Power Electronics

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Lecture - 41

In my last class I discussed space vector PWM technique and hysteresis current controlled PWM technique. I told you that in space vector PWM technique, at any given time only one switch is being switched, only one switch is being switched at a time. Where, we used 2 active vectors and the 0 vectors to synthesize the required space vector. For the sake of convenience, we divided the total 0 vector time into two and we applied 000 and 111.

It is like this, see in this figure, see, assuming that we are in sector 1; sector 1 is if theta is in between 0 to 60 degrees. So initially, we are at the origin with 000; all upper switches of the inverter are off. So, the at the end of T_Z by 2 period, we turned on only the upper switch of phase A, 001.

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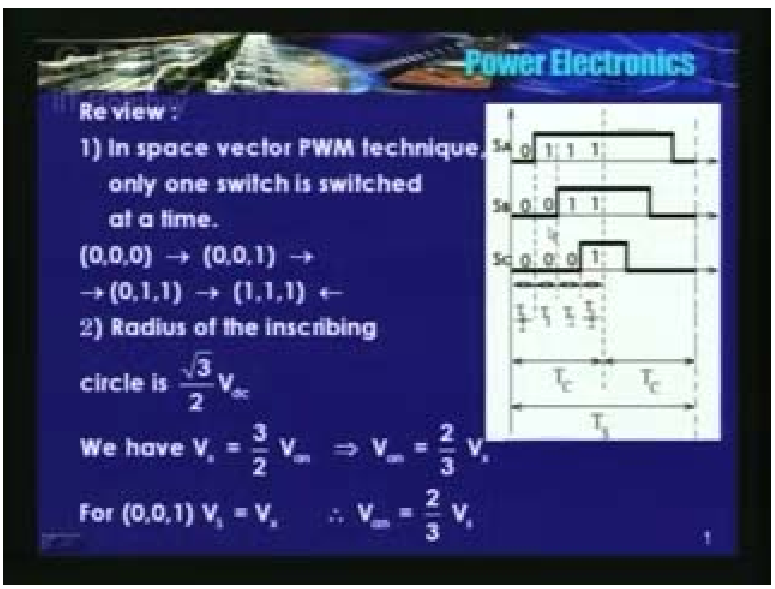

So, vector V_1 is applied for T_1 duration and at the end of T_1, we turned on the upper switch of phase B. See, we did not do anything to the upper switch of phase A, it is still on. We turned on another switch and upper switch of phase C is still off. So, it is 011. We call this vector as V_2 and that is applied for T_2 duration and at the end of T_2, we turned on the upper switch of phase C.

All 3 switches are on. That is for T_Z by 2 duration and this entire duration is T_c where T_c is the sampling period or the total sampling time divide by 2 or T_s is the period for which or during which the space vector is stationary or see in this, it is 000 to 001 only one switch is switched.

From there it is 011 and again, 111 and again go back. Same thing, whatever that happens here, it happens in this fashion. So, like that in time, only one switch is being switched.

I also told you that if all 3 phase voltages are sinusoidal, the locus of space vector is is the circle and what is the maximum value of V_S or what is the maximum value of the length of the space vector for which all 3 phase voltage are sinusoidal? It is the radius of the in subscribing circle. So, that is nothing but V_{dc} into cos 30 where Vdc is the side of or length of the each length of the each side of the hexagon. So, the maximum value of V_S for which all 3 phase voltages are sinusoidal is root 3 by 2 into V_{dc}.

Now, what is the peak value of the phase voltage that we can get in space vector PWM technique? See, while while transforming or while determining V_x and V_y, we found that V_x is equal to 3 by 2 into V_{an} that I have derived in the in my last class. So, V_x is 3 by 2 into V_{an}, so therefore, V_{an} is 2 by 3 into V_x and for 001: in other words, only upper switch of phase A is on, at that time Y axis component is 0 and V_S is V_x itself and for 001, we found that V_{bn} and V_{cn} are equal and both are negative. When V_{bn} and V_{cn}, both are negative and they are equal, at that time phase A is at the peak. In other words, V_{an} is at the peak.

So, I will substitute, see here; so, for 001, V_S is equal to V_x and therefore V_{an} is equal to 2 by 3 into V_S and this maximum value of V_S is nothing but root 3 by 2 into V_{dc}. So, I will substitute in this equation. So, I will get the peak of the fundamental component of V_{an} is 0.577 times V_{dc}.

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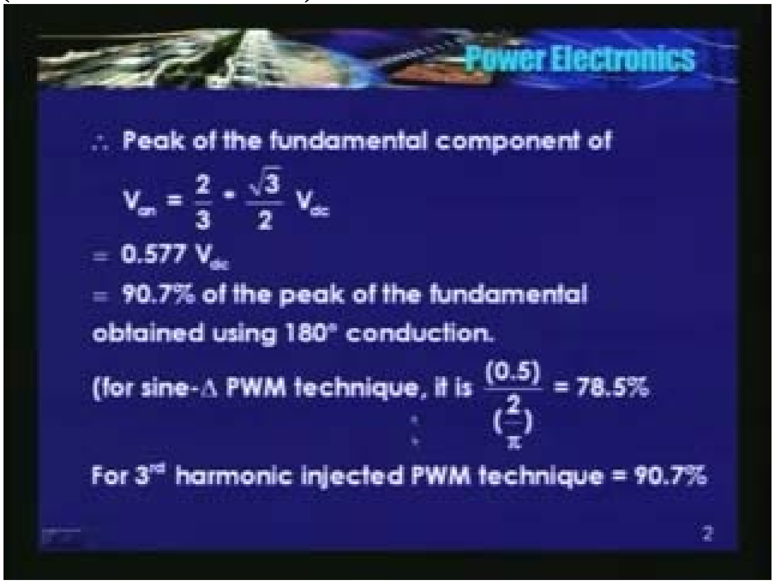

So, if I take the ratio of the peak of the fundamental component of the phase voltage that is obtained using space vector PWM technique to the peak of the fundamental component of the phase voltage that is obtained using 180 degree conduction, we found that this value is 0.907 or 90.7% and for sin triangle PWM technique, this was or this is 78.5%. So, space vector PWM technique gives higher value of the peak of the phase voltage and we found that this peak values is the same for third harmonic injected PWM technique.

So, in other words, space vector PWM technique is same as third harmonic injected PWM technique. And, how about the number of samples per cycle? I told you that all the sectors should be equally used. All the 6 sectors should be equally used and samples should be positioned symmetrically about the each sector. In one sector, samples should be positioned symmetrically with one sample at the center, remember. Only then I get the features which I told you in my in my in the beginning of my PWM lecture class, the 4 qualities, a good PWM technique should have; quarter wave symmetry, no sub harmonics, then 3 phase symmetry, at any given time only one switch should switch. So for that, n should be odd multiple of 3. So, if there are 3 samples in 1 sector, they should be positioned at alpha is equal to 10, 30 and 50.

So, in all the voltage controlled PWM techniques, say; sin triangle, space vector, third harmonic, harmonic elimination PWM technique, the switching frequency of the inverter remains constant. The rate at which you switch the inverter devices, say in sin triangle, what is the rate at which you switch the inverter devices? It is same as the frequency of the triangle. When the triangular wave crosses the sin wave, you switch the device, switch on the device and when it cuts back, you switch off. So, the rate at which the inverter devices are switched in sin triangle is determined by the frequency of the triangular wave.

So, if I keep the frequency of the sin triangle constant, the switching frequency of the inverter remains constant. Is that okay? And, it is independent of the type of load; what load it is driving, it does not matter. I have kept the frequency of the sin wave, frequency of the triangular wave constant. Similarly, in space vector PWM technique: having fixed the number of samples in 1 sector, the switching frequency is fixed. Even in harmonic elimination, we have pre determined notches. So, at any given supply frequency, if there are say, n number of switchings per quarter cycle, the switching frequency also remains constant.

So, in other words, the PWM technique that you studied so far; the rate at which you switch the inverter devices is constant, independent of the load variation, independent of the supply variation. Now, what about the current controlled PWM technique? I told you, current is controlled within a hysteresis band and switching frequency is a function of the hysteresis band. Smaller the hysteresis band, higher is the switching frequency. But then the current waveform, the the current drawn by the load, it is approximately a sin wave. A superior sin wave I will get, if the hysteresis band is very small. So, as you increase the height of the hysteresis window, your switching frequency comes down. But then the quality of the waveform deteriorates.

See, in the last class I also told you that we are controlling the current and the switch is kept on till or say, the upper switch is kept on till the current touches the upper band.

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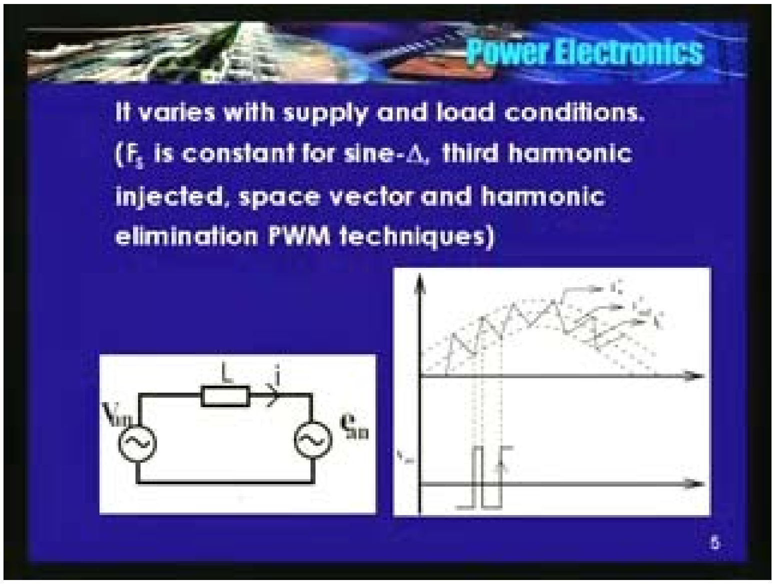

See here; at this point, the upper switch is closed, current increases and till it touches the upper band, the upper switch remains closed. See, in my last class I might have told you that this technique is insensitive to the fluctuation in the DC link voltage. Why did I tell you? It is because we are keeping the switch closed till the current touches the upper band or lower band. So, even if the supply voltage changes or input voltage to the inverter varies or fluctuates, it is not going to affect the current waveform.

Whereas, in all the voltage controlled PWM techniques, in case if you are not monitoring the input voltage to the inverter, flux level in the load may change. You may be keeping V by F constant. This V is proportional to the input voltage of the inverter. So, there is no information available for the PWM controller that the voltage is changed, the input voltage has changed. Because this rectified DC has been obtained from rectifying the input AC, 3 phase AC.

So, if 3 phase AC fluctuates, the DC link voltage also fluctuates so, and if you have programmed one V by F curve; so, flux in the load may change. Now in the last class I told, it it appears as if current controlled PWM technique has an edge over the voltage controlled PWM techniques because if the input voltage fluctuates, my current waveform does not get deteriorated in in current controlled PWM technique, whereas, my flux level changes in in a voltage controlled PWM techniques. But today I am going to tell you that if the voltage fluctuates, the switching frequency of the inverter flux changes.

See for example, see, this is the equivalent circuit; depending upon the the conducting state of the switch, I determine the phase voltage and neglecting the resistance, this is the inductance and I am assuming that there is another voltage source here, equivalent to the induced EMF. This is something, the 4 phase equivalent circuit of an induction machine, may be.

Now, what is i? V_{an} minus e_{an} divided by L is equal to di by dt. Rate of change of current is difference in these 2 voltages divided by L. Please, V_{an} and V e_{an}, they are not in phase. So, if the input voltage to the inverter fluctuates, V_{an} is going to change. So, if V_{an} changes, di by dt will change. So therefore, the switching frequency changes because we are keeping the switch closed till the current touches the either the upper band or the lower band. So therefore, in hysteresis current controlled PWM technique, switching frequency will vary as the input voltage changes.

Again, when the load has reduced, in other words, magnitude of the reference current has come down, the, your switching frequency will again change. See in this figure, e_{an} has not changed but the magnitude of current that is flowing has changed. See, in other words, magnitude of i_{ref} has changed. As this current comes down, the rate at which you switch the inverter also changes. So therefore, in hysteresis current controlled PWM technique, switching frequency varies. So, what the switching frequency of the inverter changes.

See, I told you that the frequency of the predominant harmonic that is present in the output voltage is approximately equal to the switching frequency of the converter. So, if the switching frequency itself is changing, the frequency of the predominant harmonic changes. So therefore, if you have to design a filter to eliminate this high frequency component, the filter design is going to be difficult. So, that is about PWM techniques.

See, so far we discussed about a voltage source inverter and we are taken the centre point, the DC link as the reference, V_{dc} by 2, V_{dc} by 2 and when the upper switch is on, the poll voltage is either plus or minus V_{dc} by 2. So, in line to line voltage waveform, in the positive half, there is 0 and plus V_{dc} and in the negative half, 0 and minus V_{dc}. Of course, you may have transitions in the line voltage from plus V_{dc} to minus V_{dc}, they depending upon the inverter switching. So, invariably a good PWM technique should have in the positive half, 0 and plus V_{dc}.

Now, there is another class of inverters what is known as the multi level inverter, multi level inverter.

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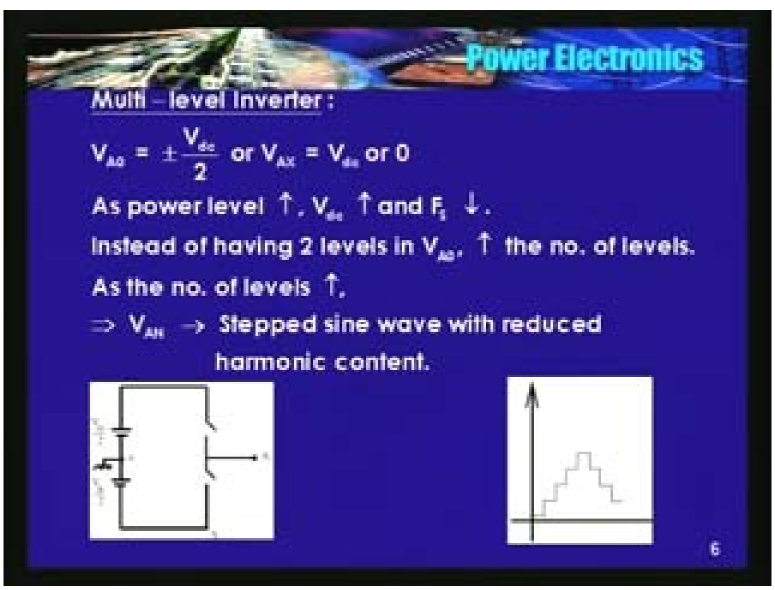

What are these multi level inverters? See, in the so call half bridge inverter; potential of A with respect to O is plus or minus V_{dc} by 2 or potential of A with respect of X is V_{dc}. See, if I close the switch, this point gets connected here. So, V_{AX}, V_{AX} is V_{dc} itself or if I close the switch, this point gets connected to this point. So, V_{AX} is 0. I told you that as the power level increases, the magnitude of DC link voltage may also change. See, there are 415 volt motors, 3 phase induction machine, there are 1.1 KV 3 phase induction machine, there are 3.3 KV induction machine, 6.6 KV induction machines. So, as the power level increases the supply voltage to machines also may increase. In fact, it increases.

So therefore, DC link voltage also goes on increasing. As the power level increases, I told you that switching frequency also decreases, it comes down. You cannot switch at high power levels, the very high frequency. Now, I said, line to line voltage has in the positive half, 0 to V_{dc}. I can say that it is a 2 level waveform. Why? 0 and plus V_{dc} or poll voltage is also either plus V_{dc} by 2 or minus V_{dc} by 2. Can I have more number of levels instead of having 2?

See, at that time, V_{AN} now may have large number of steps large number of steps. So, as the number of steps increases, I have an approximately sin wave. So, the inverters, it produces such a phase voltage waveform, they are known as multi level inverters.

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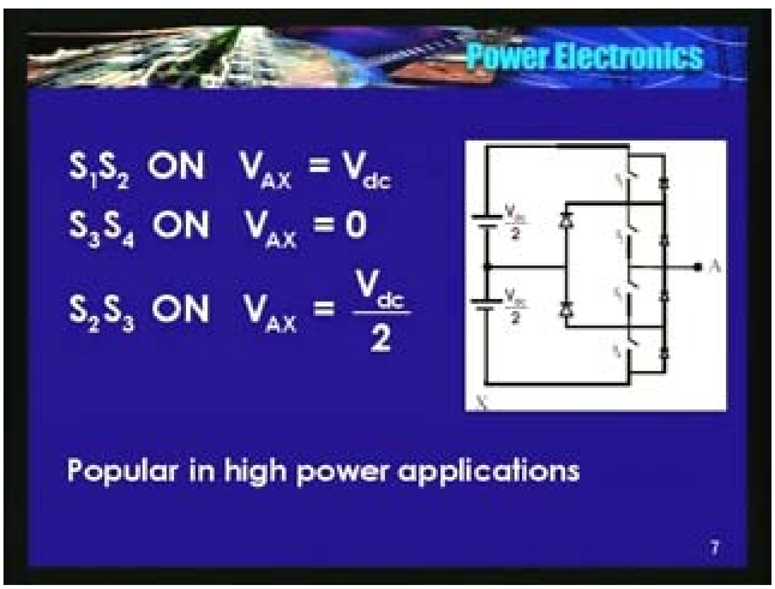

I will just give an example, see here, there are 4 switches and may be 6 diodes and the center type of or center point is connected to again these 2 diodes. How does it work? I will close only S_1 and S_2. So, what is the potential of A with respect to X? It is entire V_{dc} because when S_1 and S_2 are closed, this point gets connected to this point. So, it is V_{dc}. When S_3, S_4 are closed, of course, these 2 are open now, S_1 and S_2 are open; S_3, S_4 are closed, potential of A with respect to X is 0, V_{AX} is 0 which is same as that we got in half bridge.

Now, I will close only S_2, S_3 I will close only S_2 S_3. So, what is the potential of A with respect to X? See here; A, S_3 is closed, this point, A, this, this. It is V_{dc} by 2. So, in this case, Vd_{AX} is either 0 or V_{dc}. In this case, I have V_{AX} is V_{dc} is 0 or V_{dc} by 2. Now, there are so, it just has 3 level waveforms here. So, as the number of switches increases, I can have more levels at the point A with respect to X. So, I have an approximate S sinusoid voltage waveform.

So, this is or the inverters belonging to this class are known as multi level inverters. Generally, they are popular in high power applications. I will not cover, I will not go into to detail about the multi level inverters, slightly advanced topic. I have just told you what is a multi level inverter. There are literatures available on on this multi level inverters. The things have been covered in by IEEE papers. Those who are interested, I would suggest that they can read these papers.

Now, let me discuss some of the issues in the voltage source inverter. What are they?

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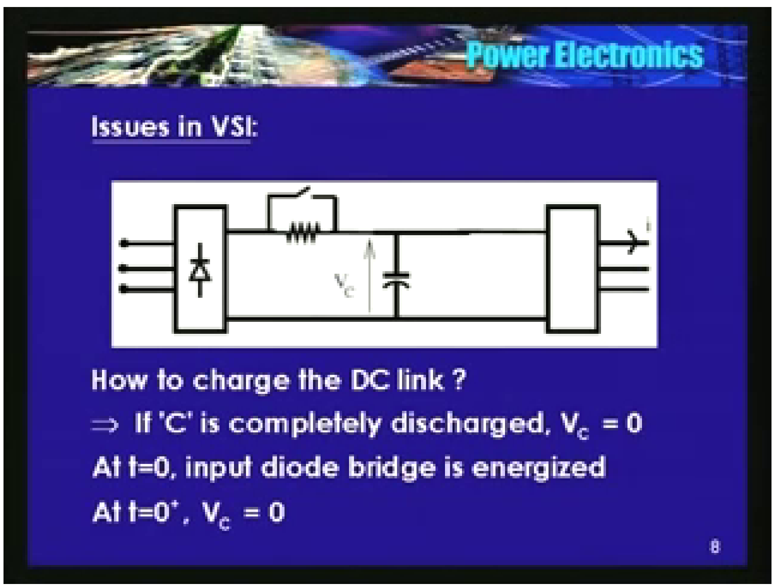

See, a general purpose AC to DC and DC to AC converter configuration. A general purpose power circuit configuration of an AC drive, in the sense, I am connecting an AC machine here. This DC is being obtained by rectifying the 3 phase utility supply uncontrolled rectification. Now, the question is how do I charge this DC link? At t is equal to 0, assume that capacitor is completely discharged. So, capacitor voltage cannot change instantaneously and you have energized the uncontrolled bridge. Capacitor voltage cannot change instantaneously, input, uncontrolled bridge has been energized, 3 phase supply, so what is the equivalent circuit here?

See, there is a voltage source here, magnitude is the peak of the voltage at this point is peak of the line to line itself and there is a short circuit here. So, in other words, there is a dead short circuit at the output of the diode bridge there is a dead short circuit. So, a large current will flow and it will damage the bridge of the diodes. So therefore, I need to regulate or I need to control the charging current or you need to control the rate at which the capacitor is charging now.

So, how do I do? So, there are 2 ways; either you connect the resistor is in a DC link or you connect an inductor, a large inductor. Now, if I connect a resistor and if I leave this permanently, there is going to be an I square R losses. So, what is generally done is capacitor is charged through this resistor and when the capacitor voltage has attained say, approximately 80 to 90% or so, 90% of the rated, you close the contactor switch or bypass this register bypass this register.
So thereby, you limit the charging current and protect the, this diode bridge. So, this is what charging the capacitor.

Now, how do I handle the energy that is being fed back to the source? Source is the out to the DC link. See, I told voltage source inverter is a 2 quadrant converter. Why 2 quadrant? Voltage cannot change, input voltage cannot change polarity but then current can reverse. There are freewheeling diodes are diodes are connected in anti parallel. So, current can flow in the positive direction as well as in the negative direction and in case, the power is being fed back by the load to the DC link through this anti parallel diodes, the capacitor DC link capacitor charges because it is receiving energy from the load.

So, if the capacitor voltage increases, the voltage stress on the inverter device is also increases because this voltage or input voltage of the inverter should be blocked by these inverter devices.

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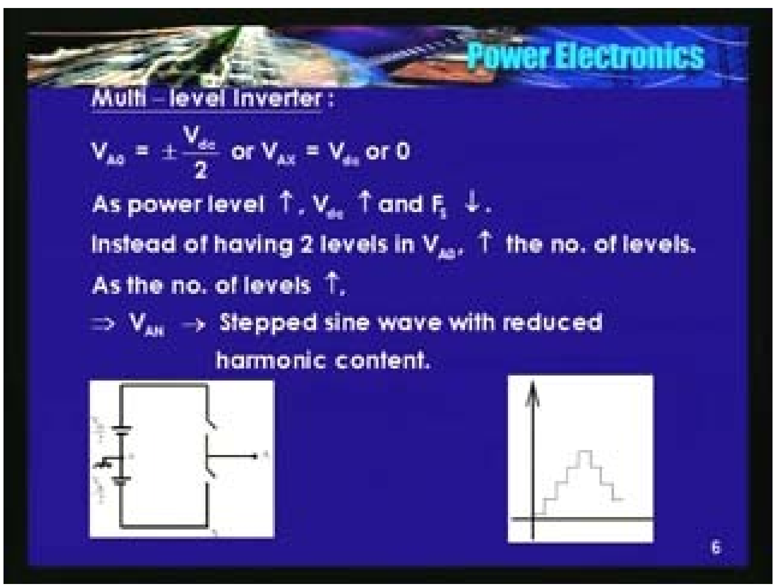

See in this circuit, when this switch is closed, voltage across the switch this switch is V_{dc} that this switch should block the entire V_{dc} here. So, if this voltage itself is changing, the maximum voltage at which the maximum voltage with this switch should block also increases. So, in other words, as the DC link voltage increases, the stress on the inverter device also increases. So, you cannot allow the DC link to increase above a rated value. How do you do this?

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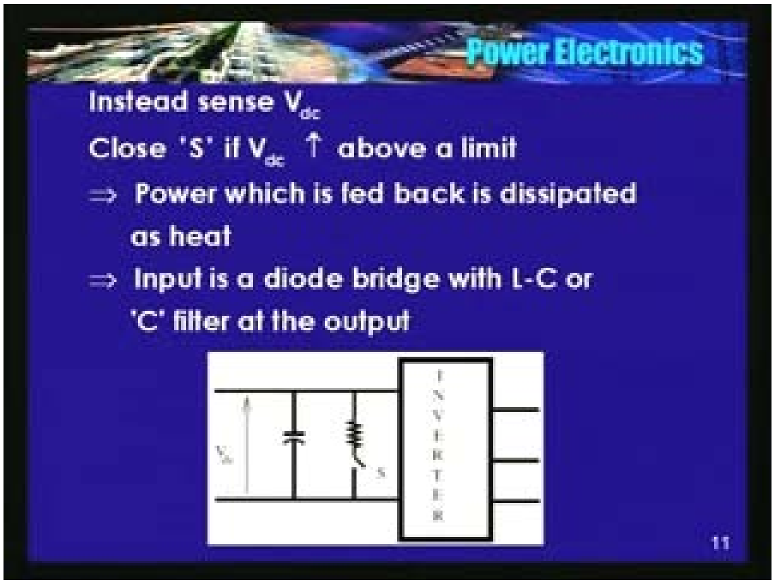

So, what has been done is if this V_{dc} is sensed and the moment it increases above the set value, use this S, the switch is closed. So, what happens? The capacitor discharges or this energy, the additional energy that is got or received from the load is dissipated as heat. So, since V_{dc}; the moment it crosses the set value, close this, dissipate the energy in the resistor and when it falls to below a certain value, open S.

Now, what is the problem at the input stage? Input stage we have an uncontrolled rectifier and at the output of this uncontrolled rectifier, there is a capacitor. You could have an AC filter also. Now, assuming that there is only a capacitor connected at the at the output of the diode bridge, how does the source current wave form look like?

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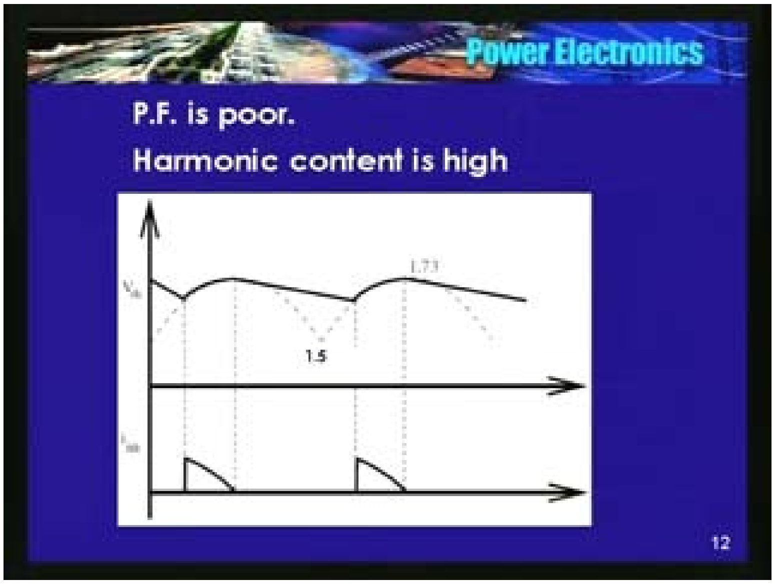

See here, this dotted waveform is the uncontrolled rectification, a 3 phase fully bridge uncontrolled rectification each of each of 60 degree duration. The peak is 1.73 per unit. I have taken the peak of the phase voltage is 1 1. So, we we have drawn this waveform 1.73 and minimum is 1.5 and at steady state, this is how the capacitor voltage will change. So, this is of 60 degree duration and each device can conduct for 120 degrees in a 3 phase full bridge. So, so D_1 or the diode which is disconnected to phase A; conducts for very short duration. See, here and here. See, these are all 60 degrees. So, very small duration it conducted.

So basically, the power factor source power factor is very poor. So, there are going to be a predominant harmonics. What is another limitation? As the input voltage of the diode bridge changes, DC link voltage also will change. Now, assume that the inverter is feeding a high HB machine. The moment I am saying high power drive, I would expect that there should be regeneration from the machine to the source or it should be possible to feed back the energy during regenerative breaking from load to to the source or in other words, regenerative breaking should be possible.

Voltage source inverter is a 2 quadrant converter. Current can reverse. So, during regenerative breaking, load supplies the energy to the DC link and from the DC link power cannot be fed back because of we have an uncontrolled bridge. That is why we are dissipating that energy using that resistor. So, what are the limitations in this power circuit configuration that I have showed you just now?

One is input side power factor is poor, second - DC link voltage is unregulated, it varies as the input varies, third - though the load is or though the voltage source inverter is capable of operating in 2 quadrants, the energy that is received from the load during regeneration cannot be fed back with this source. Can we address these limitations?

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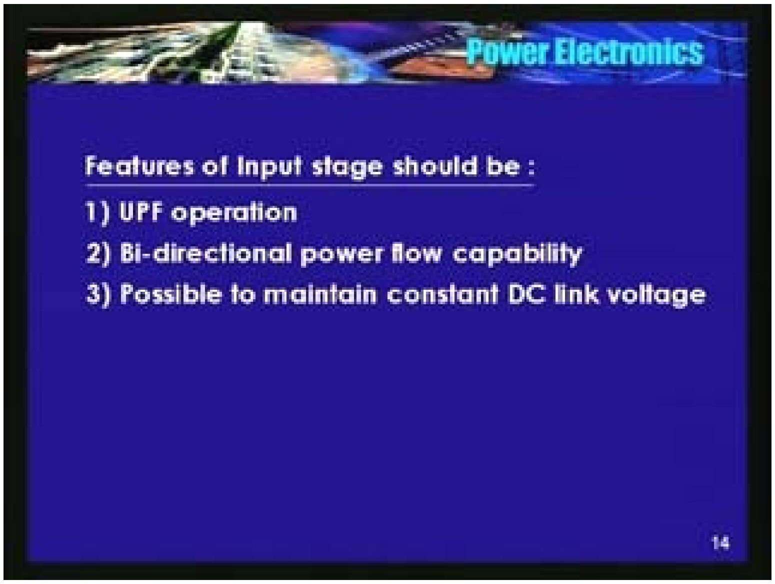

So, if I summarize; the features of the input stage should be unity power factor operation, bi directional power flow capability and possible to maintain constant DC link voltage. So, these are the features that input stage should have. How will you achieve? See here, you have studied this, this converter.

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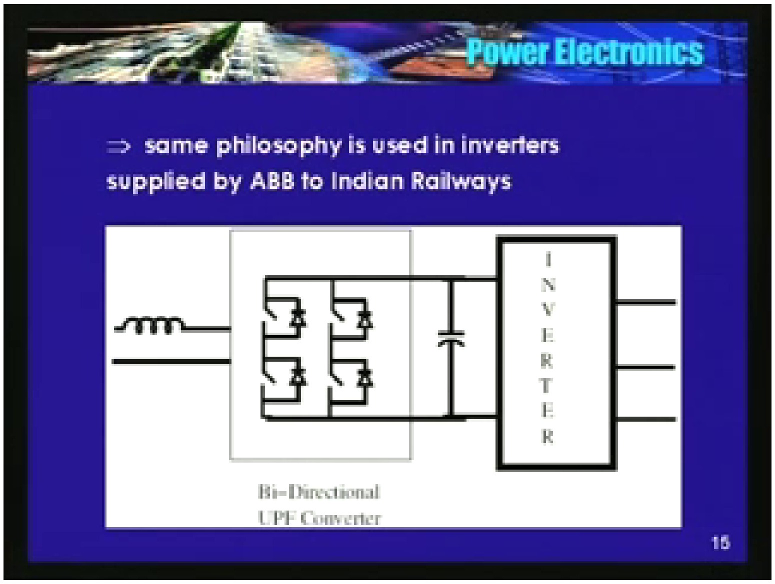

We call it as a unity power factor converter. I am just showing a single phase inverter, single phase. We have 4 control switches, may be see freewheeling diodes, capacitor voltage, here center, DC link capacitor and an inverter. So, this is nothing but a bi-directional unity power factor converter, power factor is unity. By controlling the magnitude of the source current, we can maintain the capacitor voltage constant.

In other words, if there is a perfect balance power balance; input as well as the output capacitor voltage will remain constant and it is possible. So, we can maintain a constant DC link, power factor is unity, bi directional power flow is possible now bi directional power flow. In fact, same philosophy is used in the inverters supplied by ABB to Indian railways. The the drive or AC drive that is used in Shatabdi and some of the Rajdhani express trains: Rajdhani trains and Shatabdi, they use this philosophy.

In single phase, sorry, a unity power factor stage at the input; DC link is controlled and a VSI and it is possible to feed back the power to the source. So, this is about the VSI.

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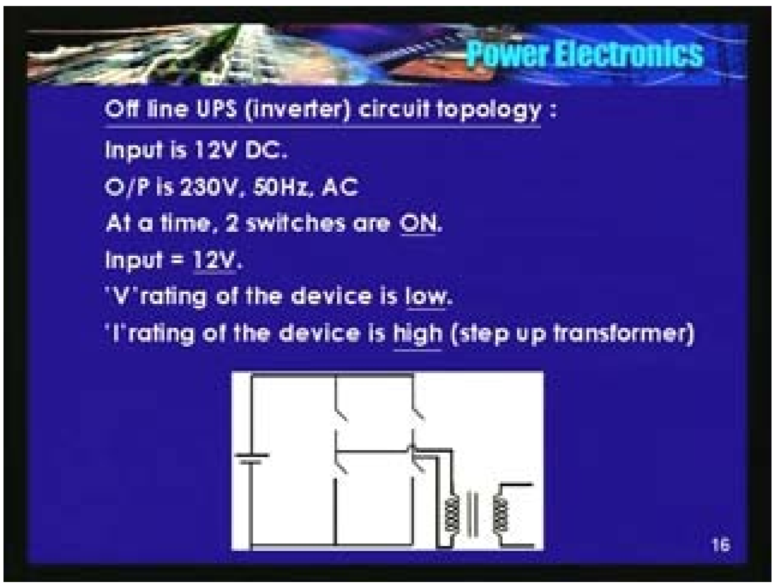

Now, let me talk about an off line UPS or an inverter, circuit topology. Why I am calling off line UPS is the inverter that we are that used in our home; the moment AC supply goes, after some time say, after a fraction of a second also, the inverter comes in. So, that is why I am calling a off line UPS.

What is the input there? A 12 volts battery. What is the output that is required? It is 230 volts 50 hertz AC single phase and I am assuming that I will use a full bridge with the 4 switches. See here, a full bridge VSI. So, at any time, 2 switches are conducting. So, at the output we have a when these 2 switches are on, V_{dc} appears and when these 2 switches are on, it will minus V_{dc}.

See, all this time we had assumed that devices are ideal. You can assume that because voltage drop across the conducting rise could be of the order of say 2 to 2.5 volts depending upon power the line. See here, now, input itself is a 12 volts. 2 devices are conducting and I am assuming that voltage drop across the conducting device is 2 volts. Now, peak to peak that is available at the output is 16 volts – 8, minus 8.

Output voltage that is required is 230 volts 50 hertz AC. So, one way is you have to step up this voltage using a step up transformer. See here, a low voltage AC that is available here; if I take 2 volts drop across each device, so I will get 0 to 8, 0 to minus 8 here and at this point we require 230 volts rms. So, this has to be a step up transformer. So, voltage rating is very low, definitely current is high.

Now, 8 volts is being applied to the primary winding. Now, this winding has its own resistance and leakage inductance. So there is the relationship between voltages at the 2 ends of the transformer; E_1 divided by E_2, it is E_1 divided by E_2 is equal to T_1 divided by T_2.

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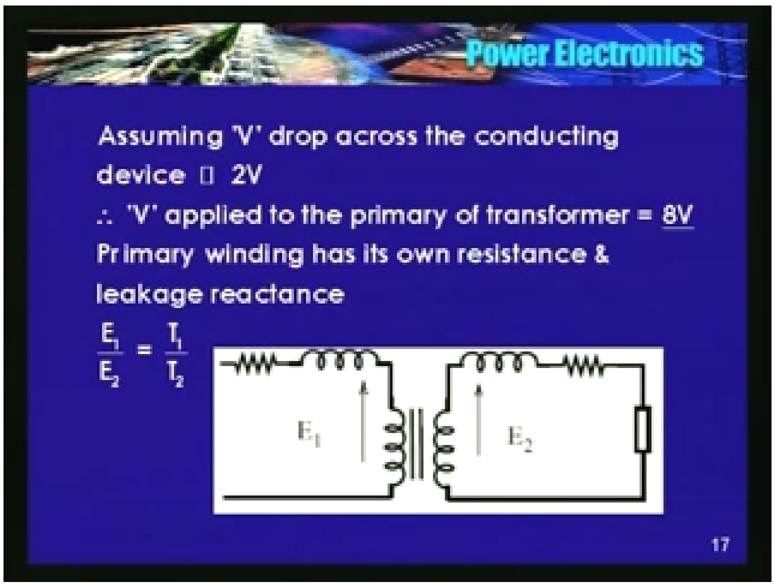

See here, it is E_1 divided by E_2 is equal to T_1 divided by T_2, turns ratio, it is not this voltage. Now, since this is 8 volts and current that is flowing is is relatively high compared to the current that is flowing in this side, I will assume that I will assume that 1 volt is being dropped in this; could be a conservative figure could be a conservative figure. So, voltage at this point available is 7 volts or so, 7 volts. But then you require at this point 230 volts 50 hertz AC.

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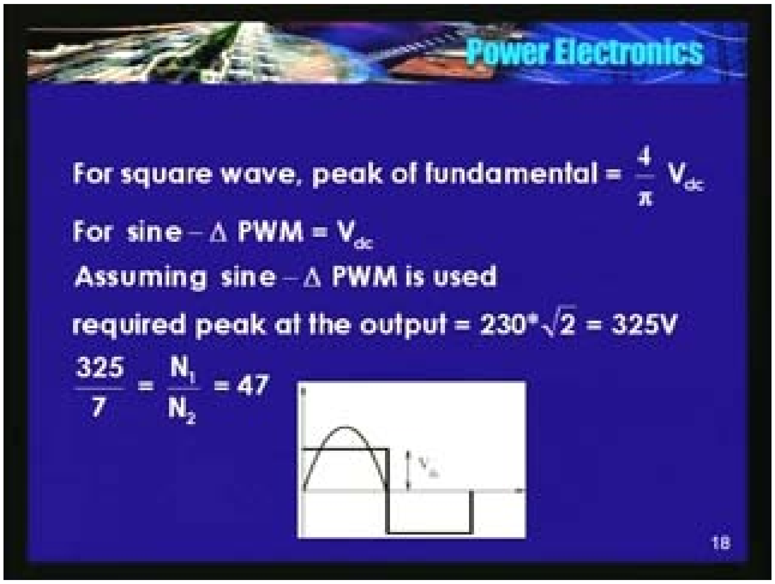

Now if I use a square wave operation or if I if the device are on for 180 degrees, the peak of the fundamental is 4 by pi into V_{dc}. See here, I have a if I if I take 180 degree conduction; this is V_{dc}, the peak of this is 4 by pi into V_{dc} and if you want a pulse width modulated inverter because square wave has a higher frequency components. In the single phase case; 3, 5, 7 all are odd harmonics.

In case if you want a pure sinusoid, definitely you need to go for a PWM technique and if I use sine triangular PWM technique, what is the peak using a sine triangular PWM technique? It is V_{dc} itself or modulation index is equal to 1. For modulation index is equal to1, the peak of the sine wave is the input voltage itself. Please, in in half bridge half bridge I said it is V_{dc} by 2: in a full bridge, it is V_{dc}. So, peak of this voltage; I am neglecting the drop here, you require 230 into root 2 here. So, 230 into root 2 is the voltage that is required here. I am assuming that this voltage will appear here, neglecting this drop.

So, what is the turns ratio? 7 here, 230 into root 2: somewhere here. So, turns ratio is of the order of 47. What is the fundamental frequency that is being applied here? You want a 50 hertz supply. So, frequency of the fundamental component seen by the transformer is 50 hertz.

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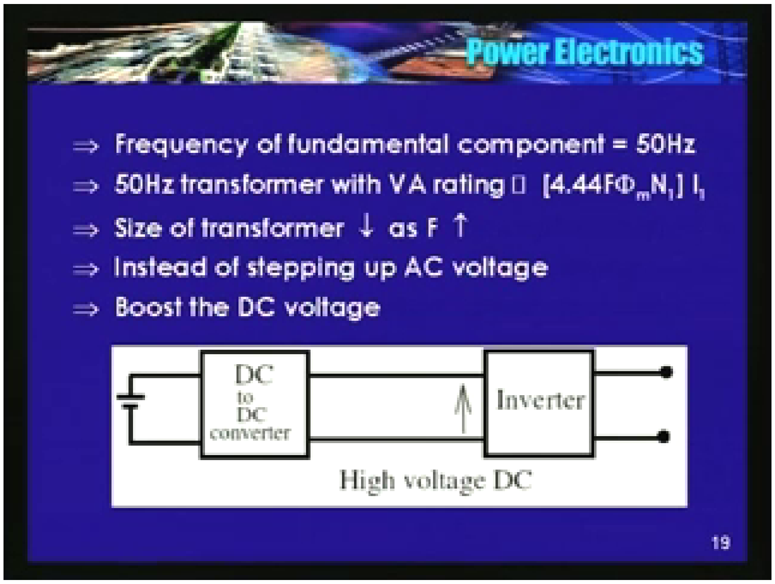

So see, if I write the equation, the V_A rating; 4.44 into F into phi m into N_1 into I_1 - this is the rms value of the voltage induced given. F is 50 hertz. So, for the same VA rating; as the frequency of operation increases, size comes down. I hope you all know this. As the frequency of the operation increases, size of the magnetic comes down. But then here, the frequency of the fundamental component is 50 hertz. So, you required a 50 hertz transformer. So, that is the reason the inverter that is used in our home is very heavy because there is a 50 hertz transformer.

Now, can I try to reduce the size of the transformer thereby, reducing the overall weight? Definitely, it cannot be used if I take this philosophy. What is the philosophy? We had a low voltage DC, we inverted it, I got a still a low voltage AC, then we used a step up transformer and boosted this voltage.

Now, instead of stepping up that the AC voltage, can I step up the DC voltage? I will repeat; we did DC to AC, low voltage AC and again used a step up transformer increased the voltage to a required value. Now instead, can you boost the DC voltage itself? See, we have studied various classes of DC to DC converters; with the transformer, without transformer. There is a boost converter, I told you that maximum ratio could be of the of could be of the order of 10 to 11 or 10 to 12. Then we used the transformer; fly back, forward and push pull. So, using the transformer and the DC to DC converter, I can boost up this 12 volt DC to a relatively higher voltage DC. Then you invert this high voltage DC to high voltage AC. High voltage in the sense, 230 into root 2 AC, using a PWM technique.

See, something like this - low voltage DC, 12 volts, a DC to DC converter, of course, using a transformer. Now, what sort of a transformer? It is a high frequency transformer, these are transformer that is used is push pull, transformer that is used in forward. These are high frequency transformer.

So, size comes down, size comes. So, here I have a high voltage DC; so if I just invert it, I should be able to get a peak value which is equal to 230 into root 2. So, the overall size of this inverter reduces, weight reduces, it is elegant elegant because we are not using a 50 hertz transformer. There is a transformer in a DC to DC converter that is we operated at a much higher frequency. But the only disadvantage here is there is no oscillation between the load and the inverter there is no isolation between the load and the inverter. More about it, we will see it in the next class.

Thank you.