the power to Maharashtra comes from Chandrapur. So, all the generators that are connected, other part of Maharashtra also connected in parallel. In, other words they are in synchronism. So, 1 condition is frequency of all the generators or frequency of the voltage generated by all these generators should be the same. So, in other words, generator which is located in Bombay, near somewhere near Mahul and generator which is located in Chandrapur, may be, 500 kilometers away, the frequencies should be the same.

Now take, if I have a HVDC transmission, now generator that is connected somewhere in Bombay and generator connected in Chandrapur, if they are tied through a HVDC transmission, a HVDC line, the frequencies need not be the same because I have 1 frequency here and 1 voltage, I am converting it into DC and I am again converting this power, DC power to AC. The frequency of this AC need not be same as frequency of this.

In other words, I have an asynchronyse type. If I were to have an AC power transmission, frequencies should be the same and they will be the same. In other words, I can have an asynchronyse type. The generators located at 2 sides need not run at the same speed. That is one of the advantages. So, these are basically equipments for power factor improvement. I told you that the moment I introduce alpha, introduce the power factor becomes lagging. So, you need to support or you need to compensate for the low power factor. So, these are the improvement equipments for power factor improvement both sides.

If here, alpha is less than 90, here alpha is greater than 90. Conversion, inversion but in both the cases, you need to provide the power factor improving equipments. What exactly they are? We will see sometime later.

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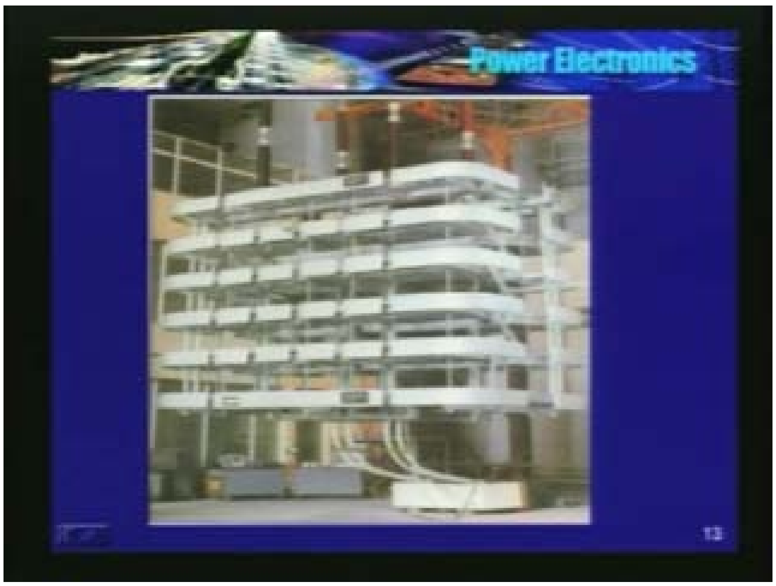

I will show you a slide. This is 1 bridge, a one unit of a HVDC link from Barsoor which is located in Madhya Pradesh to lower Sileru which is located in Andhra. This unit, the rated is 100 mega watts. It can transfer 100 mega watts of power. DC link voltage is 100 KV, DC link current is 1000 amperes, the nominal AC voltage is 220 KV. In other words, see here, this side 220 KV, this side 220 KV. Nominal frequency - here also 50 hertz, here also 50 hertz, but then, they need not be same.

DC link voltage is 100 KV, current is 1 kilo ampere, power that is transmitted is 100 mega watts. So, if this is Barsoor, this could be lower Sileru or vice versa. Stage 1, there are 2 stages there; stage 1, stage 2. This 100 mega watts HVDC link is for stage 1. Stage 2, I think it is 200 mega watts and the configuration is different. So, you need to have a power factor improvement plus other filtering equipments, a smoothing reactor and a large number of devices.

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See, I will just show you. Here is a slide, a 3.2 KV, 1 kilo ampere device. 3.2 KV, 1 kilo ampere SCR, see the size. Now, large number of devices are connected in series because DC link voltage is 100 KV, the rating of each thyristor is 3.2 KV. So, a large number of devices are connected in series. By the way, how will you trigger this thyristors?

In our lab, input is maybe, 230 or maximum may be, 400 watts or 440. So, we used pulse transformers. So, here, the DC link voltage is of the order of 100 KV. Can I use a pulse transformer? No, generally, these are triggered using optical cables. These are this is one of the ways of triggering a high voltage SCR. See the size, a large numbers are connected in series.

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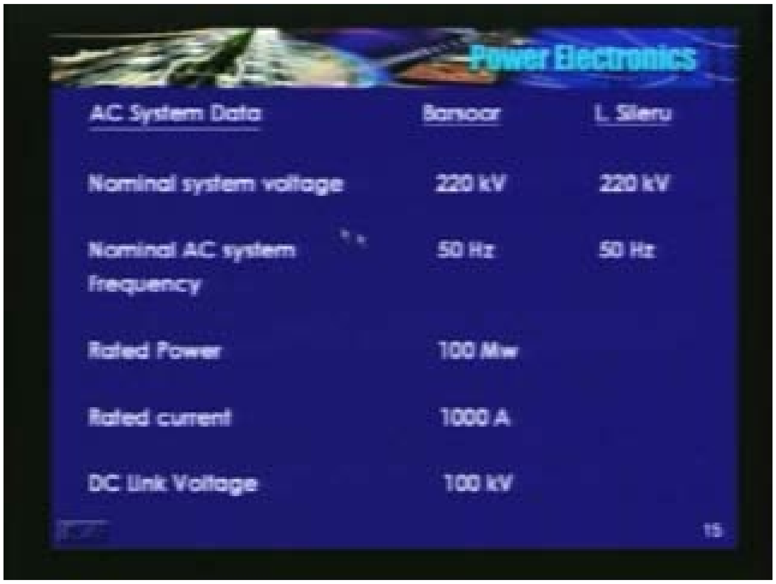

See, here is the technical data. Nominal voltage is 220 KV, both frequencies are 50. Nominal frequency is 100 mega watts, rated current is 1 kilo ampere, DC link voltage is 1000 KV. This is unit 1. Barsoor to lower Sileru, stage 1. That is about HVDC.

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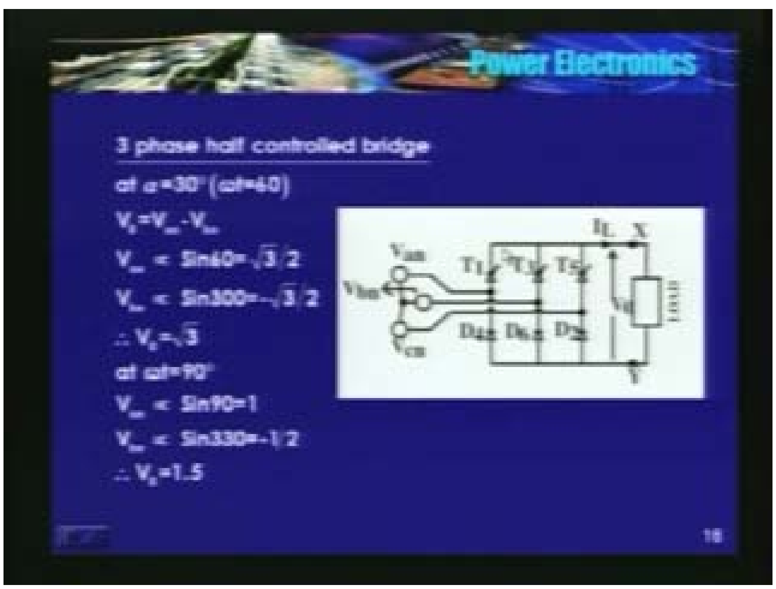

So, we discussed 3 pulse convertor, a 6 pulse convertor; 6 pulse convertor is a 3 phase fully controlled bridge. So, similar to a single phase half controlled, we will have a 3 phase half controlled bridge. I am not going to discuss in detail. I will just take 1 case and I will tell you how exactly to draw the output voltage of waveform? If you have understood the philosophy, you can draw it for any other trigger angle, alpha. So, we have 3 thyristors to form a common cathode configuration. We have 3 diodes which form a common anode configuration.

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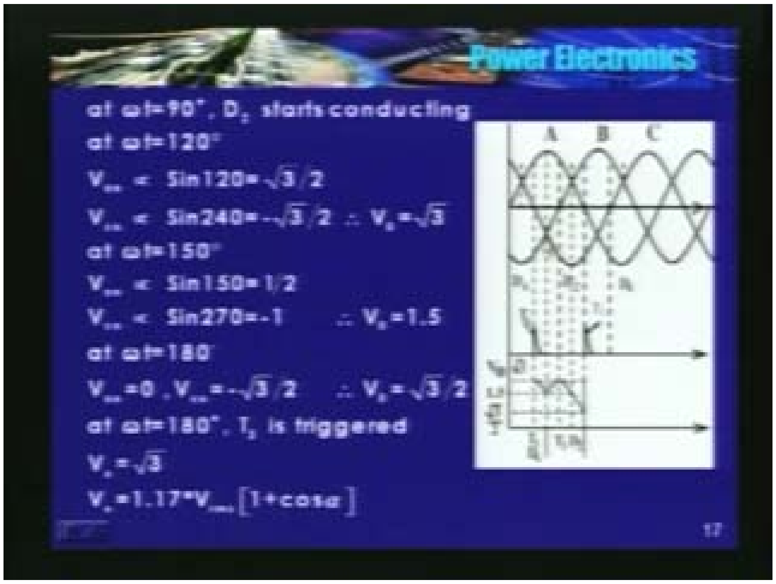

So, in the 3 phase voltage system, since the diodes are form diodes are forming a common anode configuration, change over from 1 device to another device takes place at the point of natural commutation. So, D_6 conducts here because phase B is more negative. D_2 conducts here because phase C is more negative and D_4 conducts because phase A is more negative, whereas, in the upper half, there are thyristors. So, device which conducts depends on alpha. So, this is the point of reference for thyristor connected to phase A.

So, we will draw it for alpha is equal to 30 degrees. At this point, T_1 is triggered. So, upper voltage is V_{an} minus V_{bn} because diode is conducting. So, at this point, alpha is 60 degrees, root 3 by 2, phase A is sin 60, phase B is sin 300. Both are root 3 by 2, root 3 by 2. So, output voltage is root 3.

After 30 degrees, in other words, 330 degrees or say 330 minus because at 330, D_2 takes over from D_6. So, at 330 minus, 6 is conducting. It is still V_{an} minus V_{bn}. V_{an} is 1, V_{bn} is sin 330 minus that is 0.5 itself, minus 0.5. So, output voltage is 1.5.

So, at this instant, D_2 takes over but in the upper half, T_1 is still triggering, sorry T_1 is still conducting. So beyond this, till you trigger T_3, output voltage is V_{an} minus V_{cn}. So, V_{an} is at this instant, V_{an} is sin 120 and V_{cn} is sin 240. It is root 3.

So, after some time that is omega t is equal to 150, V_{an} is half. At that instant, V_{cn} is sin 270 that is minus 1. Output voltage is 1.5, 1.5 per unit. What happens or what is the output voltage just prior to triggering T_3? Because, at this instant T_3 is triggered. Just prior to triggering T_3, V_{an} maybe, 180 minus that is V_{an} is approximately 0. V_{cn} is sin 300 that is root 3 by 2. Output voltage is root 3 by 2. At this instant, again T_3 is triggered, output voltage jumps to root 3 because the moment you trigger T_3, output voltage is V_{bn}, V_{bn} minus V_{cn} and V_{bn} at that time is sin 60. Remember, reference point for B is here, B has crossed 0 at this point so that alpha is equal to 30.

Instantaneous value of phase B is proportional to sin 60 that is root 3 by 2, sin C is also root 3 by 2. Output voltage is root 3. So, it is something like this, see. So, the average value of this output voltage is 1.17 into V_{rms} into 1 plus cos alpha, same. In the sense, in the single phase case, it is V_m by pi into 1 plus cos alpha for the half controlled bridge, 2 V_m by pi into cos alpha for the fully controlled bridge, that 2 is not there. Here also, 2.34 into V_{rms} into cos alpha for a controlled bridge. So, half controlled is 1.17 into V_{rms} into 1 plus cos alpha. So, simple to remember or you may derive this using the same philosophy.

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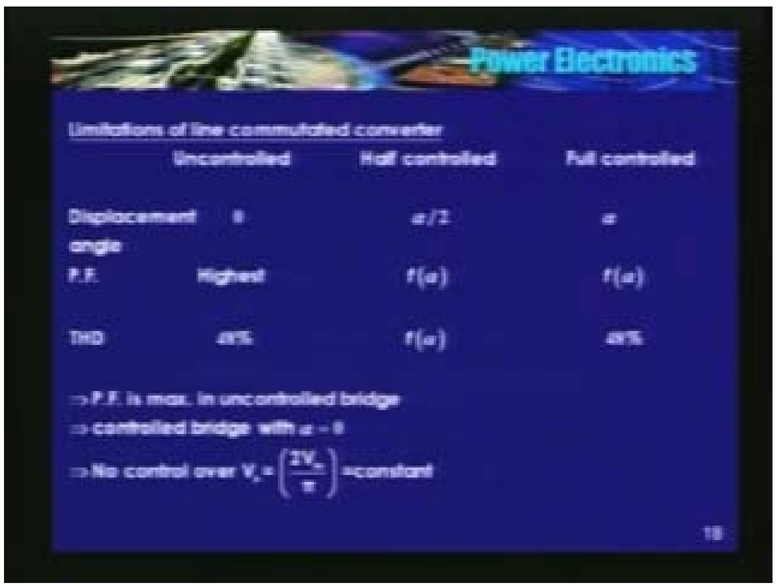

We have been studying so many line commutated convertors. We studied uncontrolled bridge, half controlled, half wave rectification and fully controlled bridge. What are their disadvantages or what are their limitations? If the current is continuous, for an uncontrolled bridge, we found that displacement angle is unity, single phase, remember. Single phase current is continuous, uncontrolled bridge, displacement angle is 0, whereas, for half controlled is alpha by 2. It is lagging now, whereas, the fully controlled single phase bridge is alpha.

So, what is the power factor? Power factor is depends on displacement factor also. So, if the current is continuous, same, power factor is highest for an uncontrolled bridge because displacement factor is unity. For a half controlled bridge and for a fully controlled bridge, it is a function of alpha. Now, displacement factor is also less than 1.

So, as alpha increases, power factor deteriorates in a fully controlled bridge. I have showed you in the vector diagram also. Similarly, the total harmonic distortion is found to be 48% in the source current. I assume the current to be constant and repel free. If I assume the current to be constant and repel free, the total harmonic distortion or the harmonic content in the source current is 48% in both uncontrolled as well as half controlled, 48%, whereas, in half controlled, it is a function of alpha.

What are the implications on the power systems? See, all of us know, in the sense, the power factor should be as high as possible so that for a given power, my size of the equipment becomes small, after all size of the equipment is in terms of KVA. So, KVA is equal to kilo watt if the power factor is 1. So, as the power factor falls for a given power, size of the equipment increases, therefore, cost increases, weight increases and space and what not.

So, in a single phase case, we found that power factor is maximum for an uncontrolled bridge or fully controlled bridge with alpha is equal to 0. So, I have a fully controlled bridge. To have the same power factor as that of an uncontrolled bridge, my alpha should be 0. In other words, average value of the output voltage remains fixed. It is 2 V_m by pi. We have no control over the output voltage.

I have a problem here. The problem is if I try, if I want to improve the power factor of a fully controlled bridge, I want to make it same as uncontrolled bridge. I have to make the alpha to 0 and at the moment I make alpha is equal to 0, I have no control over the output voltage. So therefore the purpose of using the fully controlled bridge itself is lost.

So, is there are other ways, further any other ways of addressing this problem or in other words, improve the power factor of a fully controlled bridge, making the displacement factor 1 and have a control over the output voltage?