Power Electronics

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Lecture - 23

Basics of DC to AC Converter - 2

Last class we started with the DC to AC convertor, then we started with single phase, the basic configuration of half bridge converter, then how we will be able to get a rectangular pulse of equal on and equal off duration and the height depends on the DC link. Then we found that for DC to AC that means for AC waveform, we have to control both frequency as well as the amplitude. The amplitude depends on, what we are talking about the amplitude is the fundamental component and for the pervious pulse waveform like this, this type of rectangular pulse, what we found is that by varying the S_1 on and S_2 off, we can control the frequency but we will not be able to control the fundamental.

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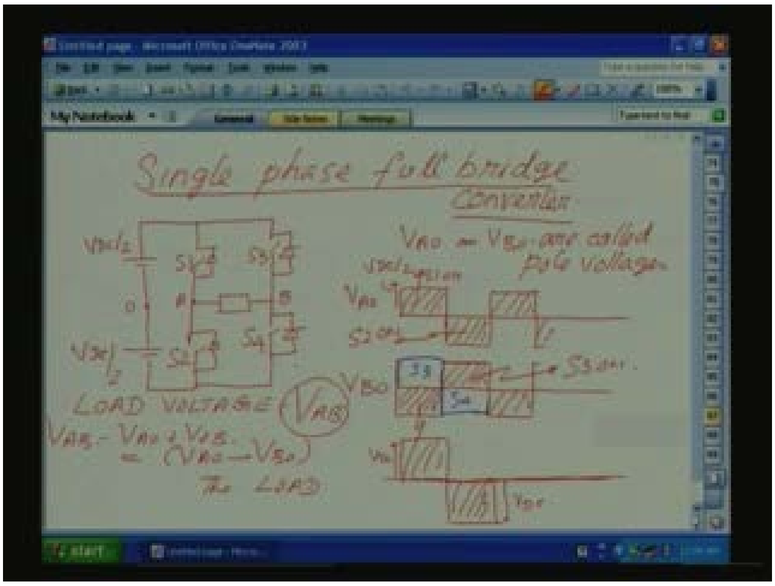

Then from the half bridge, we introduced one more leg here - S_3 S_4; then the load is connected between A and B, so A is called this whole leg, leg is called the single pole double throw switch, so pole A and pole B. So, the total voltage, the net voltage coming across the load is V_{A0} minus V_{B0}.

So here, we said, for the pole voltage A_0 when it goes to minus V_{DC} by 2 plus V_{DC} by 2 minus V_{DC} by 2; the total load voltage waveform, it will go from plus V_{DC} to minus V_{DC}. So, that way we have increased the amplitude. But here the frequency can be controlled by controlling the S_1 on and then S_1 off here and S_2 on here.

So, how to control the voltage? And, previously also we talked about the fundamental and the harmonics; this will have fundamental third, fifth, all harmonics and the harmonic amplitude will be inversely proportional to its harmonic order.

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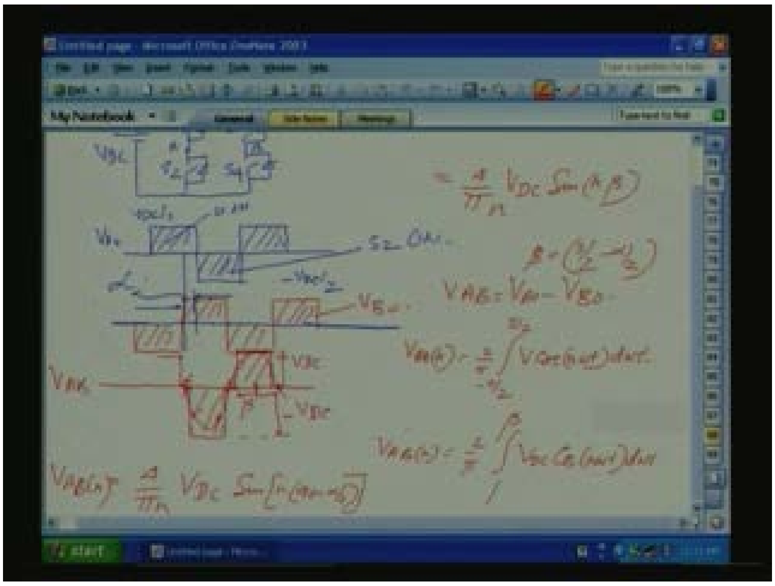

Then we said we found out that for controlling the voltage as well as frequency, we require two degrees of freedom. So, by turning on S_1 and S_2 instants, we can control the frequency. But independently controlling the S_3 and S_4 and the phase difference between that switch sequence of pole A with respect to pole B; by controlling that one, we can control the output voltage also. Here, we have done that way; here it is shown, how to control that. This is the pole V_{A0}. So here, like the half bridge converter, we are not splitting the DC link into V_{DC} by 2 into V_{DC} by 2. Instead, we are measuring the AB with respect to a common point O. O, we assume to be at the centre point of the DC link. So, fictitious centre point; that we call as V_{A0}, it will again it will be V_{DC} by 2 minus V_{DC} by 2 and given a delay.

The previous circuit if you see here, we are given full 180 degree for S_1 and S_3 on. When this S_1 is on here, S_3 is on here, the red line. So, 180 degree we have given here. Now, instead of 180 degree, slightly less than 180 degrees we have given here, this alpha. So, the moment alpha is given, there will be a period during which both S_1 and S_3 are conducting. S_1 and S_3 are conducting means A and B will be shorted to this point. So, output will be 0. So, that zero point that zero interval is placed symmetrically between this notches. So, increasing the alpha, this notch width increase or that pulse point, this will slowly reduce and the output fundamental will reduce. Then, we found out the harmonics; how to find out the harmonics and we found out how the fundamental varies.

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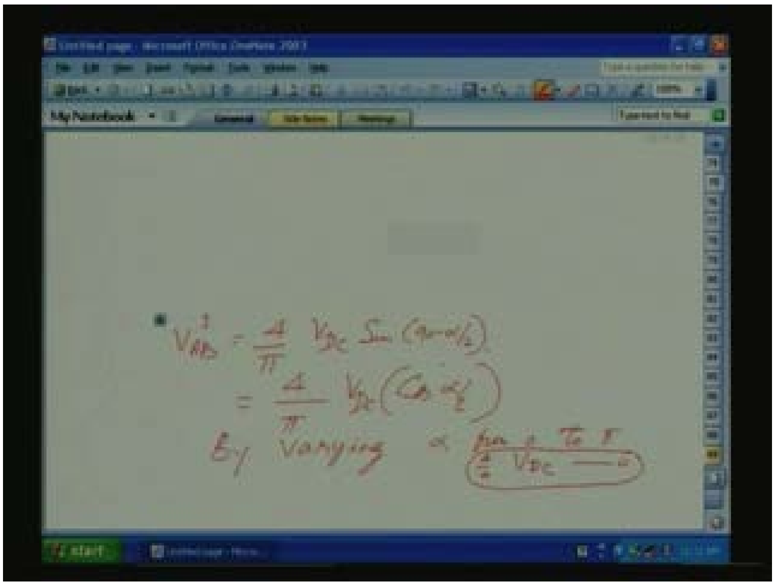

So, we found out fundamental will be proportional to alpha by 2. So, we got a voltage control by varying that overlap angle alpha but it is not proportional to alpha, it is proportional to cos alpha by 2. So, for any linear control, we want a function which is proportional to the output fundamental V. So, there we said, we will talk about the sin triangle PWM. So, before coming to sin triangle PWM, let us go to, this is only for single phase; how we can get three phase?

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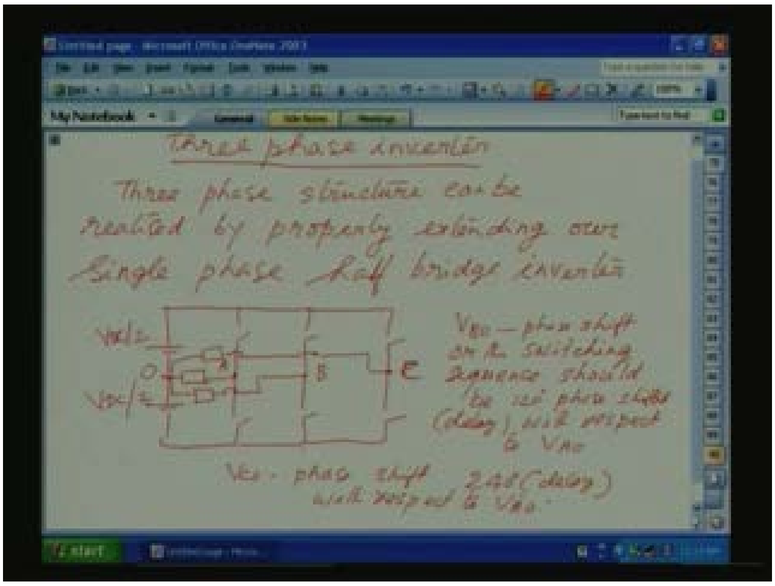

Three phase inverter, we studied the basic operation. So previously, let us see all this three phase operation is extended, is in proper extension of our single phase half bridge converter. So, this three phase structure can be realised by properly extending our single phase half bridge converter, half bridge inverter.

See, let us again go back to our basic inverter scheme, V_{DC} by 2 V_{DC} by 2. This is our centre point O, we have the switches and it is assumed that it is bidirectional, freewheeling diode is also there. Now, we have the A here, pole A and we said we can add any number of legs to this inverter and each leg can be independently controlled and it is not related to the switching of other leg.

So, for three phase; what is the next we should do? We should add three more legs here. So, this is A, this our three more single pole, this is C, single pole double throw switch. That means this pole B can be either connected to this point positive rail or to the negative rail by appropriately switching the devices. Now, where we connect the load?

So, let us take same this point. We connected here. This is B. What will happen to C? Again, C will be, we can do it this way. Then we want a three phase inverter, three phase we require means we require symmetric three phase that means the waveform should be exactly same, the positive half and negative cycle. But there is amplitude and the duration. Also, the B and C phase should be appropriately phase shifted, three phase should be B phase should be 120 phase shifted with respect to A and C phase will be 120 degree 240 degree phase shifted with respect to A.

So, that means B, the pattern the V_{B0} phase shift or the switching sequence should be or the the switching sequence, switching sequence should be 120 phase shifted with respect to A that is delay, a delay of 120 degree with respect to V_{A0} waveform. Then what will be for phase C? V_{C0} phase shift 240 degree or 120 degree with respect to V_{BA} or 250 240 degree delay with respect to V_{A0}. So, let us draw the pattern. Now, let us go to the next page.

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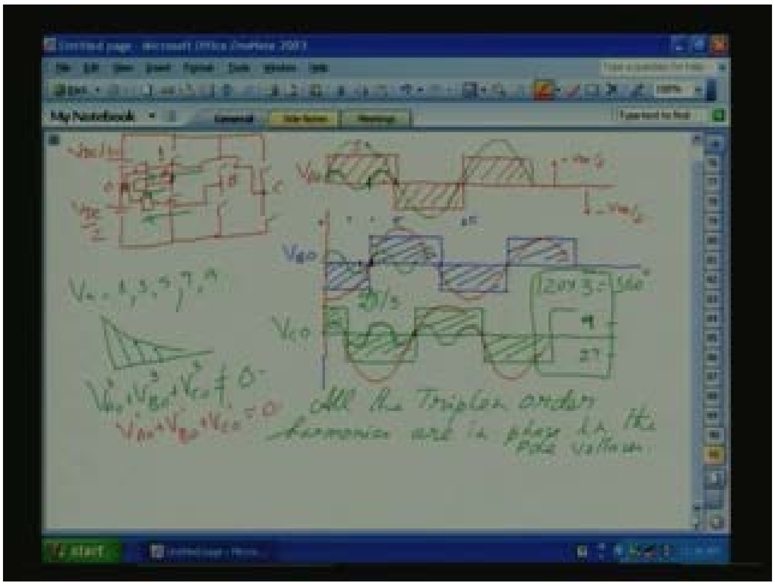

So, for the reference, let us again draw our inverter, basic schematic here. This is A, this is our load for A, zero, V_{DC} by 2, then V, then C. This is connected here and the load is connected here. Let us draw the waveforms. Now V_{A0}, this is our V_{A0} X axis. So, let us take 180 means this much. So, V_{DC} by 2 here, so we have 3 here, 3 here, again 3 here, 3 here. So, minus V_{DC} by 2, this is our V_{A0}. So here, S_1 on or top switch is on. So, this is one and when the bottom switch is on, we have minus V_{DC} by 2. So, this is plus V_{DC} by 2 from here to here and from here to here, it is minus V_{DC} by 2. This we have studied last class.

Now, what we want? The same sequence, so we are talking about each pole, the top switch and the bottom switch. Now, let us draw the B phase. So, for clarity, we will use a different colour. Let this be the axis for the B phase, so 120 degree phase shifted. We know that this is zero, this is pi and this is 2 pi. So 120, this is pi means this is pi by 2. So, this we can divide into three divisions; so this is 60, 60 each. So, 120 mean it will come here. So, after the A phase top switch is on, 120 degree phase shifted, we should start the pole B operation. So, after 120 degree, again the top switch is on. So again here, it will go like this. So, when the bottom switch, here, when this is turned on, it is minus V_{DC} by 2. Only thing is the durations for the top switch and bottom switch of A and B is the same, only the sequence is delayed by 120 degree. It goes like this.

So, this is the pole B with respect to the fictitious centre tab V_{B0} plus V_{DC} by 2 minus V_{DC} by 2 V_{B0}. Now V_{C0}, let us take a different colour for V_{C0}, let us take green. This is the X axis, so it should be the top switch of the starting instant for the C phase should be 240 from A or 120 from B. So, 120 from B this is 120, 120 means 2 pi by 3. 120 means again here; this is 120, one more 120 means it will be from here, this 240. So, C phase starts from here.

Now, this is the pole voltage C that is V_{C0} shape. So, if you see the shape, the positive the positive amplitude, positive duration for the A phase, B phase, C phase are the same. They are same wave from but there is a time delay or phase shift of 120 degree with respect to each other is there. Now, here also like before, our single phase half bridge converter, it has the fundamental V harmonics if you say, it has the fundamental third, fifth, seventh, ninth all harmonics will be there for each pole voltage waveform.

Now, as I told, we are more interested in the fundament and we want to suppress the low frequency, high amplitude low frequency harmonics as much as possible. So, the next, after the fundamental, the most a predominant harmonic is 3. It has the amplitude inversely proportional to the harmonics, so it will go like this. If fundamental is there, third will be here, fifth will be here, this way it goes.

So, how we can eliminate the third harmonics? Is it possible? Let us start with third harmonics; see third harmonics if you see here, fundamental moves by 120 degree. When the fundamental moves by 120 degree means that is let us say the fundamental for this one is something like this; the third harmonics, how much it will move? Third harmonics how to find out? For fundamental 120 degree for third harmonics, it will be 360. That means third harmonics, if the third harmonics starts from here, 120 degree; see it will be again here, it will go like this and come here. So, 120 degree from here, it is the same thing starts as if it starting from here. So, that means third harmonics is concerned, it will be in same phase.

So, if you draw here, here also if you see here that the third third harmonics; this is the third harmonics for this one, we will draw with this, the third harmonics and what about the third harmonics for this one? Third harmonics for this one from here to here, if it is starting from here, third harmonics here, 120 degree, it will have the same effect. So, third harmonics if you see, so let us say third harmonics starting from here; so, that means the third harmonics for all the three phase waveform are in same phase because 120 into 3 is equal to 360 degree.

So, this waveform also from here to here, it is 120 degree phase shifted. So, starting from here, it is same; exactly the way it starts here, it will start here. So, if you see here, all the third harmonics are in the same phase, there is no phase shift. So, this will be true for ninth multiple of three, ninth. All these are with three ninth, then what you say multiple of 3 – 27, all these harmonics, 15, all odd multiple will have all the multiple of 3, 3, 9. These types of harmonics will have will be in the same phase. So, these are called triplen order.

Any way because of the symmetry triplen order even multiple 6, 12, all those harmonics will not be there because the waveform has odd symmetry. For 6 and 12, it is even symmetry. Even symmetry means if you take the waveform, the centre point left half and the right half will be same. But here the left half and right half will be the same but it is inverted. So, it is called odd symmetry.

So, all the odd multiple of 3 will be absent here. That means all the triple n order will be absent here sorry triple n order will be in the same phase. So, all the triple n order harmonics are in phase, in phase in all the pole voltages, in the pole voltages, pole voltages. So, they are in same phase means if you see here, let us say the voltage waveform is like this; due to this voltage if the current exceeds, the current will be if you see here, the sum of these three, the sum of these three, only the triple n order if the current exists or the harmonics is V third, V_3, V_{A0} third plus V_{B0} third plus V_{C0} third.

If you add all these harmonics, it is not 0. For symmetrical three phase, what we used to say, V_{AN} plus V_{BN} plus V_{CN} phase voltage should be 0. But if you see, this is not zero. So, for this connection, I_A plus I_B plus I_C triple n order if you see, the current will be coming in same phase. So, if I_B is coming in this direction, the I_A triple n current will also be in this direction and triplen order C phase also will be in this direction, it will sum here and it is not zero. So, it will come back to the phase through the DC link if the current exists there.

Now suppose, if I break this one; now this is for the triple n, now if I draw the fundamental, let us draw the fundamental with a different colour. Fundamental, here it is drawn; this fundamental will be approximately like this. Here the fundamental will be like this; if you take the fundamental three fundamentals if you sum it, the $V_{A0}{}^{1}$ plus $V_{B0}{}^{1}$ plus $V_{C0}{}^{1}$ will be zero. Triple n will not be 0, the fundamental will be 0. For fifth and seven, fifth and seventh will also will be 0. So, if all these, if I break this one, the triple n current which is coming here this direction, they will sum here and if you remove this connection to the central point, what will happen? There will not be any return thought for the triple n. So, what is meant by this one? So, let us redraw this one again, once again.

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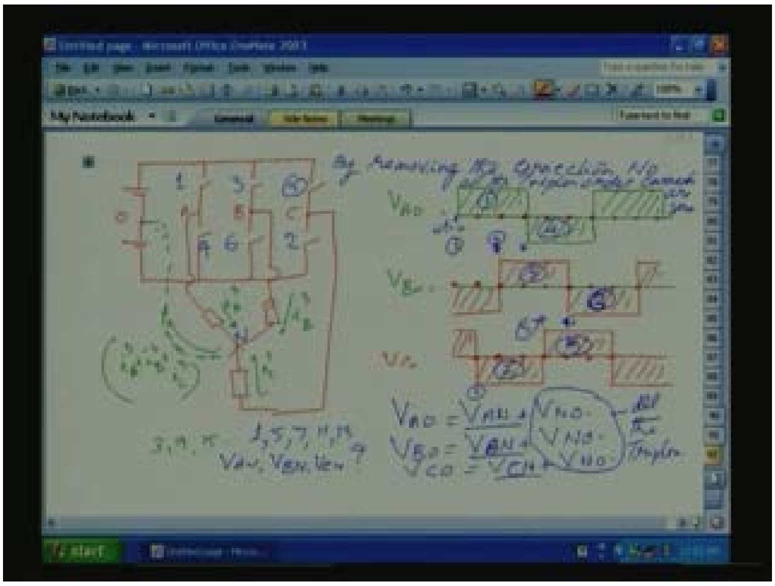

This is A, this is B, this is C; so we found for the load. We will draw it in a different way; this is A, this is B and this is C. Previously, this point, we have connected to O. That means previously, this point was connected to this side. So, we found that if the current triple n that is I_A^3, I_B^3 and I_C^3, 3 means triplen order; all will come here, it is not zero, it will sum up and it will go like this. So, when this connection is there, the triplen order will go here. That is in this current will be I_A^3 plus I_B^3 plus I_C^3; this current will flow through this point. These triplen voltages are there, they are in the same phase across this one.

Now, if we remove this one that means I will remove this path, then what happens? The triplen order third, ninth, fifteenth, all that order currents will not flow through even though voltage is present. What you mean by voltage is present? Still our V_{A0}, V_{A0} is like this; we will draw once again. This is our V_{A0}, this our V_{A0}, even though that centre point, fictitious centre point connection is removed that is this connection, broken line we will show, that shows this is removed; this connection is removed, so still we can according to our switching sequence, we can turn on top and bottom and we can measure the voltage with respect to A_0, V_{A0} is like this and V_{B0} 120 degree phase shifted.

So, let us draw the V_{B0} waveform after 120 degree phase shifted. So, it will be starting from here and V_{C0} waveform will be here. See, V_{C0} 120 degree phase shifted with respect to B or 240, so it will start from this is 240, this is our V_{C0}. Now, if you see here, let us mark this 60 degree points; these are the 60 degree points, here also here the 60 degree points are there. So, what we did? We removed the triple n order harmonics current by removing this connection. So, without using filter, a simple connection removed all the triple n order currents. But triplen order voltages are there in the pole voltages.

That means by removing this connection, now let us mark this point as N. So, this is our N. So, the connection, by removing the connection NO, all the triple n order currents are zero through the load in I_A I_B I_C; so, by removing this one. But still the pole voltages are same that means in our pole voltages V_{A0} V_{B0} V_{C0}, all the triple n order voltages will be there. So, what we are more interested is in the current.

So now, in this phase current I_A I_B I_C [3], we have only fundamental, fifth, seventh, eleventh, 13, all these harmonics only will be there. Now, the question is previously with the NO connection, our load voltages and the pole voltages were same. Now, the load voltages and V_{AN}, now the load voltages are V_{AN} V_{BN} and V_{CN}; so we have to find out what is V_{AN} V_{BN} V_{CN} load voltage. How to find out? Let us find out. V_{A0} is known, V_{A0} is equal to if you measure, it is V_{AN} plus V_{NO}. Previously, because of the connection V_{NO} was 0 because it was shorted; now it is open, so there is a voltage V_N.

Now, what is V_{B0}? V_{B0} will also be equal to V_{AN} plus V_{NO}, V_{C0} also is equal to V_{AN} plus V_{NO}. But what we want is V_{AN} sorry this is V_{B0} is equal to V_{BN}, V_{C0} is equal to V_{CN}. Let me correct it; this is V_{CN}, V_{NO} is the same. What we want? V_{BN} V_{AN} V_{BN} and V_{CN}; how to find out? See, I said, in current which is passing through I_A I_B I_C are one, fifth, seven, eleven, thirteen harmonics and we know for a three phase system, the triple n order will not be 0, all the fundamental will be 0 and we can see all the harmonics fifth, seventh, eleventh, thirteenth if you take the fifth, seventh, eleven, thirteen harmonics individually from V_{AN} V_{BN} V_{CN}, this will also sum to 0; but V_{A0} contain triple n but this waveform V_{AN} V_{BN} will not contain triple n order.

So, according to Kirchhoff's law, where the triple n order will be? The triple n order will be always dropped across NO. So, all the triple n order will be dropped across V_{NO}. So, before coming to naught one; see we have marked the switches but we had not numbered it. So, let us take starting from omega T is equal to 0, starting from here, we are turning on the switch, top switch of phase A. So, this is one.

After that, after 120 degree, top switch of B is turned on here, the next turn. So, here it will be this is one; so at this point omega T is equal to zero, we are turning on phase A, top switch. So, one is marked top switch. Then, after this one, the transition happens here that means V_{C0} going from positive to negative that means at this instant, the negative C phase C pole switch is turned on. So, this will be number two; negative means this is one, this is number two.

Then after this, again we are turning on B phase top switch. So, this is top switch is number three. So, three is here. So, here we have one, here you have two, here we have three. Then after this, here we are turning on the bottom switch of A phase. So, this will be four. So, this we can say one, this we can say two full this duration, this will be three, this full duration will be four, so this is 4.

So, here we are turning on four. After four, we are turning on this side that is top switch of C phase; this is five, so this is five. So, let me correct this one. So, five is here. Now, after this one, we are turning on the bottom of B phase. So, this is 6, so this is 6. So, the sequence is same like thyristor 135, 462. So, top switches are marked 135, 462 and you can see, every 60 degree there is a change. That is true also for symmetric operation. There are switch 6 switches, so in a symmetric if you have to turn on the switches, every 60 degree we have to turn on a switch and turn off a switch. So, this sequence is 135, 462.

Now, as I told before, this pole voltage waveform V_{A0} V_{B0}, it will contain fundamental triple n all the harmonics. But the moment NO is removed, all the triplen harmonics are harmonic currents are removed. Now, the new load voltage waveform V_{AN} is equal to the relation is V_{A0} is equal to V_{AN} plus V_{NO}. So, if you do the Kirchhoff's voltage law for the loop, V_{A0} content all harmonics. So, this harmonics should be dropped either in V_{AN} or V_{NO}.

Now, V_{AN} since the NO is removed, V_{AN} will not have triplen order harmonics. So, V_{AN} should not contain V_{AN} triple order voltages also. If voltage is there, there should be a current and drop to take care of the Kirchhoff's law. So here, what happens? V_{AN} will not contain all the triple n order. So, where the V_{AN} will go? V_{AN} will all go to V_{NO}. V_{NO} contain all the triplen order. Now, we want what is V; we want to find out V_{AN} V_{BN} V_{CN}. Let us find out.

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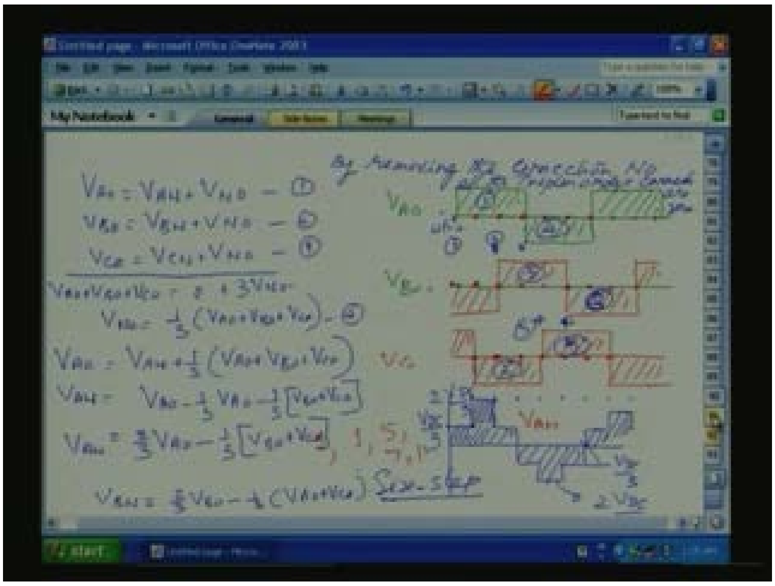

So, V_{AN} V_{BN} V_{CN}, we have got the pole voltages V_{A0} is equal to V_{AN} plus V_{NO} and V_{B0} is equal to V_{BN} plus V_{NO} and V_{C0} is equal to V_{CN} plus V_{NO}. Now, we know that all the triplen order will be dropped across V_{NO}. So if you sum it, V_{A0} plus V_{B0} plus V_{C0} is equal to, we know V_{AN} V_{BN} V_{CN} will not contain the triple n order, so all the harmonics when you sum it with the 120 degree phase shift including the fundamental, it will be V_{AN} plus V_{BN} plus V_{CN} will be zero and triple n order is not zero, they are equal; so it is V_{NO}. So, this shows the value V_{NO}, V_{NO} is equal to 1 by 3 V_{A0} plus V_{B0} plus V_{C0}.

Now, let us substitute this one to this equation one; let us, see this is 2, this is 3, this is 4. So, substituting equation 4 in 1; now our new V_{A0} is equal to V_{AN} plus V_{NO} is equal to 1 by 3 into V_{A0} plus V_{B0} plus V_{C0}. That means V_{AN} is equal to V_{A0} minus 1 by 3 V_{A0} because this has to go to other side and minus of 1 by 3 into V_{B0} plus V_{C0}, we can write it like this. This is equal to V_{A0} minus 1 by 3 V_{C}, 2 by 3 V_{A0} minus 1 by 3 V_{B0} plus V_{C0}, this is equal to our V_{AN} value. So, in a similar way, we can write down the V_{BN} and V_{CN} also, using the symmetry. So, what will be V_{BN}? V_{BN} is equal to again 2 by 3 V_{B0} minus 1 by 3 instead of V_{B0}, V_{A0} plus V_{C0}. Similar way, V_{CN} also we can do it.

Now, let us draw what is our V_{AN} waveform. V_{AN} is equal to 2 by 3 V_{A0} minus 1 by 3 V_{B0} plus V_{C0}. Let us go to go back to our waveform, we will try to draw that. See, let us draw the waveform. See, V_{AN} if we know, we can find out V_{BN} V_{CN} also because 120 degree phase shifted. So, let us take V_{AN} first 60, these are the 60 degree points; so, first 60 degree. That means this is equal to 2 by 3 V_{A0}. Let us take V_{AN} is equal to V_{B0} plus V_{C0}. So, first 60 degree V_{B0} and V_{C0} are equal and opposite and it will cancel. So, V_{AN} will be 2 by 3 V_{A0}; 2 by 3 V_{A0} means this is V_{DC} by 2, V_{DC} by 2 into 2 by 3 is equal to V_{DC} by 3. So, let us take V_{DC} by 3 is this much because that is equal to 2 by 3 V_{DC}, 2 by 3 V_{A0}; 2 by 3 V_{A0} is equal to V_{DC} by 2 and 2, 2 cancel and V_{DC} by 3.

Now, during the next 60 degree that is from here to here; so, from here. So, from the next sixty degree if you see, V_{B0} and V_{C0} are is same phase. So, V_{A0} plus V_{B0}, V_{A0} plus V_{B0} will be minus of because both are minus; V_{DC} by minus V_{DC} by 2, minus V_{DC} by 2, so minus V_{DC}. So, the V_{A0} plus V_{B0} will be minus of minus 1 by 3 into V_{DC}, minus V_{DC}. So, it will be equal to 1 by 3 V_{DC} and here again it will be 1 by 3 V_{DC} by 2.

So, here if you see here, this will go to 2 V_{DC} here. So, this will be 2 times into V_{DC} by 3. Again, again if you see, here it will be like this. So, the waveform will be if this is the X axis, the waveform will have a shape like this; every 60 degree there is a change and it goes like this and this duration is V_{DC} by 3 amplitude and this amplitude is equal to 2 V_{DC} by 3. So, this is also called as six step waveform. Why? For one cycle that is from here to here, there are six steps are there; this is 1, 2, 3 then 4, then 5, then 6, it comes here, starting point. Again, it starts here, one level. So six, these are called, this are all called as six step waveform.

This waveform will contain fundamental sorry fundamental, fifth, seventh, eleventh, all harmonics, all the triplen will not be there. This is our V_{AN} waveform, V_{AN}. V_{BN} V_{CN} will be 120, 120 degree phase shifted. So, if you see here, to get this six step waveform, we have not done anything, we had done only a very simple thing.

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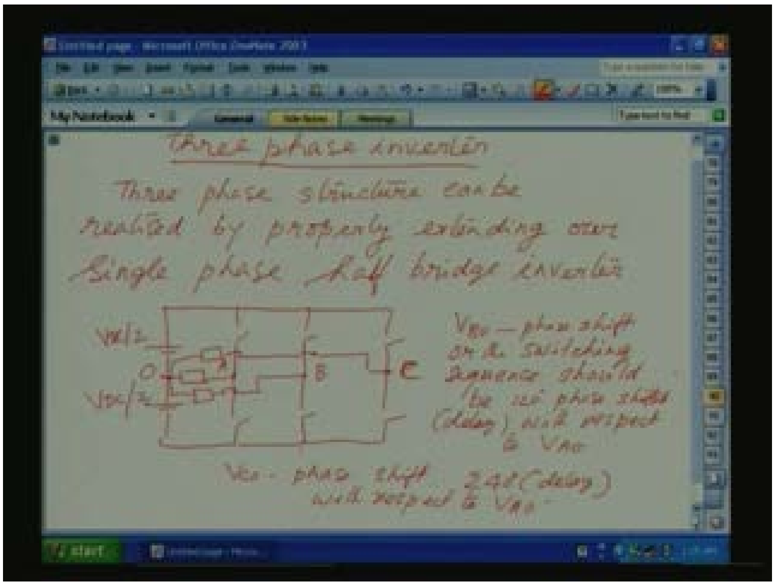

The V_{NO} connection, the neutral connection we removed. That is we only removed this neutral connection; from here to what is the connected centre point.

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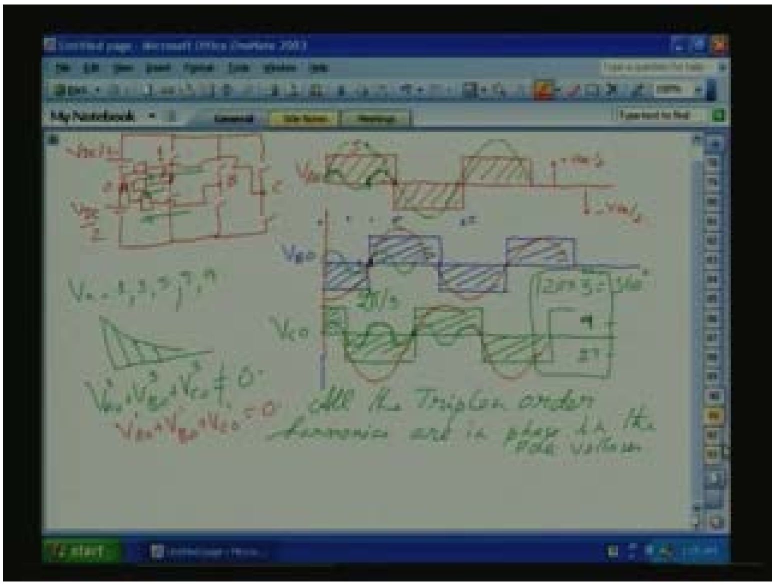

Once you remove that one, all the triple n order harmonics are removed because triple n order harmonics are in same phase. So, it will sum up. So, unless there is a return path, it will not be able to flow. So, by removing the return path that is connecting this point to this O point, we are removing the triple n order. But in the pole voltage waveform, the triple n harmonics are there.

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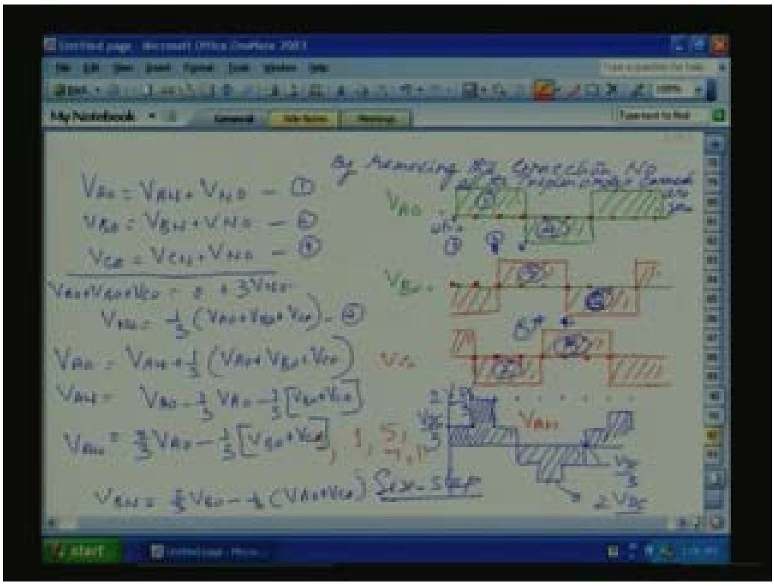

Now, the question is what is our phase voltage waveform? So, the phase voltage waveform that is V_{AN}, V_{AN} plus the triplen order will be V_{A0}. So, all this NO, V_{AN} will be dropped across the load neutral point and our DC link midpoint, we can measure. That will give the triple n order voltages and the phase voltage, we got like this. So here, all the triplen order harmonics we have eliminated. But in many of the motor drive applications, we have to eliminate other harmonics also, low order fifth, seventh, 11, 13. At the same time, we have to control the fundamental. So, how we can do this one? What is the technique we have to use it?

See, here also because the pole voltage, we can do independal switching and we are using equal degree on equal duration off but how to control the amplitude? To control, now from this waveform if you want to control the amplitude, we have to change the DC link. But DC link changing is very difficult. Suppose, a battery operated vehicle for high dynamics, we cannot keep on changing the battery. So, DC link we call it a stiff DC link but for many motor drive applications along with frequency, the fundamental amplitude also we have to vary. At the same time, the harmonics also we have to suppress.

Now, the triple n order we have eliminated but still the other harmonics are fifth, seventh; how to suppress? There again we use the PWM technique, sin triangle PWM technique or other PWM techniques are there. We will study various PWM techniques in the coming classes.