Power Electronics

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Lecture - 10

Front-end AC-Dc Converter with harmonic Control

So, last class we introduced the sine triangle PWM and with sine triangle PWM, how we controlled the output voltage that is proportional to our sine modulating wave for our converter. So, one leg only we talked about. So, what we learnt from the previous class is we can control the output voltage, output voltage variation that is for a converter like this, single leg; for the single leg, this is S_1, this is S_2.

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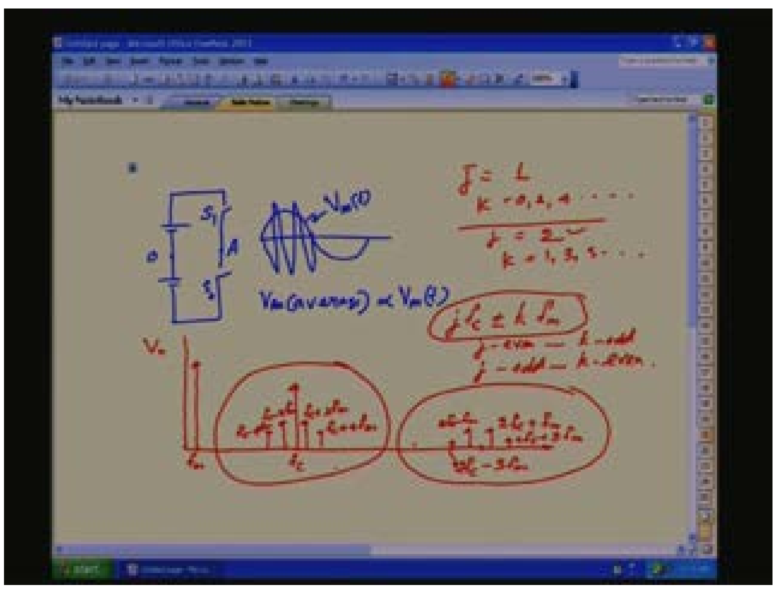

So, we are measuring the voltage, pole voltage A with respect to the fictitious center O. Then we found, for a sinusoidal reference voltage, sinusoidal reference voltage comparing with high frequency triangle waveform for switch control; we found the output V_{A0} fundamental or V_{A0} average, V_{A0} average is proportional to the V_m (t), modulating wave that is our reference wave.

Now, we have not talked about the harmonics. Also, I told, because of the high frequency triangle PWM, the next high amplitude harmonics will be around the carrier frequency side;

carrier frequency, triangle frequency side. So, by going for high frequency triangle waveform, we can shift the high harmonic, high amplitude harmonic to the high frequencies side correspondingly the ripple current drawn from the source will be, will be controlled. It is highly reduced.

So, let us talk about the harmonics, so PWM. See, if you really do the Fourier series and try to find the harmonics, it will get into puzzle function, complicated function. Let us take a simple thumb rule. This, I have taken as I told before, from a very famous text book by Professor Ned Mohan. So, we will be talking about the harmonics now.

So, the harmonics order and this is amplitude of the harmonics n and this is the frequency number n, harmonics number. The fundamental happens at the frequency V_n, some amplitude. So, let this is the amplitude, this amplitude we know, it is in proportional to our reference phase amplitude. Here, you will have the fundamental frequency. Now, harmonics will be for a sine triangle waveform will be the sum and difference of the carrier frequency and the modulating frequency. That means the harmonics order will be j f_c plus or minus k f_m. Now, for now, from here, from this thumb rule; we can find out the harmonics, order of harmonics present in the sine triangle PWM.

So, what we have to do? For j even, we have to substitute k all odd values. When j is odd; we have to substitute, we have to substitute even values for k. Let us take J is equal to 1 that is here, J is equal to 1. Then, K can have J is equal to 1 means that is odd, K can have all the values 0, 2, 4. So, let us take J is equal to 1. The next harmonics happens at let us take K is equal to 0. So, it will happen somewhere here, f_c, this is f_c. Then you have you get the sidebands here, K is equal to 0. Then you have f_c plus 2 and f_c minus 2, f_c plus 2 f_c minus 2. Then again, you will have with decrease, as the harmonic order increases; the sideband amplitude will also increase decrease. f_c plus 4, fc minus 4. So, this way it goes.

Now, let us take j is equal to, j is equal to 2. Then k will have values 1, 3, 5. Here, I have met f_c plus 2 f_m, here f_c plus 4 f_m, here also f_c minus 2 f_m, f_c plus 4 f_m; based on this equation. So, we will get some and difference of the carrier and the modulating frequency. Now, let us take j is equal to 2 that is 2 times the carrier frequency and we will be taking it sidebands. Now, at 2 f_c when j is equal to 2, the 2 f_c; we have sidebands at 2 f_c plus f_m, 2 f_c minus f_m.

So, if this is the point at 2 f_c, we will not have any harmonic at 2 f_c from this relation; we will have at the sidebands of 2 f_c, at the side at the sidebands of 2 f_c only we will have harmonics that is here, 2 f_c plus f_m, here 2 fc minus f_m. Then again here, sidebands that is 2 f_c plus 3 f_m plus 3 f_m and here this one 2 f_c minus 3 f_m. So, this way, harmonics, again we can give the value for j is equal to 3, we can find out. But as the harmonic order that harmonic order increases, amplitude decreases.

So, we are more worried about the harmonics at f_c and its sidebands and the harmonics at 2 times the sidebands. And, I told you before, the sine triangle PWM, this harmonics amplitude if you can, f_c we can shift it to high frequency side; what is the advantage? Its sidebands also will get shift to the high frequency side. Then the current drawn due to the harmonics because of the impedance L omega increases, the ripple current amplitude reduces and the current draw drawn will be more close to the fundamental that is nearly sinusoidal. So, to shift f_c to the higher frequency side, we have to increase the carrier frequency.

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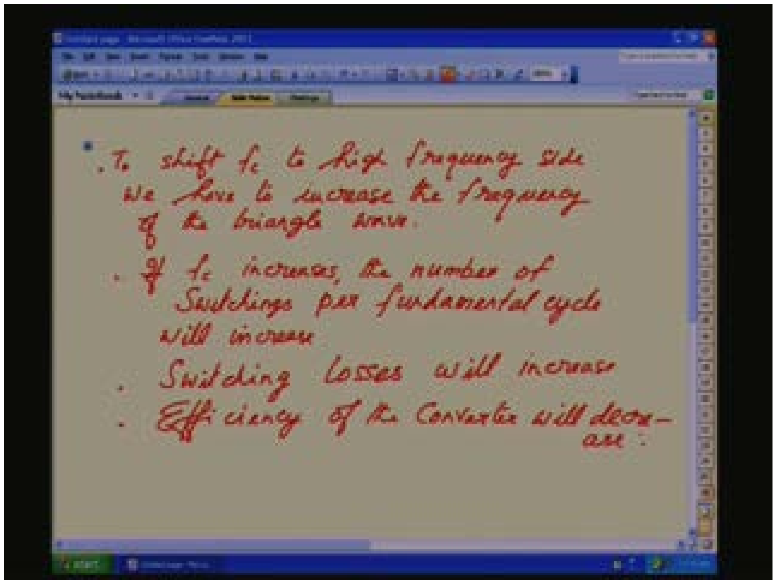

To shift f_c to high frequency side, side, we have to increase the frequency of triangle wave, the frequency of the triangle wave. So, what is the disadvantage? If f_c increases, the number of switching's per fundamental cycle will increase. If f_c increases, the number of switching's that is S_1 on and then S_1 off and S_2 on, the number of switching's, switching's per fundamental cycle, fundamental cycle is the modulating wave period per fundamental cycle will increase. So, what will happen? The switching losses, because we are using hard switching, hard voltage we have voltage and current we are switching.

So, for any switch, even though we have assumed ideal condition here, the switch will have during a finite turn on and turn off time. During that process, switching losses will be there. So, switching losses will be more and the efficiency of the system will come down. So, switching losses will increase. So, what will happen? Efficiency of the converter will come down, decrease, efficiency of the power converter will decrease, will decrease, efficiency of the converter will decrease. So, we cannot resort to high frequency period. Typically, for high power applications, the switching frequency compared to fundamental, we have to limit between f_c should be limit between 500 to 600 or less than 800 hertz. So here, f_c is not very far from the fundamental.

So, the switching losses will increase. So, we cannot resort to high frequency PWM. At the same time, we do not want high amplitude harmonic current.

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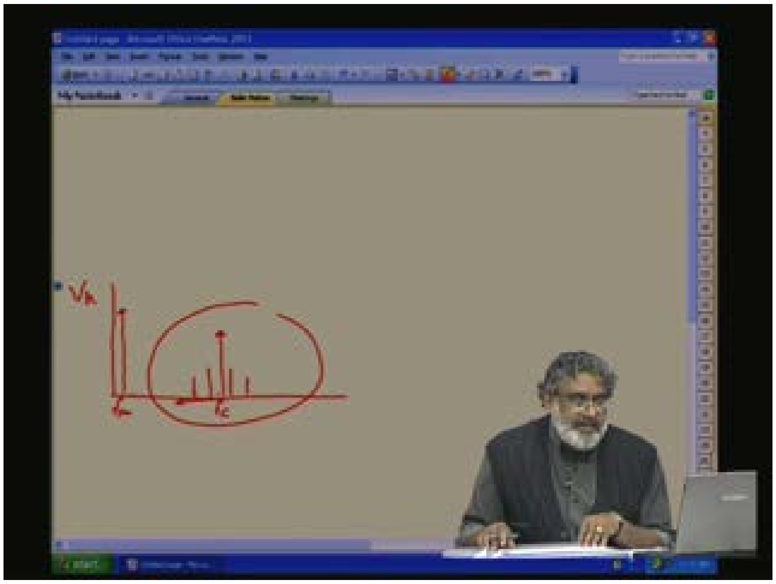

The frequency, amplitude and the frequency for the system, I have drawn previously; here we have the harmonics amplitude and here you have the f_m. Then you have the f_c here, then it sidebands here; so, f_c f_m. So, f_c decreases, it comes here. These sidebands becomes very close to the fundamental. So, your low under harmonics that is fifth, seventh will get boosted up. f_c is still further closer; this sidebands become lower than the fundamental frequency. So, this is called sub harmonics. Harmonics frequency less than the fundamental also will introduce. We will come into system. Harmonic current will increase; for PW if you draw motor drive application, torque pulsations will increase.

So, we do not know, we do not want to resort to high frequency switching; at the same time, we want to eliminate or suppress these harmonics. How it is done in a front end ac to dc converter?

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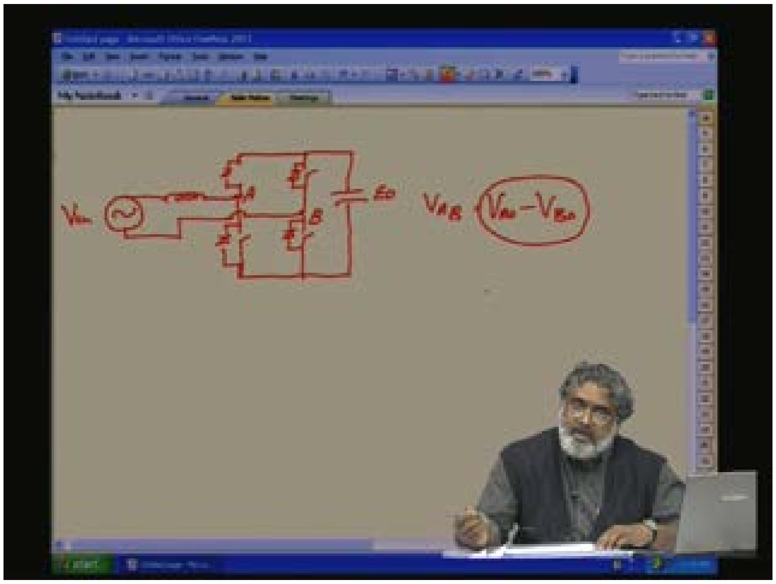

See previously, in the previous case, if you see our original front end ac to dc converter; this is our V_{in}, then you have the inductor. So, inductor will suppress the harmonic amplitudes. Then, we have the switches, these are the freewheeling diode. This is, this side is pole A, this side is leg A or pole and you have the E_0 here. So, this limb will be connected here and this side will go here. So, we have talked about one limb with respect to E_0, E_0 and our A. So, power flow can be according to our converter ac, this power flow can from in the ac side to the dc side as well as dc side to the ac side. So, we have analyzed the PWM with respect to the dc side and we found out the A pole voltage waveform with respect to the fictitious center.

Now, if you see here, in our converter, there is one more leg is there; the B leg is also there. The net voltage, what we want across AB is equal to V_{AB} is equal to if you take the fundamental, the V_{A0}, the average variation due to sine triangle V_{A0}; V_{A0} minus V_{B0}, this is our fundamental. So, V_{A0} minus V_{B0}; so what we want the fundamental component of V_{A0} and V_{B0} should get added. At the same time, this switching's of V_{A0} and V_{B0} are independent of each other that means V_{A0} will also contain the harmonics at f_c and it's sidebands and V_{B0} also conduct the harmonics at f_c and sidebands. So, we have 2 degrees of freedom that is one is for a phase leg, the leg A; other one is for the leg B.

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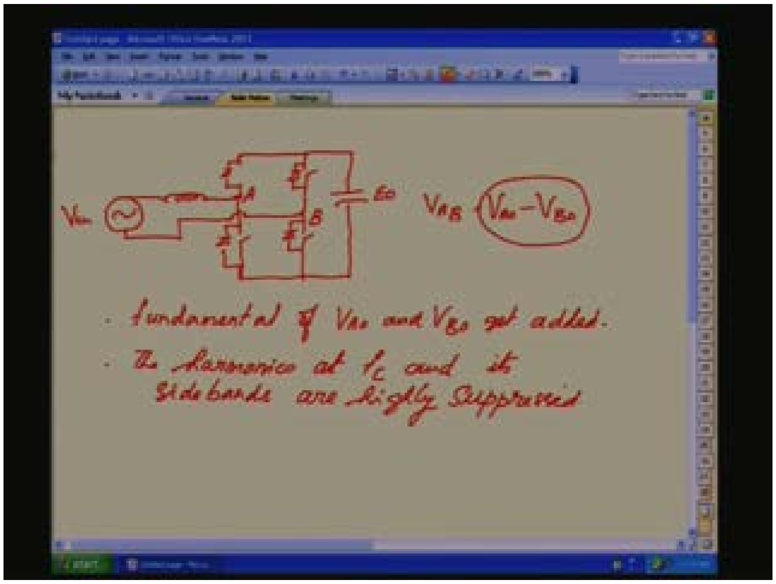

So, V_{A0} and V_{B0}, we can generate in such a way, fundamental; fundamental of V_{A0} and V_{B0} get added and we can choose the PWM, sine can triangle PWM because we have two degrees of freedom as I told because A and B because 2 legs; the second one, we can choose the sine triangle PWM. The phase shift between sine triangles, we can choose in such a way, the harmonics at f_c and its sidebands gets eliminated or get highly suppressed; sidebands, the harmonics at f_c and if sidebands are highly suppressed, highly suppressed or eliminated.

So, what is the advantage? So AB, we can control independently; we do not have to resort to high frequency PWM so that the switching losses can be reduced. At the same time, we do not have to worry that f_c is very close to f_m. So, low order harmonics can boosted up because we can choose the PWM of A and B in such a way, the harmonics and a fits can be highly suppressed. How it can be done?

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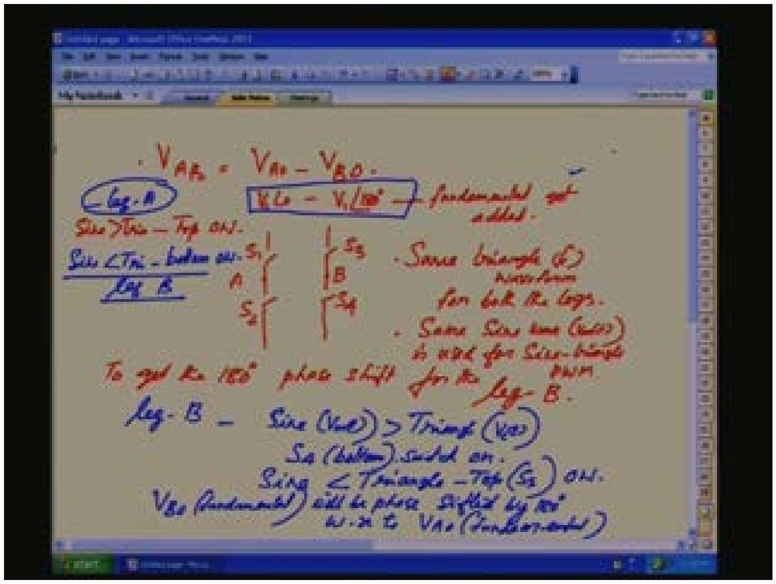

See, we are using sine triangle PWM. We are interested it is V_{AB}. V_{AB} is equal to V_{A0} minus V_{B0} and we are using sine triangle PWM where the output fundamental is proportional to psi. So, we will be using sine triangle PWM such a way; the leg for A, we will use the V_B the fundamental amplitude or a fundamental amplitude V_{B0} and V_{A0} should be the same but the phase angle of V_{B0} that means if the fundamental is V_1 angle zero here, here we want V_1 angle 180 degree. So, already V_{B0} fundamental is 180 degree phase shifted with respect to V_{A0} fundamental. When you subtract, both will get added. That means the output will get added; because of this already 180 degree, this fundamental, fundamentals are in phase and get added, fundamental get added.

So, how to get this 180 degree phase shift? See let us draw, only the switch schematic of A and B; this is A, this is B, this is S_1, S_2, this is S_3, S_4. Let us make it that way. So, we will be using the same triangle, same sine wave, same sine; we will be using the same triangle for both the legs, same triangle wave form, same triangle that is f_c, same triangle wave form for both the legs. So, you use same triangle we will be using.

At the same time, same sine wave that is a modulating wave that is V_m (t), it is used for sine triangle PWM. See, if you use the same sine and same triangle, then V_{A0} fundamental and V_{B0} fundamental will be in phase. But we want V_{B0} fundamental should be phase shifted by 180 degree. So, to get the 180 degree, 180 degree phase shift for the B leg B; what we will use? The switching sequence, we will interchange.

That means previously we said, when sine greater than triangle; what we say? Top switch is on, that was a condition we used. Then when sine less than triangle, we will say the bottom switch is on. So, the bottom switch is on, it is assumed that we are switching off the top switch and switching on the bottom instantaneously and we will assume the switching transitions are instantaneous. Now, this is for leg A, this is the condition.

Now, to get the 180 degree phase shift, we will change a switching sequence for leg B. For the leg B the conditions are different. For the leg B, say I will write it here, leg B, the condition; we are using the same sine wave, same modulating wave for both the cases. Sine greater than triangle that is our carrier wave V_c, V_c (t). What we are doing? Here, according to this figure, not the top switch is on; S_4, bottom switch is on. Then, sine less than triangle that comparison, we will do the top that is S_3 on.

So, the switching sequence is reverse, that we will ensure that the V_{B1} is 180 degree phase. This will ensure that the V_{B0} fundamental, it will have the same amplitude we are using the sine triangle amplitude. The V_{B0} fundamental will be phase shifted by 180 degree with respect to V_{A0} fundamental, with respect to V_{A0} fundamental that is this condition, we want this condition. So, what is the advantage? When you subtract, this will get added. Fundamental V_{A0} and we are more interested the fundamental; so fundamental, we can control by controlling the V_m (t) for both cases. So, fundamental we can adjust, control it.

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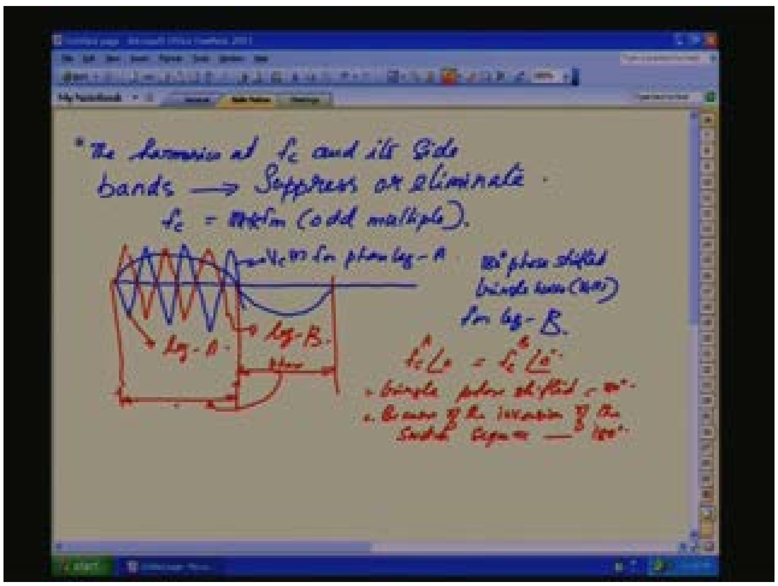

Now, how about the harmonics? As I told, the harmonics, harmonics at f_c and its sidebands, we should suppress it or the harmonics, individual harmonics from the A_0 and V_{B0} should, we should, both we should suppress or it should be highly reduced. We have to suppress it or we want to eliminate it, suppress or eliminate. If you see in the previous figure, the f_c has the maximum amplitude; the sine triangle PWM f_c has the maximum amplitude. So, how do let us look at how f_c can be cancelled? And, if we can suppress the other sidebands, that also it is okay.

So, fundamental, we should get added and how to get the fundamental, it should get added; we know it. Now, how to get the harmonics? So, what we will choose? f_c here, f_c we will choose as 11 times f_m. That is f_m is the frequency of the sine wave, the triangular frequency 11 times that is an odd multiple. See, there is a why odd multiple?

See, we want our output wave form proportional to our V_m (t), sinusoidal wave form. Sinusoidal, sinusoidal is an odd function. So, to get the odd symmetry, the triangle wave form also for the PWM wave form; odd symmetry means that upper half should be exactly symmetrical with respect to the lower after 180 degree. So, to get that odd symmetry, we are using 11 times. So, this is typically used. So, f_m is for a 50 hertz mains or 60 hertz mains; 11 into 50. So, around 55 so that as I told before, the switching frequency less than 6 700 hertz is a ensured here. So, 11 times we are using, triangle wave form and we are using the sine triangle, V_{A0} the sine triangle is like this. So, if it is this is our V_m (t); V_m (t) both, V_m (t) is the same for both V_{A0} and V_{B0}.

So, triangle wave form, let us say, this is the triangle wave form for the, if this is the triangle wave form we are using for V_C (t) for phase leg A; what we will use? We will use 180 degree phase shifted, degree, 180 degree phase shifted, 180 degree phase shifted triangle wave that is V_C (t) for leg B. So, what is the advantage? See, this is the wave form, that wave form will typically, typically look like this. See, exact wave form, 180 degree phase shifted. So, this is for, this is the wave form for leg B and this is the one for leg A.

Now, what will happen to the harmonics because harmonics already, f_c we said, already it is 11 times f_m. So, the harmonic, the phase angle, the phase relation of f_c, the phase relation of f_c with respect to A and with respect to V will be 180 degree phase shifted. See, this how do you, how do you say 180 degree phase shifted? Because the triangle waveform is 180 degree phase shifted and is an odd multiple. So, if you if you see the comparison here, what is happening for phase A during this period? This is what is happening. Phase A during this period will appear; for phase B, the final PWM waveform, it will here. So phase, if the phase A here will be exactly matching to phase B here because of the 180 degree phase shift. So, from the PWM waveform we can say that the because of the triangle, the harmonics at f_c will also be 180 degree phase shifted. So, 180 degree phase shifted here.

So, the phase angle of the carrier wave form, f_c its 180 degree phase shifted. Then for the phase B, there is one more phase shift 180 degree because the logic is interchanged not the top switch when sine is greater. So, there is one more 180 degree. So, carrier wave form, fundamental gets 180 degree wave form, the carrier wave form f_c have a phase shift of 180 plus 180, 360. So, the PWM, the f_c, the phase angle of f_c, f_c A will be equal to f_c B will also be will be equal to at the same phase because 2 times; one is one is triangle phase shifted.

See, we will show the simulation study of this one later than we will verify this one. Triangle phase shifted by 180 degree and then one more, the sequence of operation is also changed because of that is not the B phase, not the top switch; bottom switch is on when sine is greater than the triangle because of the inversion of the sequence of operation of the switch sequence. This will also introduce one more phase shift for the carrier frequency wave form. So, carrier frequency for the A phase as well as B phase will be in phase. So, what is the advantage here?

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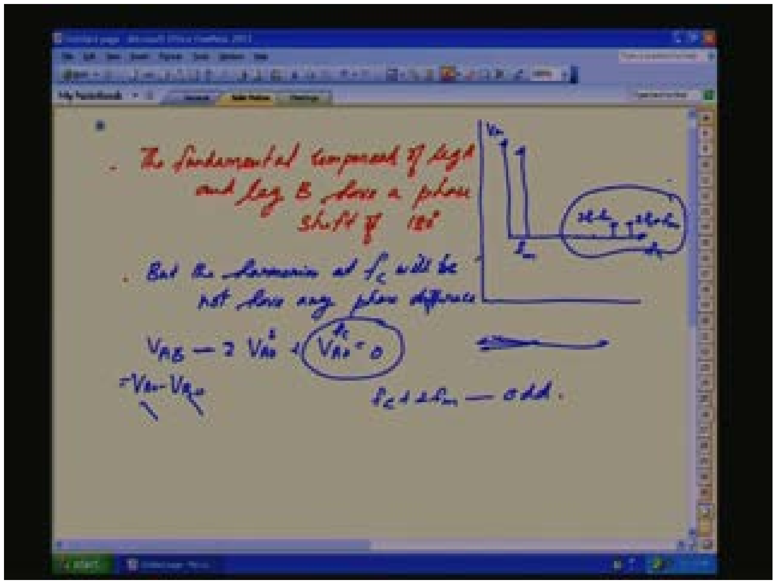

If you see here, the fundamental component of leg A and leg B, fundamental leg B, leg A and leg B have a phase shift of, phase shift of 180 degree with respect to each other. Then but the, but the harmonics at f_c will be will not have any phase shift or that means they are in, the phase relation between the harmonics f_c at V_{A0} V_{B0} will be the, will be in the in same phase. The phase, the phase difference is 0. We will not have any phase difference.

So, when you take the V_{AB} wave form, that V_{AB}, the harmonics of the V_{AB} wave form; we will have the amplitude of the fundamental will be two times the fundamental component of the V_{A0} or so 2 times V_{A0} fundamental plus V_{A0} at f_c. V_{AB} is equal to V_{A0} minus V_{B0}; so it will have fundamental will be there, V_{A0} at f_c will be 0 because we are subtracting. Because of the subtraction, both have both the f_c have that the same phase, it will get cancelled. So, f_c will get cancelled. Then what will happen to f_c plus 2 f_m?

See, f_c is already an odd function. f_c plus 2 f_m will also odd. So, it will also have the phase difference as closest 180 degree. So, for f_c, the phase difference will be exactly like this; for other one if we can multiply by the number and see, it may be very close, here it will come. So, the net value will be highly suppressed and already the sidebands amplitudes are suppressed; so, in the V_{AB} wave form again because of the subtraction, opposite effect, with a small phase difference, it will get suppressed. This is true with f_c plus for m for f_m also because it has that is also an odd function.

So what, so what is the final conclusion from this one, from this PWM wave form? We have fundamental with 2 leg, 2 leg; leg A and B. If you see here, this is V_n and f_n will have high amplitude, fundamental at f_m. All the sidebands here get cancelled. Then the next harmonic is happens at 2 f_c plus f_m and 2 f_c minus f_m. So, next harmonic amplitudes appearing in the current or voltage wave form will be at the sidebands of 2 times f_c. So, there the amplitude as you go, the harmonic order increases, the amplitude gets reduced. So this way, properly choosing the 2 degrees of freedom, we can have a control of the harmonics. Now, so in that case can we suppress this 2 f_c and 2 f_c plus f_m and 2 f_c minus f_m?

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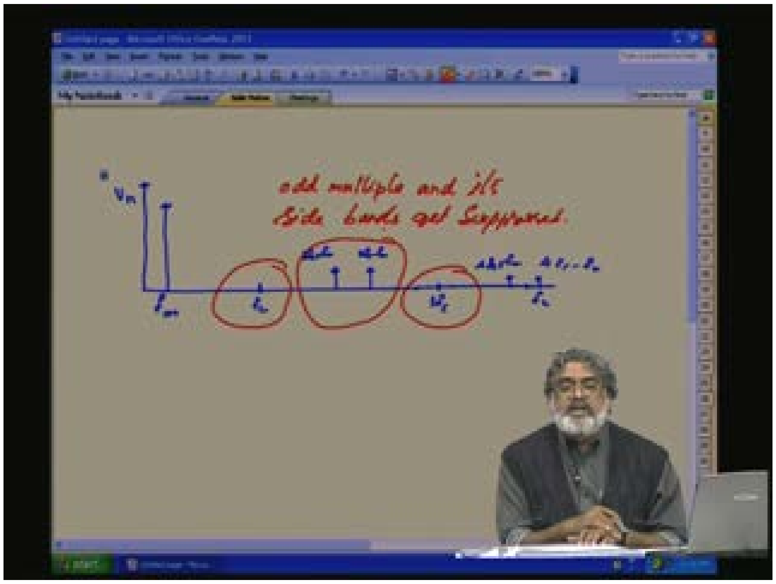

See, one more thing I want to tell you here; see, if you see the harmonics, harmonic spectrum, the V_n and the f_n you have the fundamental at f_m, then the all the sidebands at f_c we got cancelled, then we said, you have the next harmonics at happens at 2 f_c plus f_m and 2 f_c minus f_m, then the next harmonics at 3 f_c, this is also an odd function. So, its sidebands also get suppressed. So, all the harmonics at f_c and its odd multiple and it sidebands get cancelled or get suppressed from this configuration. Then we have harmonics at the even multiple and its side sidebands that 2 f_c. So, that means again from here, 4 f_c plus f_m and 4 f_c minus f_m. Then only we will have all other.

Here, if you see, all these harmonics get cancelled. That is all these odd multiple and its sidebands. That means odd multiple and its sidebands get suppressed, highly suppressed when we use this triangle frequency and odd multiple of sine wave and at the same time, the triangle wave form for B phase is 180 degree phase shifted with respect to the A leg and the switching sequence, we are using same fundamental but the switching sequence is as a 180 degree phase shift for the second phase.

So, that will make sure that the fundamental get added and 180 degree phase shift along with the switching sequence 180 degree, we will see to that odd multiple and all its sidebands have a phase difference with have zero phase difference. So, when you subtract, both will get from the, both legs get cancelled. Then is there any way we can suppress or eliminate this part? Then we require one more degree of freedom. See, for that we should use a configuration like this. See, let us say, these are used for high power applications.

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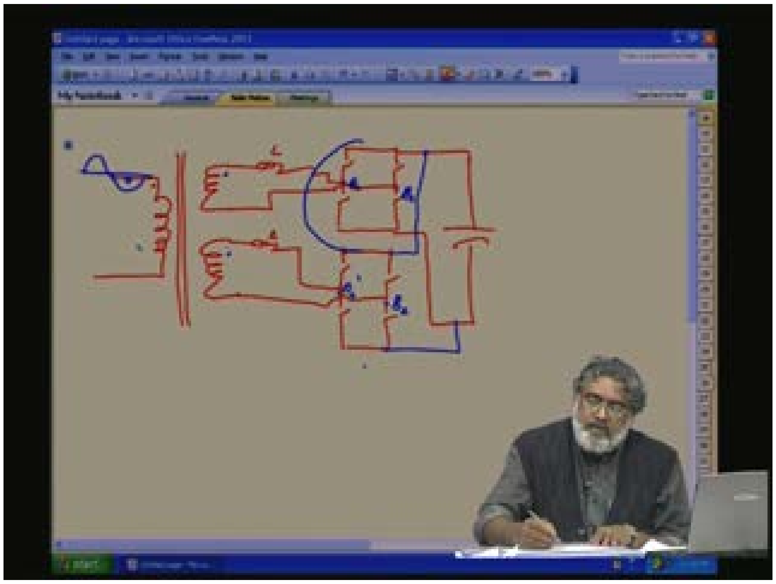

So, you have single phase mains here, the configuration will be like this; this is the transformer, this is our main, single phase. Then we will have the one secondary here, another secondary here. Then you have the inductance here that is L, L here. Then you have one converter here. Here to suppress the next harmonics, second, harmonics at the sidebands of second f_c, we will use one more converter in series and parallel configuration.

So, let us see, how it can be done? I think this configuration originally done by Siemens for the attraction drive applications front end ac to dc converter. So here, this front ends mains will be around 25 KV line. This will go here, so we have two converters. Both will be feeding to our output dc that means this will also go here, this will come here and from the other side, this will go here and this will come here.

So, what we want? The harmonics we said, suppressed. What do you mean by harmonics with respect to the first converter harmonic suppressed? The current drawn by the first converter, the harmonics at f_c and its sidebands will get cancelled. That means the reflected current from the mains, that suppressed harmonics will be there. Now, through this converter and interaction between these two converter if we can suppress the second and its sidebands, then that will if we the if the second harmonics produced by this converter and this converter has a 180 degree phase difference, then this will not reflect here. It will get cancelled here in the transformer minty circuit and it will and it will not reflect here and the current drawn here will be as close as to a sinusoidal with small ripple.

So, mains will not get corrupted and the mains will have and we are controlling the close loop control such that we are getting a unity power factor also. That is a best way to drop power from the mains. Now, the question is how do you suppress the harmonics current? We do not want the second harmonics because of this one more converter is added, the second harmonics and its sidebands, we should not get reflected here in the primary.

So here, what we are doing; the same principle, identical principle what we used for here, we will be using here as far as the sine triangle is concerned, individual phase leg A; this is AB, this is let us say A_1 B_1, this is A_2 B_2. Same technique we will use, same modulating wave will use. As for as the B_2 switch sequence is concerned compared to A_2 that triangle will be 90 180 degree phase shifted and the switching sequence will be reversed. But what we will do here?

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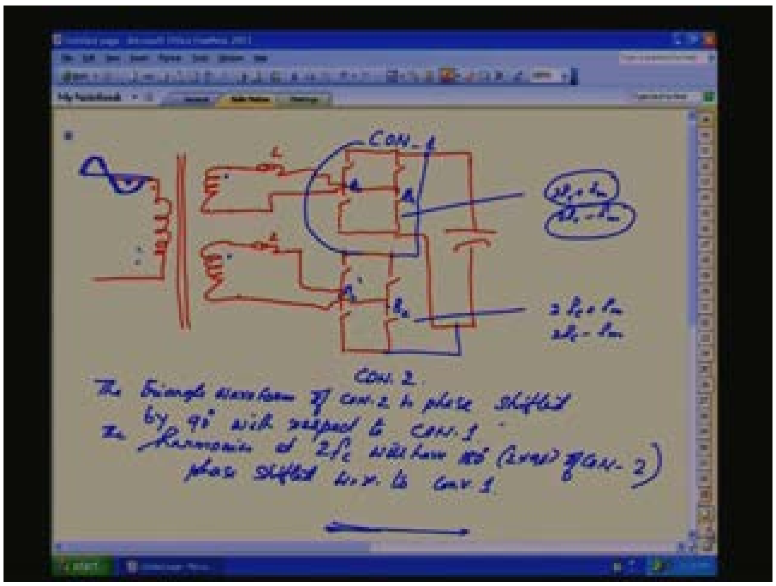

The triangle waveform this one to this one, second converter that is converter one, this is we will say converter 1, this we will say converter 2. The triangle waveform here, we will say, the triangle wave form of converter 2 is phase shifted by 90 degree with respect to the converter 1. So, what you mean by 90 degree? We will draw the wave form slowly and then find out. What is the advantage? So, both converter, we will have f_c, we will have 2 f_c plus f_m and 2 f_c minus f_m. See, 2 f_c plus f_m 2 f_c minus f_m, here also this converter also has sidebands at 2 f_c plus f_m and 2 f_c minus f_m. So, 90 degree means what will happen? So, it is 90 degree phase shifted with respect to the converter 1. So, what happens?

The harmonics at 2 times the carrier frequency, the harmonics at 2 f_c will have 180 degree phase shift because it is 90 degree phase shifted triangle, so 2 into 90 phase shifted. The harmonics at 2 f_c will have 180 degree, 180 degree phase shifted; the harmonics at 2 f_c of converter 2. Converter 2 will phase shifted 180 with respect to converter 1. But so 180 degree, so 2 f_c plus f_m that also very close, very close to 180 degree. That means as I told because if you do the harmonic, so it will be very close, slight phase shift will be there because it is not exactly 2 f_c, 2 f_c plus f_m.

But because f_c is very high, so this 2 f_c plus f_m also very close to 180 degree phase shift; 2 f_c and its sidebands will be will be 180 degree, close to 180 degree phase shift as for as converter 1 and converter 2 and the flux due to this transformer 1 and transformer 2 will cancel here. That means it will not get reflected here. So, the harmonics at sidebands of 2 f_c plus f_m and 2 f_c minus f_m and the sidebands will get highly suppressed here.

But not at the 4 f_c, 4 f_c means again 4 into 90, 360; that are in phase. But if you see here, 4 f_c is very far away. So, that will not have much effect. So, the fundamental will be very close to a sinusoidal with harmonics due to the harmonic amplitude at 4 f_c and its sidebands. That means what it shows? All the harmonics at f_c and sidebands and 2 f_c and sidebands, 3 f_c and 3 f_c sidebands that means what it shows because of this one, we can finally summarize. Now, so what are the advantages here?

So, we will conclude. So, we have two converters connected parallel to the load and the sine triangle PWM we are using and the triangle wave form, we are properly phase shifting and the sequence of operation with respect to one converter; the leg for A and B, we are interchanging. So, what happens, this conclusion?

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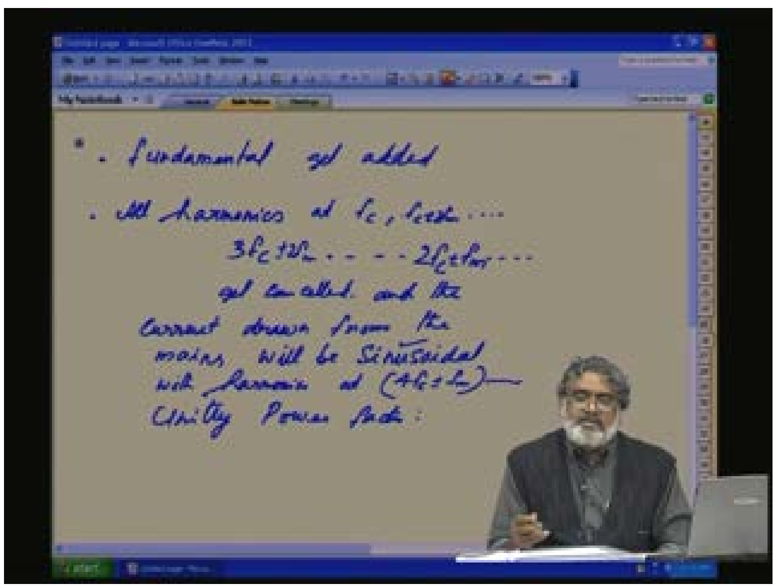

Fundamental get added and all harmonics; harmonics at f_c, f_c plus or minus f_m, then 3 f_c plus or minus f_m, f_m, 3 f_m, all that bands, then? sorry f_c plus 2 f_m and f_c plus? Plus or minus 2 f_m that is because when this is odd, this has to be even. Here, two f_c minus f_m plus or minus f_m and all other odd multiple of f_m plus minus 2 f_c get cancelled and the current drawn from the mains that is our single phase line from the mains will be sinusoidal, close to a sinusoid with harmonic amplitudes, with harmonics at 4 f_c plus or minus f_m. This very far away also with control that is close loop control, we are also trying to get unity power factor. That means the fundamental current is in phase with the mains force, unity power factor also.

This is a standard ac t, very ac to dc converter used for traction drive application. I think originally it is used by the Siemens for attraction drive application where they used 11 times f_m; f_m is 50 hertz, 11 times f_m used for the carrier frequency and they suppress and suppressed all these harmonics.

Now, you have close loop control of this one to get unity power factor and how to form like the close loop control. Before coming to the close loop control, how we design the C value and L value. We will study in the next class. Then once the design part is over; what are the basis for designing the L value and C. Then for then close loop control, how do you form the close loop and how do you design the close loop parameter in the subsequent classes.

Thank you.