Power Electronics

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Lecture - 22

Basics of DC to AC Converter # 1

Today we will start with invertors, basics of invertors. So, invertors are called DC to AC convertors. So, invertors are called DC to AC convertors, DC to AC convertors.

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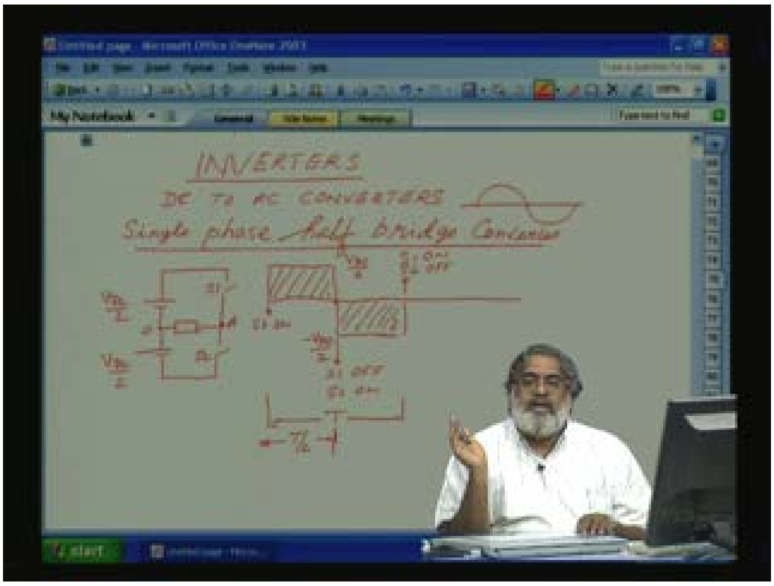

So, DC is our source; it can be battery or our phase controlled convertor or our front end AC to Dc convertor. So, let us assume our DC is fixed. How to get AC? AC means alternating voltage. The moment AC, where AC comes into our mind, we always think AC is sinusoidal. But for all purpose; for UPS or for modern applications, we want as far as possible nearly sinusoidal output voltage and current. But you get the nearly output sinusoidal voltage and currents are very difficult. So, what we will do? We will get as closely as possible, sinusoidal voltage and current.

Last class, with PWM for front end AC to DC convertor, we have studied about pulse width modulation technique. So, in pulse width modulation technique, we learnt how to get output wave form proportional to our modulating wave. That modulating wave can be sin wave. So, before coming to that, let us take the basic AC wave form. How to get a basic, the basic convertor DC to AC basic convertor? This is called single phase half bridge convertor, single phase half bridge convertor. The basic configuration, let us our DC we are splitting it into 2. If the total DC is DC, this will split V_{dc} by 2 and V_{dc} by 2 here. Then, this is our switch. Here, this the centre point here, we connect the load.

Now, let us start from the simple DC convertor and the simple load. Let us consider this as a resistive load. Then our switch, we will assume; whenever we give a control pulse or gate pulse, the switch is immediately on and when the gate pulse is removed, switch is off here. So, we will such type of switches can be realised using transistors, mosffets or IGBT. Now, let us say, this is our A. Let mark the switches; S_1 and S_2. Now, let us say S_1 is on; S_1 on means the voltage wave form across A_O will be, a point will be connected to this point, S_1 is on, switch is closed and VA_O will be V_{dc} by 2, this is V_{dc} by 2.

Now, we are turning off S_1 that means we are S_1 on, here. At this point, we are turning off S_1 and turning on S_2. So, let us assume the switching transitions are instantaneous. So, S_1 is immediately switched off and S_2 is turned on. So, what will happen? Now, the V_{A0}; S_1 is off, S_2 is turned on, this point, A will be connected to this point. So, our V_{A0} will be minus V_{dc} by 2, minus V_{dc} by 2. So, at this point, S_1 is turned on; at this point, S_1 off and S_2 on. Again at this point, we will be turning off S_2 and turning on S_1 on. So, this will repeat.

So, equal duration on and equal duration off or in other ways, equal duration on for S_1 and equal duration on for S_2 that is a must. Why? Otherwise, this area here, if the durations are not same, the top area and the bottom area will not be the equal will not be equal. So, what happens? There will be a DC shift. But what we are talking about? DC should be 0, output should be AC, need not be sinusoidal. It is an alternating wave form; the moment AC means the period should be there. So, that period is from here to here, this our period and for DC to be 0, exactly this point should be T by 2. That means half period top switch is on; next half period bottom switch is on. So, we generate the simple, the very basic AC wave form.

Now, for a resistive load, what will happen to the current? Current will be proportional to the voltage. So, depending on the resistance, the current can have the same wave form. This height will be V_{dc} by 2 divided by R.

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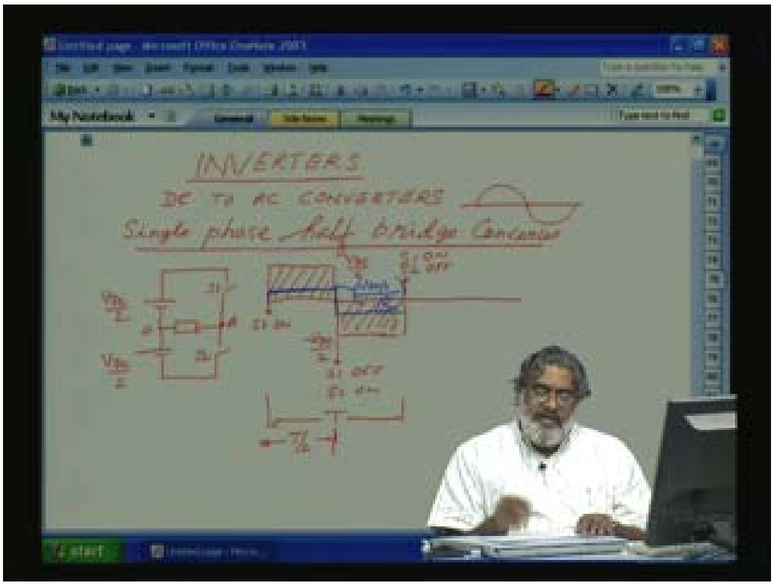

So, need not be a square pulse but it is a periodic pulse that depends on the resistance R. So, we generated the basic AC voltage wave form. But almost, all the time, load may not resistive; load can be back emf load, load can be inductive. So, let us take a general inductive load. So, what happens? So, we will redraw, we will make this is inductive, V_{A0} inductive.

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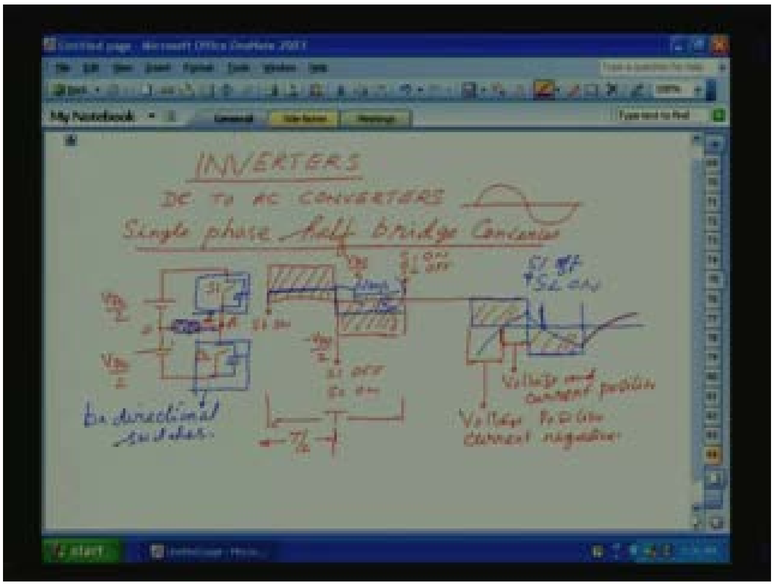

Then we will, what will happen? Again, whether the load is resistive or inductive, we are switching on and switching off the devices with equal duration. So, here you will get a V_{dc} by 2. Now, what happens? What happened to the current through the inductance? Let us take inductance with inductance with resistance. So, what happens? When this is turned on, current will slowly raise. So, if you see the steady state operation; current will go like this, come like this, again here, it will go like this.

So, at this point, the di by dt is negative. So, it will go in the negative direction. So, equal positive and negative. So, if you see here, for a purely inductive load or assumed the resistance is very negligible and we are apply equal positive across the equal positive during the first half and equal negative during the second half, so that is this one. So, for the voltage, there is no DC. So, current also cannot be DC because of the Kirchhoff's law. But this current will have a wave shaped like this; if is inductive load, inductive with resistance; there is a time constant, raising and decreasing.

But if you see here, part of the time when the output voltage is positive, during this period, current is negative. Only during this period, both voltage and current is negative, voltage sorry voltage and current positive. At this point, during this period; voltage positive, current negative, there is a difference between resistive load and the inductive load. See, current is negative; see we cannot switch the wave from depending on the load. We will be switching the inverter sorry we will be switching the inverter with equal duration positive cycle, equal duration negative cycle to get our basic AC voltage wave form. So, it is independent of the load.

But here if you see, the current is negative. So, even though, at this point, A is connected to S_1; previously if the current was in this direction, positive, let us take the positive direction, let us take in this direction, so current will be when the switch is closed, current will be following like this. Now, in this point, current is negative. Negative means it will be in this direction. So, A is connected here. So, how the current will flow? So, we want a bidirectional switch. So, in this negative direction, to take care of that one, we put an anti-parallel diode here.

So, when S_1 is on, when S_1 is on, S_2 is off. So, when S_1 is on and if the current is in this direction, it will go through the diode. Now, when S_2 is on, S_2 is on; S_1 is also on, S_1 is off. But when the S_2 is on means this point is connected to this one. That means diode, anode point is connected here and this point is here because of S_2 is on, diode will be, during the full S_2 on period, diode D will be switched off. It is reverse biased.

So, whenever S_1 is on only, diode will conduct depending on the current direction. That means this is true in the negative direction also. See, if you see, during this period, what happens? Current is positive, it is going in this direction; now at this point, we are turning off S_1 off and S_2 on but the current is still positive. Positive means current is in this direction. Now, S_1 is turned off. So, what happens? Current direction cannot change instantaneously in the load. So, this current, you should have a freewheeling diode here.

So, for the inverter, what we talked about a switch is a by directional switch, the control switch, IGBT or transistor or power MOS with an anti-parallel, the freewheeling diode together constitute a switch for the inverter; same thing also here. That means this are by directional switches that means current can go in both the direction. Now independent, so what we have come out with here?

We have come out with an inverter with using 2 by directional switches and by equal duration of the switching on period for the top and bottom device, we got an AC wave form a square wave form. We know, this square that depends on the V_{dc}, the periods are equal. So, we got an AC wave form with equal positive and equal negative that means DC is 0, it will contain only AC waveform and independent of the load, whether it is resistive or inductive load or independent of the current direction, we can switch the inverter.

Now, the moment as I told, if you want an AC wave form; what you want? We want nearly the sinusoidal voltage wave form or the load should take nearly sinusoidal current and the harmonic currents due to the harmonics should be much much smaller. For that, the L should be very high so that the L omega, omega varies with harmonic frequencies, it should be very high so that the current amplitude due to this harmonics should be as low as possible. But that may not be all the time possible. So, for such a system, let us see a wave form like this; what are the harmonics involved.

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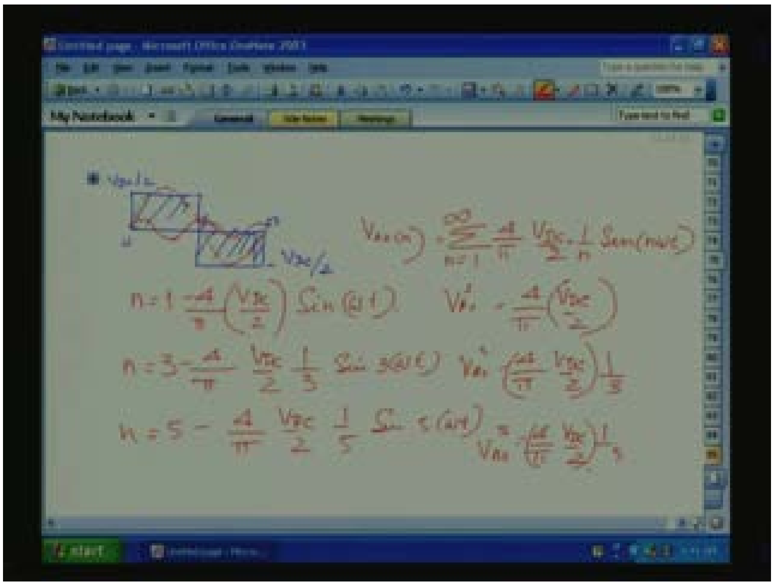

Let us draw the wave form; this one equal duration, 0, pi, 2 pi, this is V_{dc} by 2, this is minus V_{dc} by 2. So, what all harmonics it will have? It will have a fundamental. See, it can have a fundamental, fundamental will be something like this; then it cannot have a second harmonics. If you see here, second harmonics are even, these are second means even function but this has an odd symmetry. So, second harmonics will not be there, it will have a third harmonics. Third harmonics means it may be, it will be something like this, third harmonics, then it can have fifth harmonics.

So, how to find out this amplitude of this harmonics? We can do the Fourier series. So, the harmonics V_{A0} (n) harmonics, we can do the Fourier series will be, it will be sigma n is equal to you can do the Fourier series, into infinity. It will be 4 by pi V_{dc} by 2 into 1 by n sin n omega t, these are the harmonics. Let us say, n is equal to 1, we will get the fundamental; fundamental will be 4 by pi into V_{dc} by 2 into sin omega t according to this Fourier series expression. So amplitude, $V_{A0}{}^{1}$, amplitude will be 4 by pi V_{dc} by 2.

Let us take next; n is equal to 3. It will be 4 by pi V_{dc} by 2 1 by 3 sin 3 omega t. So, what is the amplitude? $V_{A0}{}^{3}$ amplitude is equal to 4 by pi V_{dc} by 2 into 1 by 3 that is this 10. Now, let us take n is equal to 5, then the amplitude will be equal to 4 by pi. Now, the fifth harmonic time will be 4 by pi V_{dc} by 2 1 by 5, from this equation, sin 5 omega t. So, $V_{A0}{}^{5}$ is equal to 4 by pi V_{dc} by 2 into 1 by 5.

So, if you see here, fundamental is equal to 4 by pi V_{dc} by 2, third harmonics is equal to the same fundamental amplitude divide by 1 by 3 and fifth harmonics if you say, the same fundamental divide by fifth. So, if you see the harmonic amplitude, if you plot it, it will be like this; if you want to draw the amplitudes and the harmonics order.

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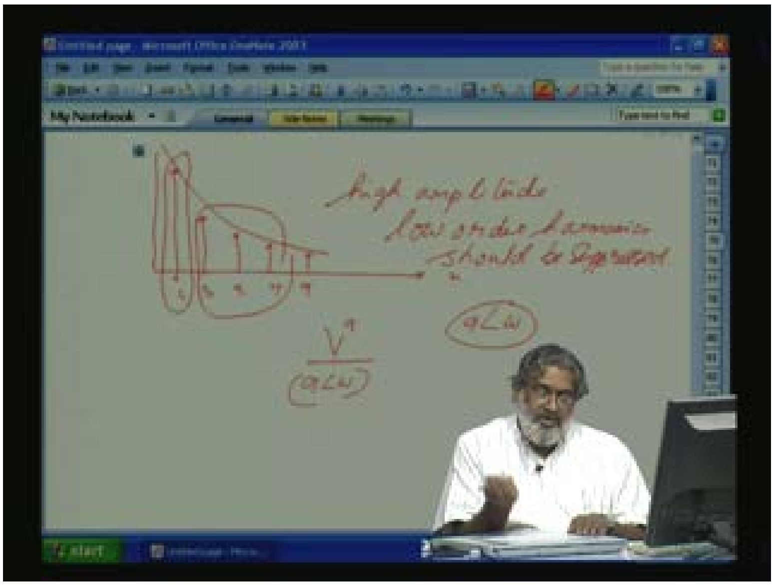

So fundamental, fundamental will have some amplitude that is a 4 by pi V_{dc} by 2. Then third harmonics will be one third of that one, fifth harmonics will be one by fifth, seventh harmonics will be like this. So, as the order increases, amplitude will be inversely proportional to the order. So, it will go like this; fundamental, third, fifth, seventh, then ninth, it will go like this. So, if you see here, so this is the fundamental.

Now, what we want for the output voltage, for an ideal DC to AC convertor? We want the sinusoidal component only because if this harmonics are present, this harmonics will produce its own current wave form and this harmonics will not, will not be able to produce a real power it but at the same time, it can create lot of I square R losses. That efficiency can come down because of the current.

Now, what we want? We want all these harmonics to go. Especially the high amplitude, all high amplitude, low order harmonics should be suppressed; high amplitude harmonic low order harmonics should be suppressed. So, if we can suppress; then or the amplitude should be reduced or eliminated. Then what is the advantage? Then the current will be due to the harmonics far away from this one and the impedance for that one is suppose it is for the impedance, for inductive load; for ninth harmonics, it will be nine L omega, impedance will be more and so V^9 by the current, 9 L omega amplitude of that current will be much much less compared to, harmonic current due to ((…25:06)).

So, how to suppress or reduce this one? The moment if you want to eliminate any harmonics, the immediate idea is to put a filter. So, you put a filter so that third, fifth, seventh, theoretically possible, third, fifth can be highly suppressed. But the problem is as power electronics engineers, see these are mathematic, with mathematical concept but if you put it, the cost of the system will increase.

So, we should also give a DC to AC convertor with a cost effective solution. That means minimum components, as minimum components as much as possible with increased reliability. So, filter is not a or putting filter is not a good concept because these invertors we use for a UPS application with 100 amp 100 amperes or 50 amperes or 10 amperes;

so if want filter of LC that L cage as to be proper to that much and that much copper is required and to suppress third harmonics, the cut-off frequency should be very close. So, size of the inductance will go and the cost will also. So, filter is not an optimum solution.

Another thing, we were talking about the DC to AC convertors; AC convertors means alternating wave form. So, the AC output also should be controllable that means for an AC wave form, both voltage that is magnitude and frequency should be variable; we should be able to vary according to want we want, the load one.

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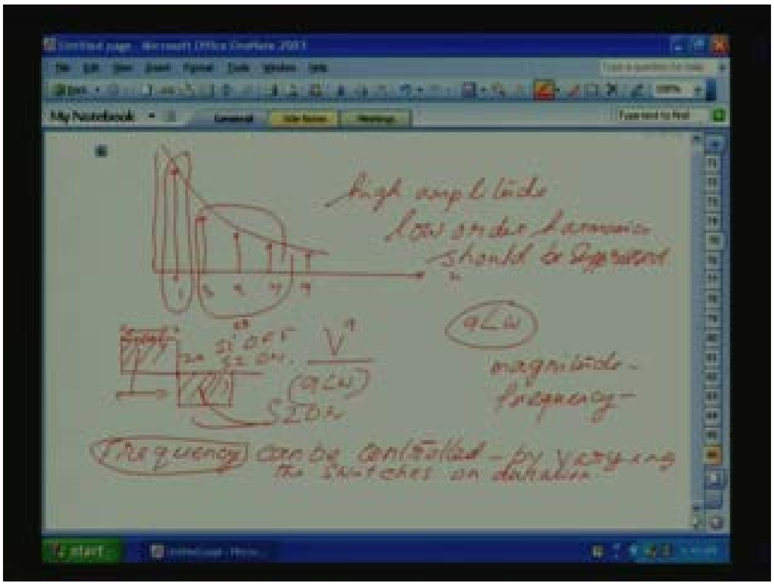

So, in our pervious single phase AC to Dc convertor with a rectangular pulse like this, with equal duration on and equal duration off; if you see here, the frequency that is zero pi this 3 pi, this duration depends on when you turn off S_1 and when you at this point, S_1 off and S_2 on. At what point, we are making S_1 off and S_2 on? So, this inductance this instant, we can shift it this way or this way. So, by controlling the instant at which the switches are turned on and turn off, the frequency can be controlled.

So, in the previous circuit, what I want to say, the frequency can be controlled by controlling the device turn on and turn off period, off duration; controlled by varying the switch's on duration. That means this period; this period, S_1 on, this period this period, S_2 on. So, by controlling these 2, we can control the frequency that is frequency. But AC wave form means amplitude. So amplitude, what we are talking about the fundamental, if we want the real fundamental; let us for the time being, forget about the harmonic, the fundamental amplitude also should be controlled, then only we can have an controlled DC to AC variation.

So, how this? So, the present pervious circuit with that switching sequence, what I told you will not be to control it. Now, let us take about not the single phase half bridge, let us talk about the full bridge convertor. So, with full bridge convertor, the amplitude can be doubled compared to this one. Let us go to that full bridge convertor, single phase full bridge converter.

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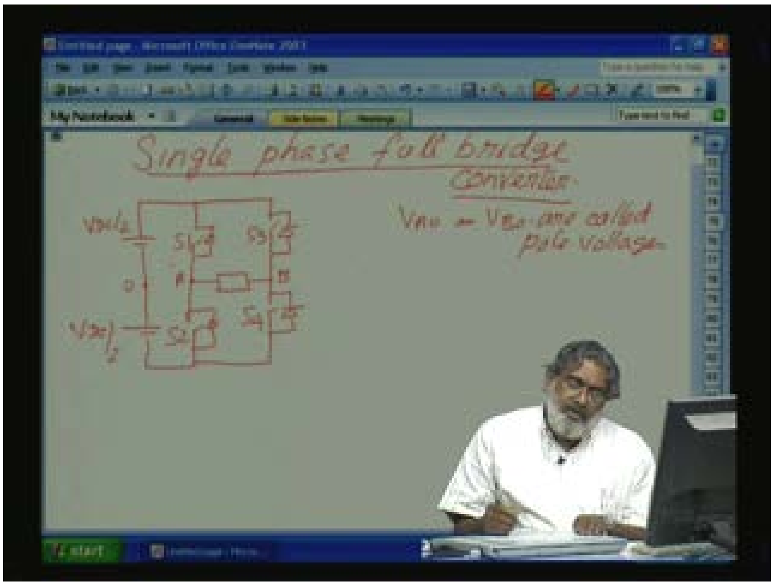

So, what we want to do here? The same, our DC is V_{dc} by 2, DC part is still the same; we have the O here, V_{dc} by 2, we have the switch here. Now, the switch is a bidirectional switch, we have the diode also here. So previously, load was connected between this point to the O. So, to increase the voltage, this point we will remove and that is A and the load is this part is here; we will put one more set of switches here, like this. This is B, so this is our switch S_1, now S_2 S_3 S_4.

Now, let us see, previously when the S_1 is turned on, we have taken the A point; here what we call the leg A and we will measure the leg A voltage and leg B voltage with respect to a common reference point that we can measure. We can either measure from this side, bottom side or we can from this side. So, in line with our half bridge convertor, both pole, the leg A we and leg B voltages, we will measure with respect to O.

So, the voltages V_{A0} V_{B0} are called pole voltages, V_{A0} and we have 2 poles here; and, why this pole? This concept you know, we have saw it, single pole double throw switch. See that means this A is a pole, when this is one, A can be connected to this side, top side; when the S_2 is on, A can be connected to this side. So, from that concept of single pole double throw.

Similarly, B can be connected; when the S_3 is on, it is connected to the positive rail and the when the S_4 is on, B can be connected to the negative rail. So, V_{A0} and V_{B0} are called pole voltages; in literature also it is like this, it is called pole voltages or leg voltage. That pole voltage concept from the single pole double throw switch. These are all switches, these are represented as switches. Now, these switches are not mechanically controlled, electronically controlled that is the only difference. So, these are poles. So V_{A0} V_{B0}, so if you see, this V_{A0} and V_{B0} or this poles, A pole and B pole; according to our wish, we can connect it either to the positive or negative, these are independent. But to get the maximum voltage, let us see.

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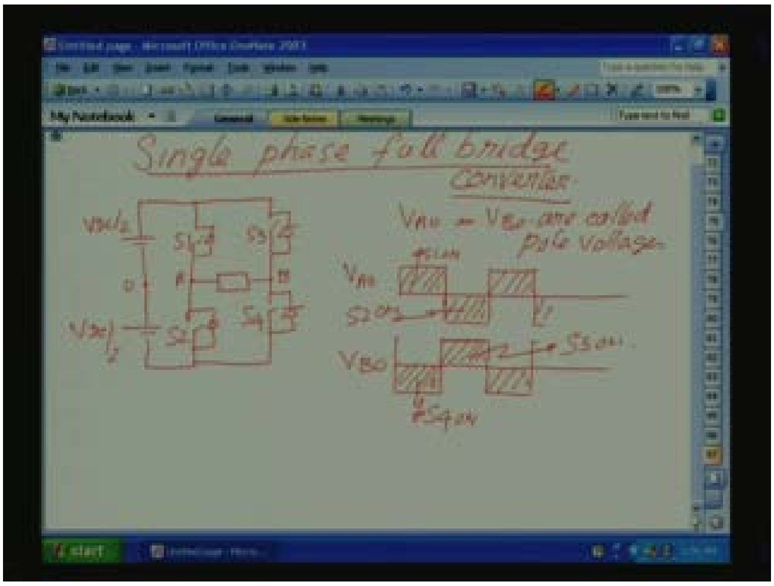

Let our V_{A0} V_{B0} is like this; see it goes like this, this is our V_{A0} pole voltage, this is V_{A0} and what happened to our V_{B0}? So, V_{B0} also we are controlling this way, V_{B0}. I will do the other way, so our V_{B0} is like this. So, if you see here, this case; during this period, S_1 on and during this period S_2 on. So, the pole A is connected to either to the top side or the bottom side, here.

Now V_{B0}, here V_{B0} is connected to the bottom. So, it is during this period, S_4 on and during this period, S_3 on. Now see, this A and B, what we call the pole A to the point, pole A the point pole A and pole B that point are at the opposite end of our load.

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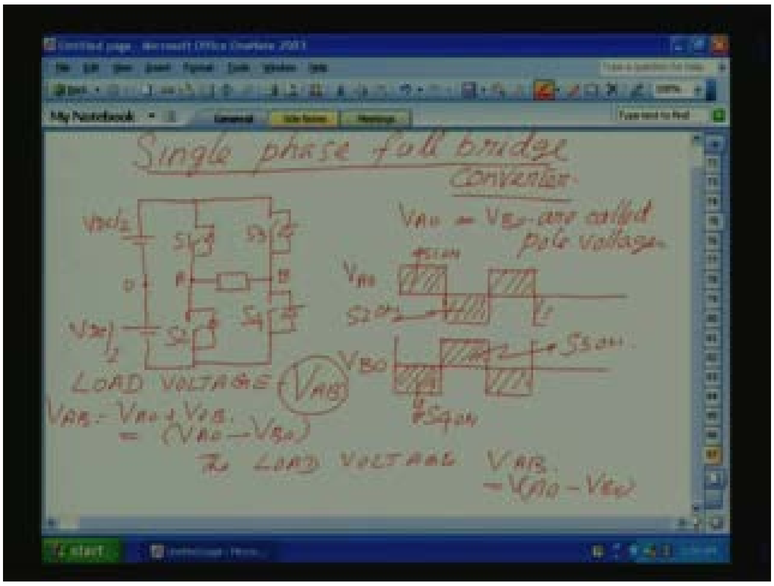

So, our load voltage wave form, the load voltage wave form is equal to V_{AB}, correct? But what we got here is V_{A0} and V_{B0}. So, what is V_{AB}? That is we have to go from voltage A to B, we can go from V_{A0} to zero, V_{A0}, then we can go from this 0 to B. So, V_{AB} is equal to V_{A0} plus V_{0B}. That means we are measuring the voltage V_A with respect to zero, then we will measure the voltage at point zero with respect to B. So, if you do it, we will get the V_{AB} voltage; V_{A0} plus V_{0B}. This is also equal to V_{A0} minus V_{B0}. So, what it shows?

The net pole voltage, net load voltage is the subtraction of pole voltages. So, that means the load voltage V_{AB}, V_{AB} is equal to V_{A0} minus V_0 is equal to V_{A0} minus V_{B0}. So, if you do it here; what will be our load voltage?

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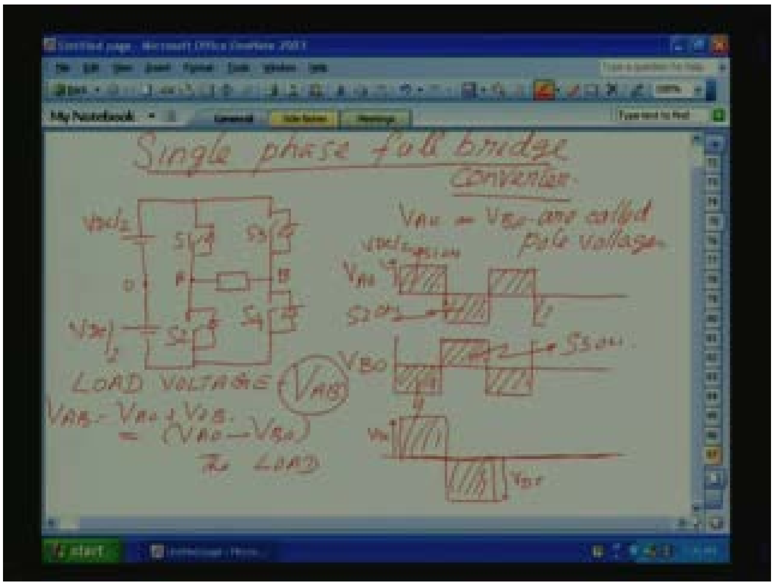

Let us draw; this is our X axis, V_{A0}, minus V_0. So already, this is V_{dc} by 2 and this is minus V_{dc} by 2. So, plus V_{dc} by 2 minus of minus V_{dc} by 2 will be V_{dc}. So, this will go to V_{dc} here. So, this amplitude is equal to V_{dc} but this amplitude is equal to V_{dc} by 2. Similarly, V_{A0} minus V_0, this is positive, so minus will become this will become negative. So together, this 2 minus V_{dc} by 2 will become minus V_{dc}. So, this way, it will go. So, this height is equal to V_{dc}.

So, by properly synchronising the pole voltages, V_{A0} V_{B0}, we got the same output frequency but the output voltage is equal to voltage is doubled. So, what we did? We here, we have rectangular pulses with equal duration for the pole voltage A and V_0 and properly synchronising the wave form V_{A0} V_{B0}, we got a output voltage V doubled to V_{dc}. But here also we got the increase in the voltages. But here also, we are able to control the voltage.

Suppose, I want a DC voltage; what mean the controlling the voltage? Controlling the voltage means we have to control the fundamental component. How to control the fundamental component? So, we want the frequency to be controlled independent of the amplitude and we want to control the amplitude independent of the frequency. So, 2 control functions are needed. So, we require 2 degrees of freedom.

So, from the previous circuit using only one limp, we can control the frequency. Here also, the second limp we have added. Here also, we can control the frequency but if you see, this control of V_{A0} and V_{B0} are independent of each other. So, from that we can derive the second control option. What you mean by it is independent of V_{A0}? It can be controlled independent of A_0. Suppose here, this V_{B0} $_{B0}$ instead of this way, if I have switched like this that is this position that is here S_3 on, here S_4 on; then what happens?

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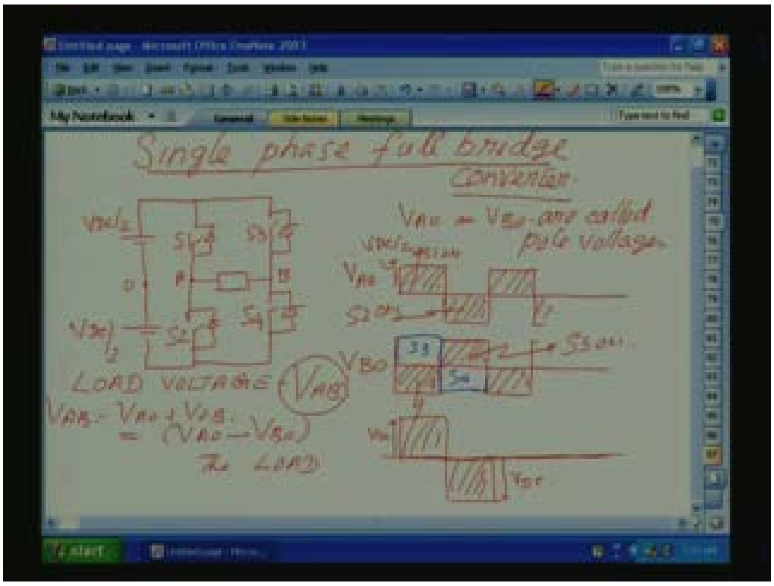

These 2 wave forms are identical, magnitude are identical, frequency is identical. Then what will happen to the output voltage? Output voltage will be 0. So, V_{A0} and V_{B0} are identical. So, V_{A0} minus V_{B0} will be 0 even though individual pole voltages are not zero. So, that means there is control flexibility is possible because of the independence of pole voltage and V_{B0}, pole voltage V_{A0} and V_{B0}. That probably, we can make use of for controlling the output voltage.

How to do that one? Let us that means the switching instant of V_{B0} can be, the switching instants of the V_{B0} with respect to A_0 can be varied, shifted. Now, we have shifted previously 180 degree. Why 180 degree? We can vary with theta, it can vary from not only 180 degree; zero to 180 degree, any instant between 0 to 180 degree. That means the V_{B0} can be placed, the pervious V_{B0} can be placed or delayed with respect to A_0 between 0 to 180 degree. So then, the how the output voltage will be? Let us see.

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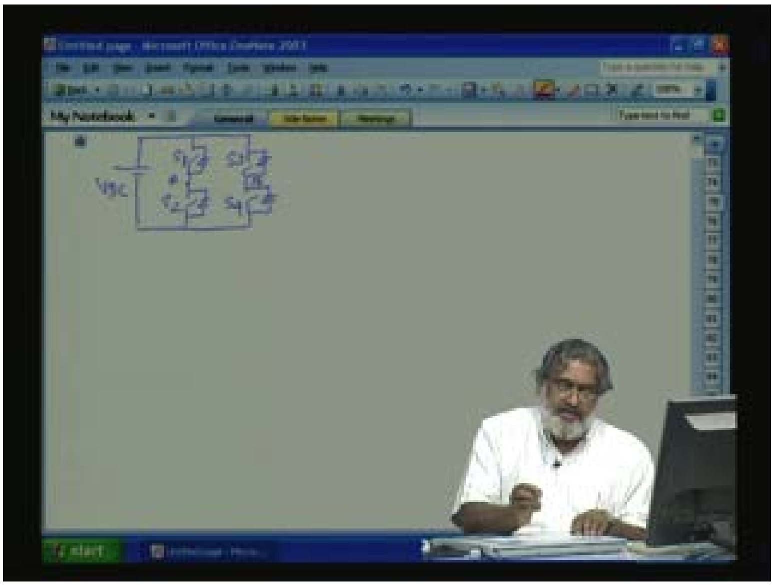

Now, let us draw our V_{A0} wave form. So, our convertors we will draw now again. See here, I will put V_{dc} because we do not want the O point, load we need not connect it there. The load points are connected across A and B; you have the diode here, S_1 S_2 S_3 S_4. So, but the A voltage wave form; A and B, we can still measure with respect to or we can assume it, A is measured with respect to the factious centre point of V_{dc}. Still if you do that one; our V_{A0} will be like this - plus V_{dc} by 2 minus V_{dc} by 2.

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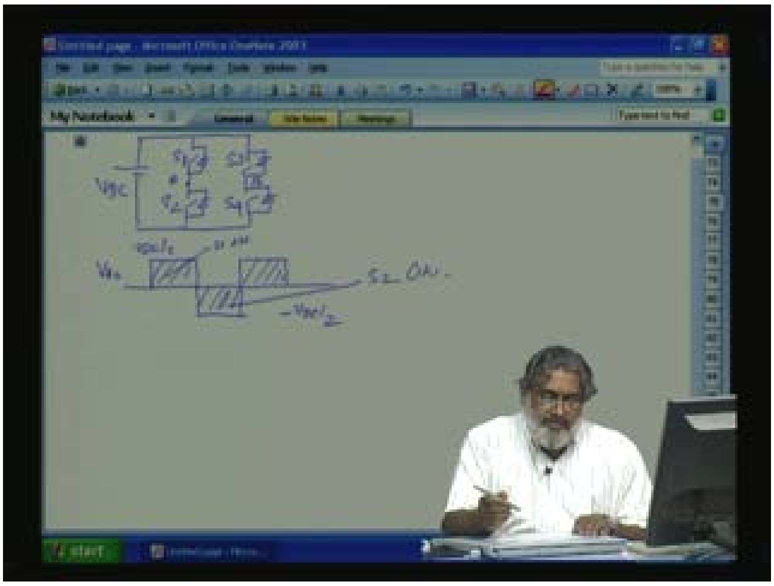

This is our V_{A0} wave form, this is our X axis; this is our V_{A0}. So, we are measuring the pole A with respect to the factious center point A. So, this will be V_{dc} by 2, this will be minus V_{dc} by 2 and S_1 on, S_2 on. Now, I told, we have the freedom of choosing the switching instead for B. But the top and bottom as to be in equal duration. That only ensure that the pole voltage have there is no DC component, it is all AC waveforms only; all AC means all the harmonics, DC will not be there.

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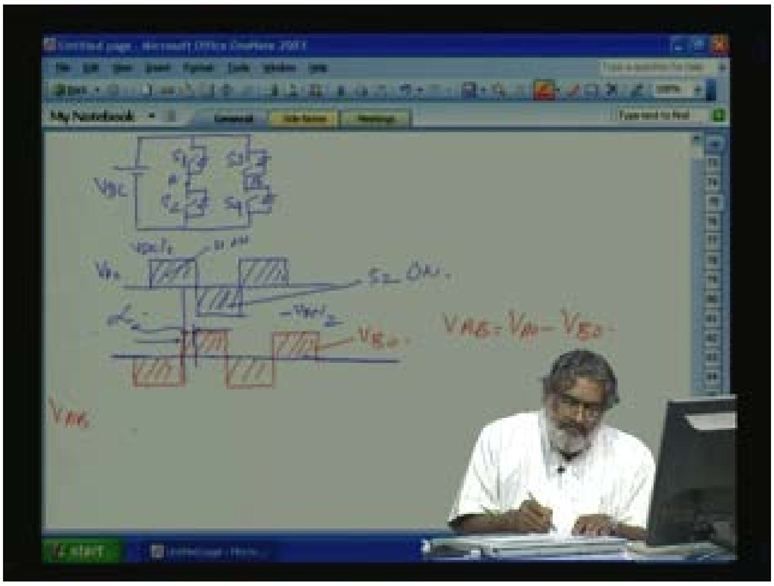

So, let us delay the B with respect to an angle alpha. This is our angel alpha, alpha. Now, D will be, we will start from here; so we will probably draw with a different colour. So, B will be starting from here, this is our V_{B0}. So, with this delay of alpha; how the V_{AB} will be? V_{AB} is equal to V_{A0} minus V_{B0}. So, V_{AB} will be if you see here, during this portion, V_{A0} minus during the alpha portion, V_{A0} and V_{B0} are your polarity is the same. So, subtraction will lead to a zero voltage on the output side.

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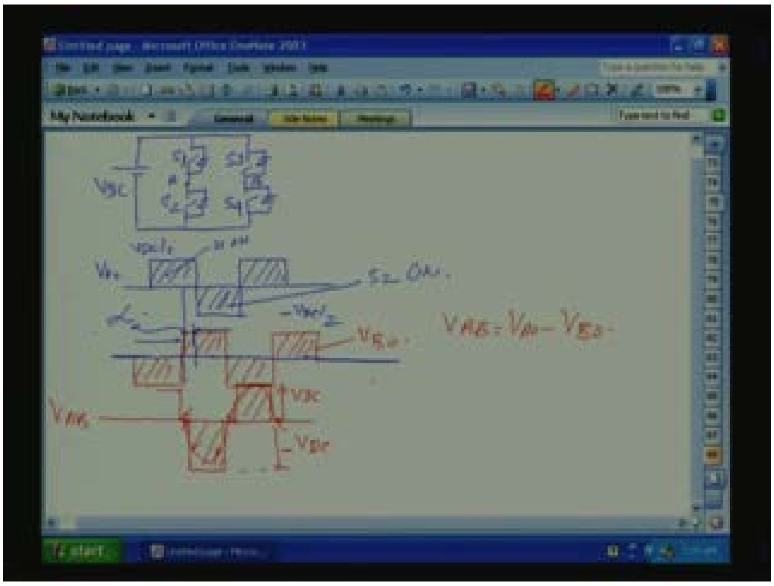

So, during this period, output will be 0. Then you have a voltage is equal to V_{dc} here. During this portion, it is zero and during this portion, it will be negative, V_{dc}. So, you have pulses like, duration like this. So now, the wave form will be like this. This height is V_{dc} and this will be and this one will be minus V_{dc}. But during this period alpha, this is alpha; here, alpha here, the output is 0. So, what happened to the fundamental now?

If you see, the fundamental like pervious; fundamental will be placed at some where here, maybe it will go like this, again it will come, zero will at exactly at the symmetric here, alpha by 2. So, let us take the harmonic content of this one.

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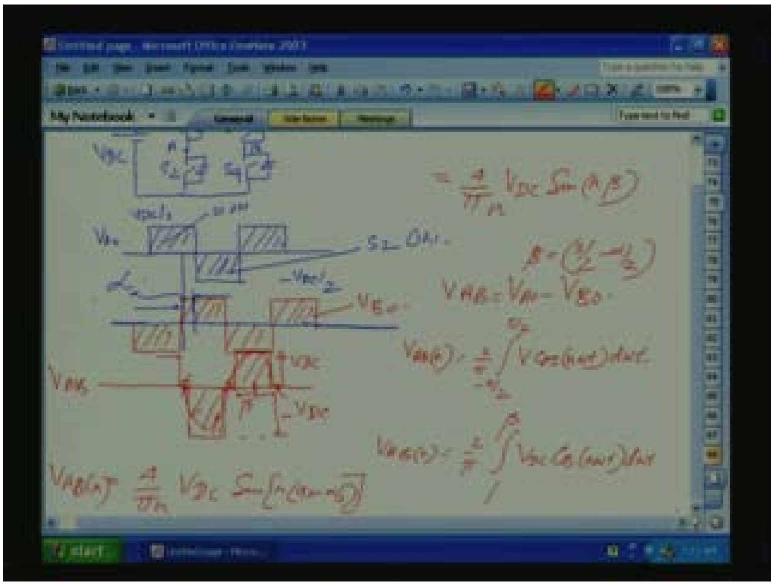

So, we can find out now; the new V_{AB} (n) is equal to; see period we can take it only as pi we can take it. So, 2 by t 2 by pi integral minus pi by 2 to pi by 2, we are taking the half the V cos n omega t d omega t, the Fourier series. This will be equal to see if you see, we are integrating minus pi by 2 to pi by 2. So, if you see here, pi by 2 means from that one alpha by 2 period, it is zero, both this side and this side. So, this duration, on period, we can represent as beta and this as also beta. So, this will be V_{AB} (n) is equal to 2 by pi integral minus beta to beta into V is equal to V_{dc}, V_{dc} cos n omega t d omega t.

So finally, this will be equal to; this will become equal to 4 by pi V_{dc} sin n beta. So, 4 by pi V_{dc} sin n beta. What is beta? Beta is equal to pi by 2 minus alpha by 2. So, we can substitute this one here. So finally, our equation will be V_{AB} harmonics, n will be 4 by pi V_{dc} into sin n into 90 minus alpha by 2; 4 by n pi. See, 4 by sorry here also n in harmonics will be there, 4 by n pi. So, here it will be 4 by pi n V_{dc} sin 90 plus alpha by 2. So, what will be the fundamental? So, the fundamental will be V_{AB}; fundamental will be 4 by pi V_{dc} into sin 90 by alpha by 2.

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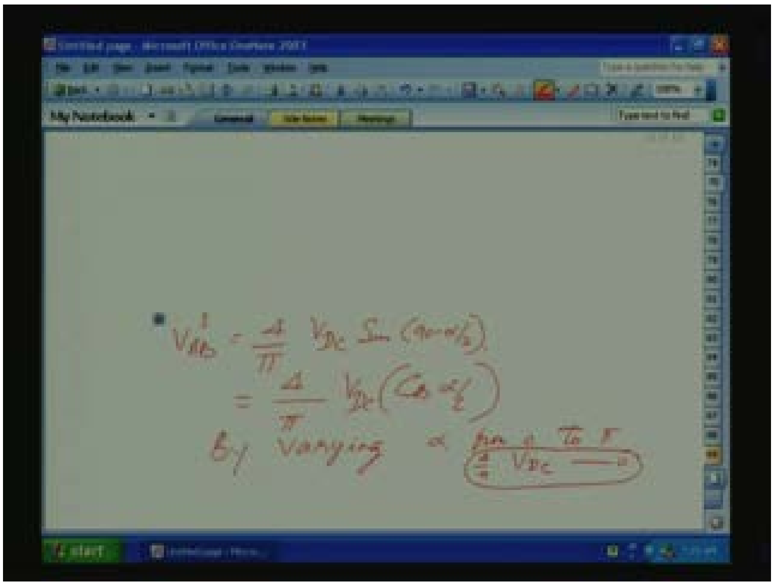

So, this will be that fundamental component will be finally 4 by pi, V_{dc} into cos alpha by 2. So, by varying alpha, by varying alpha from 0 to, that alpha duration by 0 to pi, the output voltage can be increased from V_{dc} to 4 by pi V_{dc} to 0. But the problem here is we are varying the alpha but the output is proportional to cos alpha. This is not a linear control, this way also we can control the output and frequency also we can control.

Now, we should when we use this one for UPS or motor drive applications for linear control, output should be proportional to the function we are using. So, there we can use the sin triangle PWM and we talk about the sin triangle PWM in the subsequent classes. Now, we have talked about only one phase; most of the times we are require 3 phase. How do you control the phase voltage waveform? This, we will study in the next class.