Power Electronics

Prof. B. G. Fernandes

Department of Electrical Engineering

Indian Institute of Technology, Bombay

Lecture - 20

In our last class we discussed the principle of operation of the pulse width modulated or PWM AC to DC converter.

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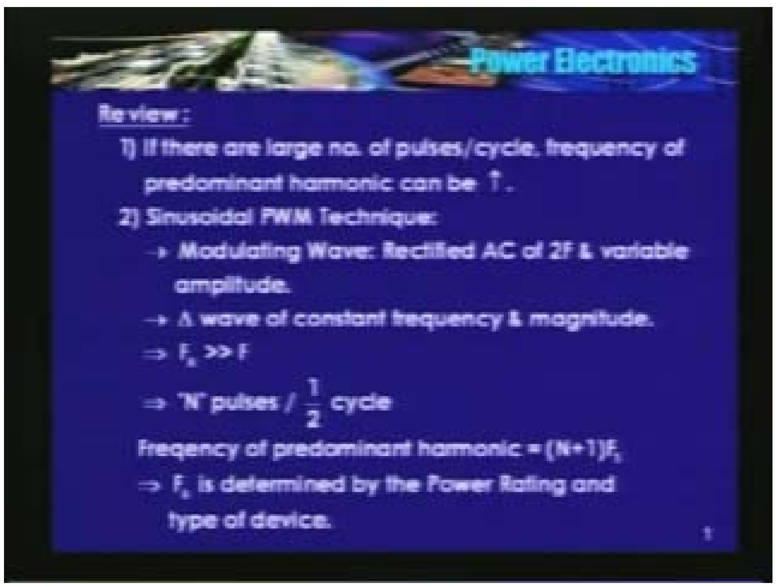

Our observations were; the first one is if there are large numbers of pulses for cycle, the frequency of that predominant harmonic that is present in the source current increases. Second one is sinusoidal pulse width modulated technique can be used to determine the turn on or off of the switching devices, whereas, sinusoidal predominant technique, I told you that there has to be a modulating wave which is nothing but a rectified AC, input AC. Frequency is same as that of the supply but the magnitude should be variable.

There is a carrier wave which is a high frequency triangular wave. The frequency as well as the magnitude are held constant and the frequency of this, of the carrier is much higher compared to that of the modulating wave or the supply wave.

So, if there are N pulses for half a cycle, the frequency of the predominant harmonic that is present in the source current is approximately N plus 1 into the supply frequency. I told you that as the frequency of the predominant harmonic increases, the filter components that are required to eliminate this predominant harmonic decreases, the size decreases. So, higher the frequency, smaller is the size of L and C. But then as the frequency increases, inverter losses increases.

So therefore, the frequency of the triangular wave depends on the type of device and the power rating. Say for example, if I have, if the load is of a few HP, say, 2 to 3 HP motor and if I have a IGBT device which is fast, I can switch, may be, as high as 10 kilowatts or so. But then if the power rating is of the order of say 100s of kilowatt and if I use GTOs, the frequency could be less than 1 K, less than 1 K. So therefore, it depends on the power rating as well as the device.

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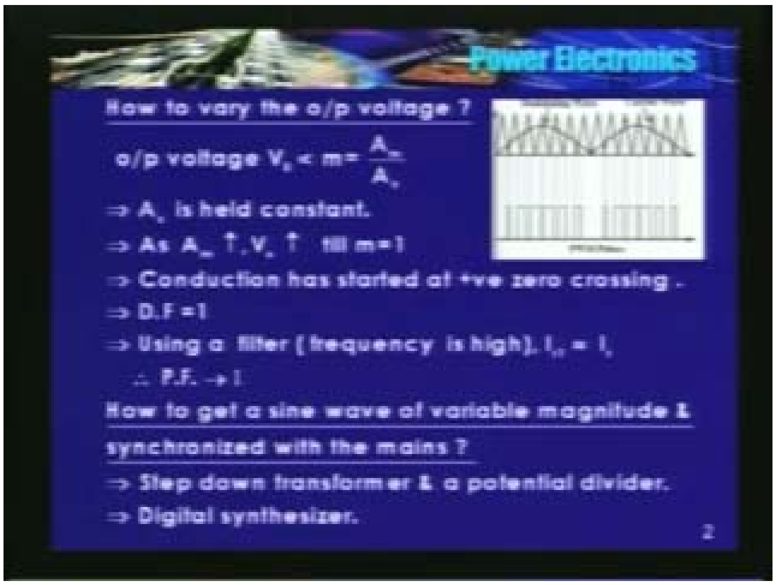

Now, how to decide or how to vary the output voltage? How do I vary the magnitude of the output voltage? See this slide, magnitude of triangular wave is constant but then magnitude of this sinusoidal or modulating wave, I said should be variable. If the magnitude of this modulating wave is very small, you will find that device is off for a longer time and is on for a shorter time.

In the first quadrant, S_1 and S_2, if they are on for a shorter duration and if it is off for a longer duration, power supply to the load decreases, whereas, if they are on for a longer duration and off for a shorter duration, power supply to the load increases. Therefore, if I increase the magnitude of the sinusoid, a rectified wave, the magnitude of the output voltage also increases. So, there exists a relationship between the output voltage and the magnitude of the sinusoid. V_0 is proportional to M where M is the modulation index. It is equal to the magnitude of the sinusoid divided by magnitude of the carrier.

Since, AC is held constant, V_0 is proportional to M or V_0 is a function of the modulating wave. So, S_1 starts conducting in the near, near the 0 crossing of the modulating wave. Therefore displacement factor is approximately 1. There are large numbers of pulses, so, frequency of the predominant harmonic also increase. So, I use a small L and C which filter this predominant harmonic.

It so happens that the fundamental component of the source current is approximately equal to the RMS value. So, the power factor also improves. So, the power factor of a PWM converter is approximately 1 unit. Now, the question is how do I get a modulating wave whose frequency is twice the supply frequency, magnitude is variable?

One way is use the step down transformer and a potential divider. Step down transformer rectify it, I will get a rectified sine wave then I will use a potential divider. Now, this is manual control, in the sense, you need to change the magnitude or you need to change the potential divider, the position of the variable point to vary the output voltage.

The second one is you can digitally synthesize a sine wave. I will explain the working of this circuit very briefly.

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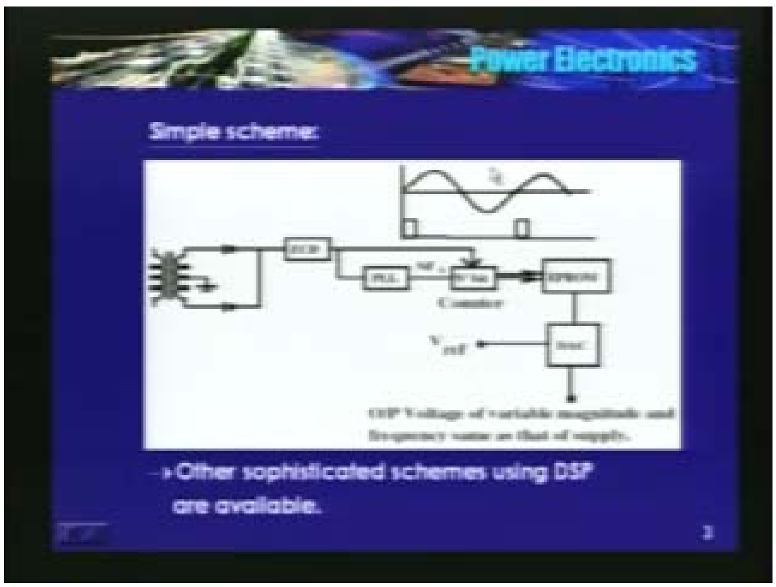

What I did is I took a sinusoid, a centre tapped transformer. I rectified it, a full wave rectification here then I gave to a 0 crossing detector nothing but an op-amp. Then I got 2 pulses here, at the 0 crossing. Now, I will digitize the rectified sine wave and I will store it in an EPROM, both 0 to pi and pi to 2 pi, null, store it in the EPROM.

So, if I divide this half a cycle by 256 parts, so in from 0 to 511, I will store the rectified sine wave. Now, these 0 to 511 locations should be addressed in this period. So, I need to have a counter which address the EPROM, counter should start the 0th location at the positive 0 crossing and at 511 position just prior to the next 0 crossing. But then, this N bit counter requires a clock. There has to be a relationship between this clock and the supplied frequency.

So, if there are 512 locations here, a counter should get 512 clock pulses in this period. So, what I will do is, I will use a PLL as a multiplier. So, N could be here, nothing but 2 to the power 9 that is 512 N bit counter. The digital data is converted to analog data using a DAC or digital to analog convertor.

Now, we know that the magnitude of the sine wave is proportional to the voltage at the reference period. So, by changing V_{ref} I can change the magnitude of the sine here, magnitude of the modulating wave. So, at this point I have the reference wave is also the modulating wave which is a rectified sine wave of same frequency as that of the supply and magnitude variable, that magnitude is proportional to V_{ref}.

Now, this V_{ref} can come from either from a microprocessor or a microcontroller. This is a very simple scheme to synthesize a sine wave. There are more sophisticated schemes using DSP's are available, may be, you can read the text books, you can find out.

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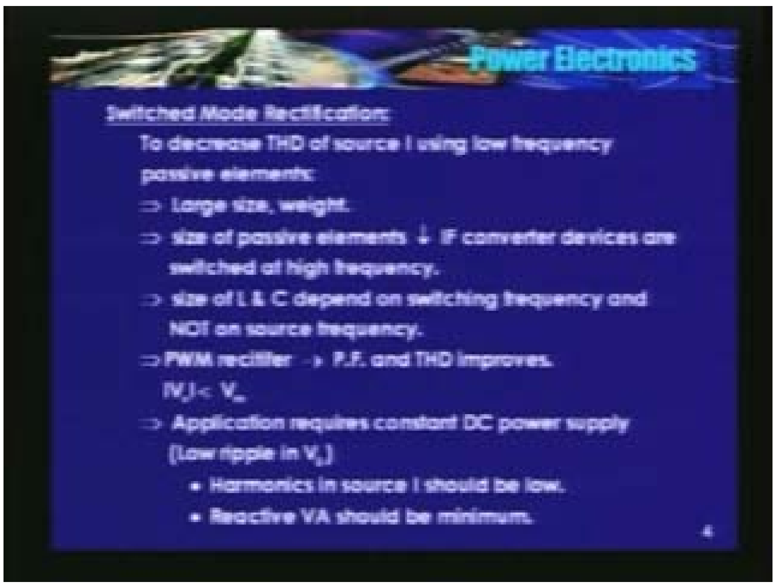

So, in a PWM convertor, I told you that there are large numbers of pulses, frequency of the predominant harmonic increases. But then the magnitude of the output voltage is proportional to the modulation index. So, modulation index can take a value of 1.

So, the output voltage is always less than or equal to the supply voltage. The power factor of the PWM converter is approximately equal to 1. Now, take an application, wherein, I want a slightly a higher voltage than the input, a constant DC voltage is required. I cannot use a PWM rectifier for the simple reason that I want a higher voltage than the input. Second one is harmonics in the source current should be as low as possible so that I use a smaller filter. Third is the reactive V_a or power factor should be very close to unity, reactive V_a should be minimum.

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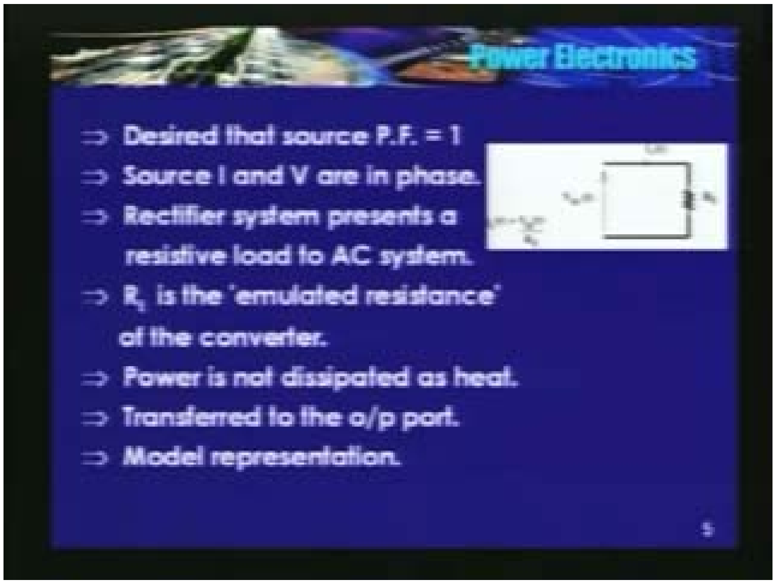

How do I achieve this? You can achieve it using the switch mode rectification. In switch mode rectification, power factor is approximately equal to 1. So, the angle between the source voltage and the source current is 0. In other words, for the source, this entire switch mode converter along with the load appears as if it is supplying a resistive load. I will repeat, I said angle between V and I - source voltage and source current is approximately 0. So, for the source the entire system, the rectifier as well as the load connected to the rectifier appears as if it is feeding to a purely resistive load.

See, this is the equivalent circuit. Angle between V_{in} and I_S is 0. That can happen only if the load is resistive, purely resistive. We are not connecting Re at the output. In another words, power supplied by the converter is not dissipated as heat. It is just a mere representation or the entire the convertor can be modeled as if it is supplying to a resistive load. Power is not dissipated power is transferred to the output port of the converter. So, Re is known as emulated resistance or this technique is also known as the resistance emulation. Let us see, how it works.

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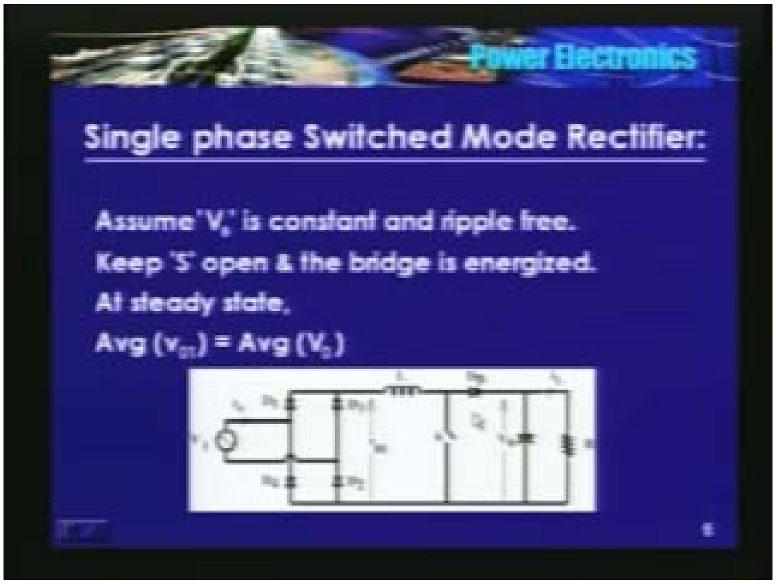

A simple, a full bridge diode rectifier, I have used an inductor L and a switch here, a diode and this is the output stage. A capacitor and I connected a resistor here. Let me tell you one thing, I do not need to connect a resistor here. You can connect some other load to this terminal. What sort of a load, we will see some time later. As of now, I connected a resistor.

This switch is a fast device, self commutating fast device. The switch is triggered at a frequency which is much higher than the supply frequency. So, assume that I have energized the bridge and I kept the switch open for a longer time. So, at steady state, average value of V_{01} is equal to average value of V_0 because average voltage drop across the inductor is 0 and I am considering V_B to be ideal.

So, average value of V_{01} is same as average value of V_0. This is case 1. We will see what happens if I, as soon as I energize the bridge, if I start switching S? That we will see some time later. Having attained a steady state, I will close S for some time. So, what is the equivalent circuit now? When I close S, you see here, this point gets connected to the negative DC bus or the cathode, the negative of the capacitor gets connected to the anode of diode DB. So in other words, diode DB is reverse biased and at the input, there is a short circuit.

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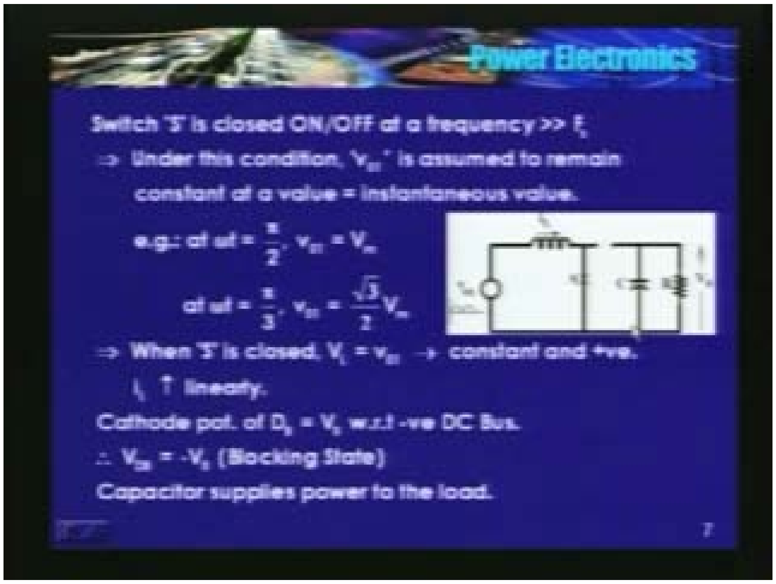

Here is the equivalent circuit. A rectified sine wave, an inductor, switch is closed. So, there is a short circuit here, there is an open circuit here because diode is reverse biased. Voltage appear across the diode is V_0 and the load. I told you that switch S is closed at a frequency much higher than the supply. So, what we can assume is that V_{01} remains constant at a value which is equal to its instantaneous value.

In other words, suppose, if I am closing the switch at omega t is equal to pi by 2, V_{01} is assumed to be remain constant at V_m and may be, at omega t is equal pi by 3, V_{01} is root 3 by 2 times the peak value. So, it remains constant at that particular value when during the switch is closed. So, what happens in this loop?

V_{01} is constant. There is a short circuit here, so voltage across the inductor appearing is constant. Therefore, I_L or current through the inductor increases linearly and at the load side, capacitor is supplying power. Now, I might have said that output voltage will remain constant and you may say that now capacitor is supplying power, definitely, output voltage will fall. Now, let me tell you one thing, this switch is closed for a short very small duration and it is opened. Stored energy in the inductor is transferred to the capacitor and the load.

So, this process takes place large number of times. So therefore, though the capacitor is supplying power when the switch is on, I am assuming that V_0 will remain approximately constant. Is that okay? Though the capacitor is supplying power when the switch is closed, I am assuming that V_0 remains practically constant.

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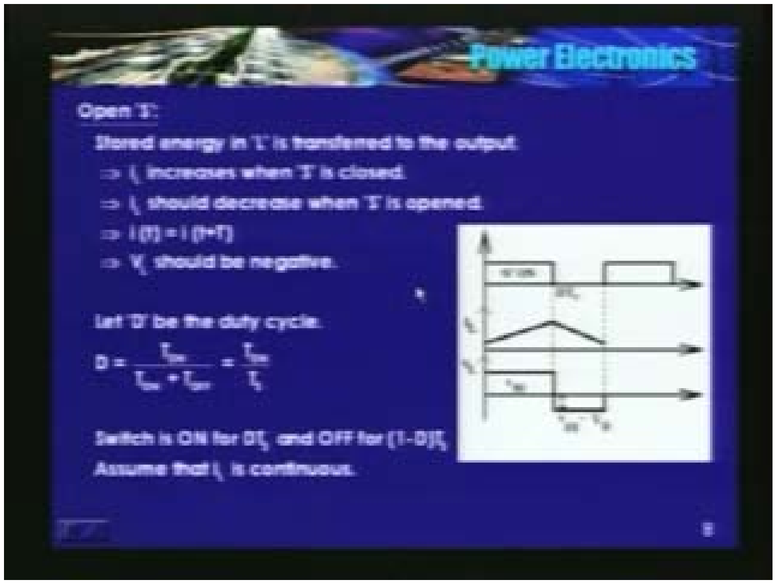

So therefore, what is the equivalent circuit when the switch is opened?

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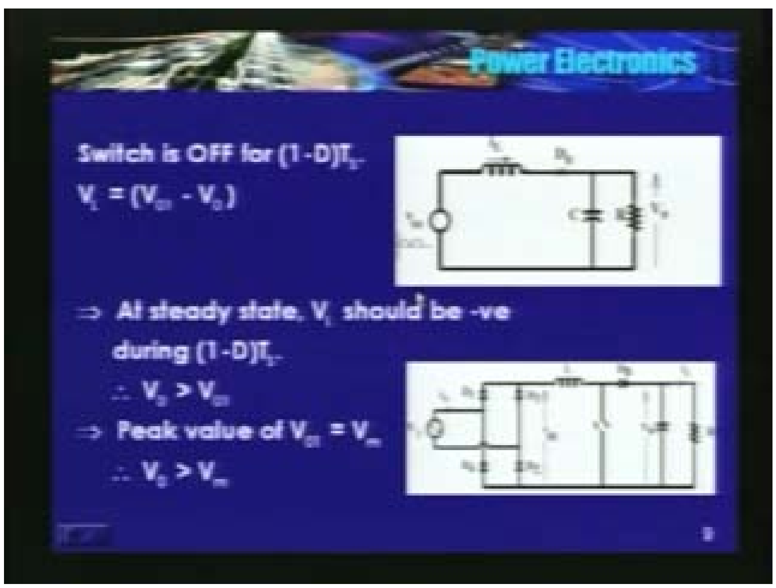

When the switch is opened, the equivalent circuit is something like this. Now, inductor current should be continuous. Current starts flowing through DB and the load, this is the equivalent circuit. Now, when the inductor is charging or when the switch is on, voltage across the inductor is V_{01} itself and when the switch is opened, voltage across the inductor is V_{01} minus V_0.
See, V_{01} is when the switch is on and this time, the switch is off, so voltage across the inductor when the switch is off is V_{01} minus V_0. Why did I show V_{01} minus V_0 is negative here? Why?

How am I supposed to know that V_{01} minus V_0 is negative? See the current waveform. When the switch is closed, positive voltage appears across the inductor, current increases linearly.

So, at steady state, if the current increases when the switch is closed, current should fall when the switch is opened. So, at well steady state, at steady state what happens is IFT at T is equal to 0 should be equal to IF, the current at T where T is the time period. So, this value is equal to this, only then I can say that circuit has attained a steady state. So, current increases when the switch is closed, current should fall when the switch is open.

Now, for the current to fall when the switch is open, voltage across the inductor should be negative. V_L should be negative, only then di by dt is negative. So, voltage across inductor when the switch is opened is V_{01} minus $V_{0.}$ This should be negative, so therefore, V_0 should be higher than V_{01}, V_0 should be higher than V_{01} but then V_{01} is a rectified sine wave. It varies from 0 to V_m. I told you that V_0 is held constant so that the therefore, the minimum value of V_0 should be peak of $V_{m.}$

In other words, circuit will function satisfactorily only if V_0 is higher than the peak of V_m because this voltage should be negative and V_{01} can attain a value of $V_{m.}$, so therefore, V_0 should be higher than peak at the input wave. I have been saying V_0 remains constant. Now, what sort of a harmonics or what is a pulsation here in V_0, I will discuss some time later. It need not be a straight line, what it is? We will see sometime later.

So, I will explain the principle of operation here. Closed switch store the energy in the inductor, opened switch transfer the stored energy in the inductor to the output. The condition is the V_0 should be higher than peak of V_{01}.

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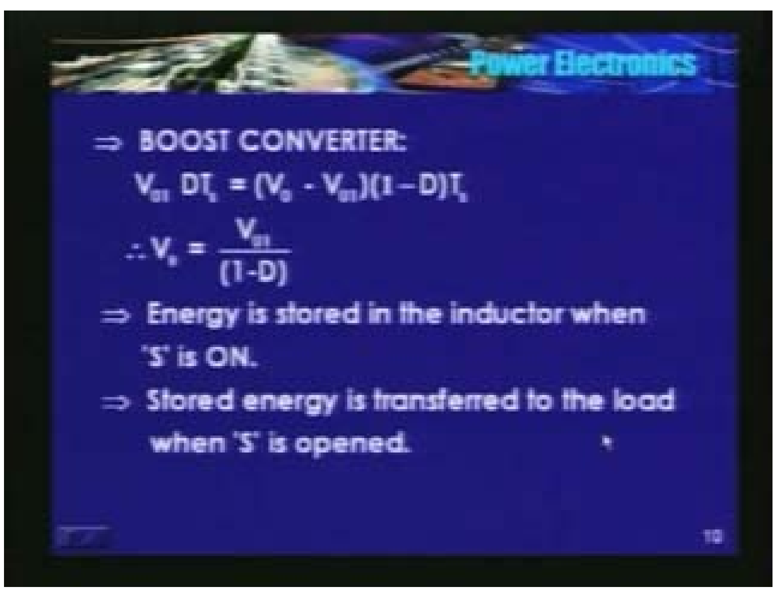

So, it is nothing but a boost convertor because output voltage is higher than the peak of the input.

So, if I equate the voltage across the inductor that is V_{01} during this time, when the switch is on. Switch is on for D into Ts where D is the duty cycle, duty cycle is given by T_{on} divided by T_{on} plus T_{off}, whereas, T_{on} plus T_{off} is nothing but, sum of T_{on} plus T_{off} nothing but Ts, the period, time period.

So, V_{01} into DTs is a volt second when the switch is closed or voltage across the inductor when the switch is closed. Magnitude is V_{01}, DTs is the duration for which the switch is closed, V_0 minus V_{01} is the voltage across the inductor when the switch is opened and switch is opened for 1 minus D into Ts duration. So, if I equate it, average voltage across the inductor at steady state should be 0, we will find that V_0 is equal to V_{01} 1 minus D.

Now, how do I choose the value of D? Is there a strategy? There are 2 strategies, the common strategies or 2 popular strategies, there are much more than that. So, the first strategy is you keep the switching frequency of the switch constant. Why to keep the switching frequency constant? We will see some time later and also keep the duty cycle constant or the time for which the switch is on, you keep it constant during the entire cycle.

Now, how do I choose this value of D? You choose the value of D in such a way that the current is just continuous. The inductor current is just continuous at omega t is equal to pi by 2.

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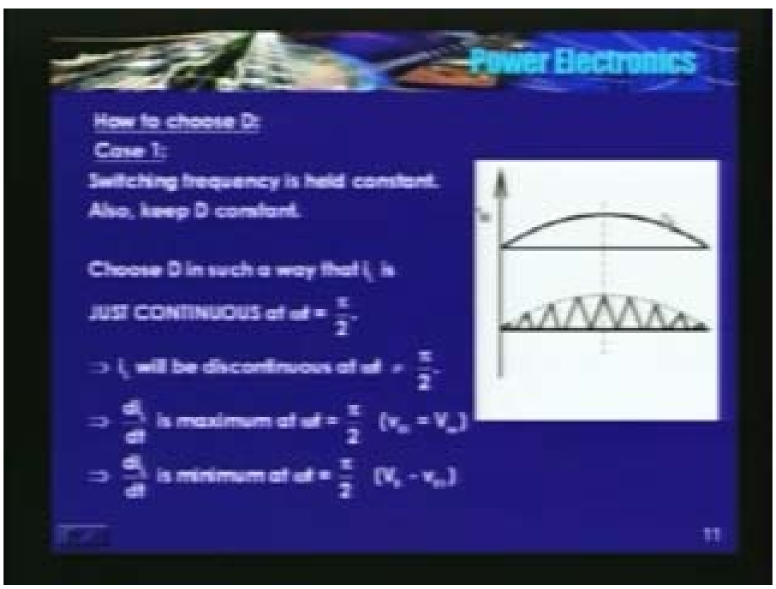

In other words, see, here is V_{01}, the inductor current is just continuous at omega t is equal to pi by 2, in the sense, just prior to closing the switch, current is just touched 0, current increases. At this instant, I am opening those switch, say, after D I have to open the switch. Current falls and it has just touched 0, immediately I am switching the device again.

So, it is just touching the 0 axis. So, I am calling it as just continuous at this point. You will find here, you see, the current has become 0 and for sometime current remains 0. See here, current has 0 and after sometime looks like switch is closed, current increases. So, for finite duration switch is open or sorry for finite duration there is no current flowing through the inductor, whereas here, near the peak current just touches 0.

Why are we doing this? I will make another statement, just listen to me. If the current is just continuous at omega t is equal to pi by 2, it will be definitely discontinuous in the remaining period. If it is just continuous at omega t is equal to pi by 2, there will be durations of 0 current in the remaining periods. This is for sure. Why am I saying this? Now, the V_0, V_{01} varies sinusoidally here.

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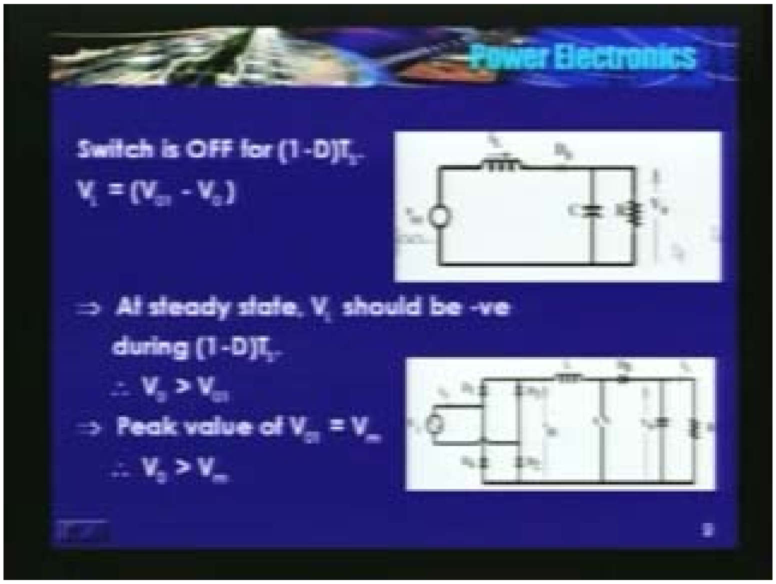

In the circuit if you see, L is constant, duration for which S is closed is also constant so that for the peak value of the current is given by V_{01} divided by L and we assume that switch is closed on and off at a very high frequency and during that period V_{01} will remain constant. Its value is proportional to the instantaneous value of V_{01}. But then V_{01} itself is varying sinusoidally. Therefore, the peak value of the current will follow a sinusoid.

The peak value of the current will follow a sinusoid because switch is closed for a fixed duration, V_{01} is proportional to the peak of sorry V_{01} is proportional to the instantaneous value of the sinusoid. So therefore, the peak value of current is proportional to V_{01} itself. Since, di by dt is proportional to V_{01} when the switch is closed, di by dt is maximum when omega t is equal to pi by 2. di by dt is V_{01} divided by L, so V_{01} is maximum at omega t is equal to pi by 2. When this d negative di by dt is maximum, in the sense, when I close the switch, current reaches, current rises very fastly when omega t is equal to pi by 2.

What happens when I open the switch at omega t is equal to pi by 2? di by dt is minimum when omega t is equal to pi by 2, in the sense, minus di by dt. Why so?

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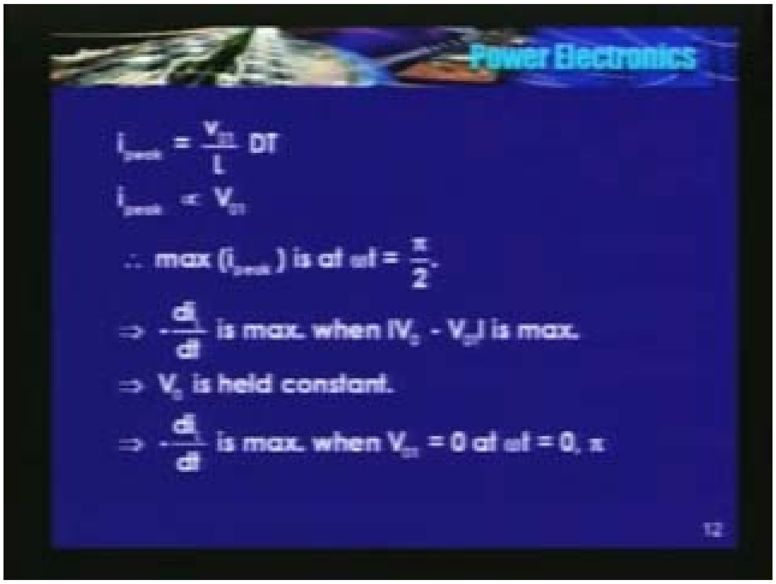

See, this the slide, whatever that I explained just now, i_{peak} is V_{O1} divided by L into dt. i_{peak} is proportional to V_{01}. So, maximum value of i_{peak} is at omega t is equal to pi by 2. di_L by dt is maximum when the magnitude of V_0 minus V_{01} is maximum. So, V_0 minus V_{01} is the voltage appearing across the inductor when the switch is opened. This is the voltage appearing across the inductor when the switch is opened. So, negative di by dt is maximum when this is maximum. V_0 remains constant, whereas, V_{01} is changing. It varies 0 to its peak value. Therefore, di by dt is maximum when V_{01} is 0.

In other words, the rate of decay when the switch is opened is maximum near the 0 crossing because at that time V_{01} is 0 and rate of decay of current when I open the switch is minimum at the peak. At that instant, see, this difference is minimum, V_0 is already constant, V_{01} is equal to V_m at omega t is equal to pi by 2, so therefore, this difference is minimum when omega t is equal to pi by 2. This is the voltage appearing across the inductor when the switch is opened.

So, if this is minimum rate of decay is also very slow or when this is maximum which happens when V_{01} is near the 0 crossing, positive or negative, the same. So, this is maximum when V_{01} is at the 0 crossing. Therefore, the rate of decay is also maximum near the 0 crossing.

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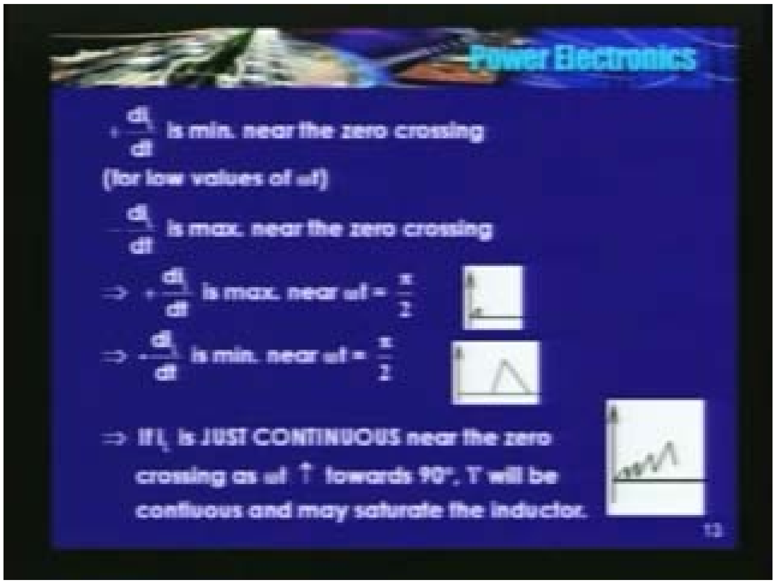

See in this figure, see near the 0 crossing, V_i is or the instantaneous value of V_{01} is very small near the 0 crossing. So therefore, when the switch is closed, the forcing function is very small. So, when I near the 0 crossing, since the forcing function is very small, the rate of rise of current is also low. See here, current near the 0 crossing current increases very slowly, whereas, when omega t is equal to pi by 2, the forcing function is at the peak is equal to V_m. So, current rises very fast.

When I open the switch, the voltage across the inductor is maximum near the 0 crossing. So, therefore, negative di by dt is maximum here. So, current instantaneously current decay is at a much faster rate compared to omega t is equal to pi by 2. So, current rises slowly, decays faster, whereas here, current rises very fast, decays very slow. See here, current increases slowly because forcing function is very small.

V_{01}, instantaneous value of V_{01} near the 0 crossing is very small. Switch is closed for a fixed duration, increases very slowly, dies down very fast because V_0 minus V_{01} is maximum near the 0 crossing, whereas here, rises very fast because forcing function is at the peak, decays very slowly.

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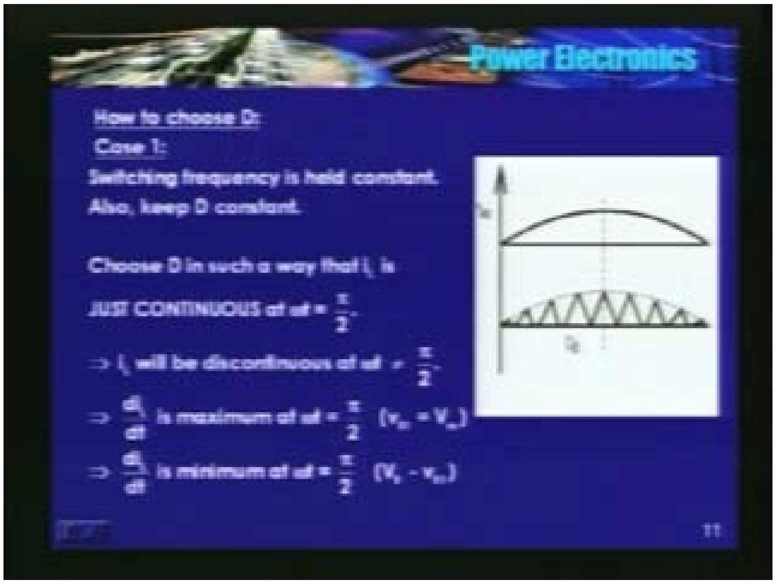

So therefore, what I come back to the statement which I made before is that if the current is just continuous here, current will be definitely discontinuous in the remaining period. Why? Here current rises to a peak value, maximum value of the inductor current is at omega t is equal to pi by 2 and it decays very slowly. It has a maximum value, decays very slowly and I am telling that current is just continuous at this point.

So, what will happen here? A very small current decays much faster. So therefore, if the current is continuous at this point, there will be durations of 0 current in the remaining period. So, if the current is continuous near omega t is equal to pi by 2, it will be definitely discontinuous in other regions because maximum value of current decays slowly but it becomes 0, just touches 0. If that is the case, when the current is minimum and dies down much faster, there has to be a 0 current period before the switch is closed in the next time.

Now, you may ask why not the current being just continuous near the 0 crossing? What will happen if the current is just continuous near the 0 crossing? See, here that means near the 0 crossing it just touched 0 and immediately the switch is closed again.
So, what will happen? I said near the 0, peak value of the current is very small because V instantaneous value of the input voltage is very small. This decays very fast and immediately the switch is closed near the 0 crossing.

Now, what will happen? As V_{01} increases, mind you, from 0 to omega t is equal to pi by 2, V_{01} increases sinusoidally. So, the peak value of current also increases. But then as omega t increases towards pi by 2, it decays very slowly. So, a small value of current, it has just touched 0 here. So, definitely in the second cycle, it will attain a much higher value than this. But then rate of decay is slower here. So, it will not touch 0.

I will repeat, see, I have a very small value of current and it touches 0 here because it decays very fast in the when I switch, when I close the switch, say, for the second time, since V_{01} has increased, this peak has increased. But then rate of decay, it is slower compared to this. Rate of decay is slower compared to this period.

So, when I close the switch for the third time, there will be some current in the inductor, current will not become 0. Now, V_{01} is also increased, peak value further increases but then again dies down at much lesser rate compared to the previous. So, this current increases. So, in other words, you may have a situation, wherein, current goes on building up. See, it was just touched 0 when instantaneous value of input voltage is 0, approximately 0, sorry, a very small current decays fast. It just touches 0 but then the next instant, the peak value is higher and decays slowly. So, it will not become 0 at all.

The third case, it will attain a much higher value, decays very slowly. So, this current will be much higher than this. So, it so happens that it goes on building up and it may saturate the inductor. So, there are very good chance of inductor getting saturated as you go towards omega t is equal to pi by 2. That is the reason, if the current is just continuous at omega t is equal to pi by 2, it will be definitely discontinuous in the remaining period and if the current is just continuous at omega t is equal to 0, near the 0 crossing, it may so happen that current will build up and may saturate the inductor and if the inductors saturates, you may be able to see the smoke coming out from the converter. Why?

If the inductor was saturated, there is no rate of change of current. Current is limited by the internal resistance of the inductor itself which is very small. For all practical purposes, we neglect this resistance. So, the relationship is i is equal to V_{01} divided by small r and the inductor is saturated. But then unfortunately, again, V_{01} is goes on increasing when I approach, when I go towards pi by 2. You may see the smoke coming out from the circuit. So, that is the reason, you choose a value of d if the current is just continuous at omega t is equal to pi by 2.

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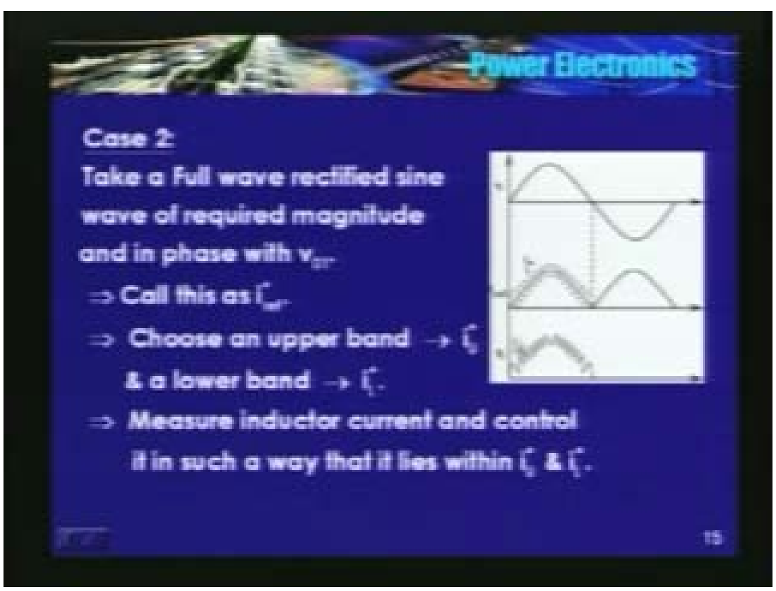

Now, which is the second most common technique? See, here is it. I will take a rectified sine wave, the input or I synthesize the sine rectified sine wave I have whose frequency is same as that of the supply. I will call this rectified sine wave as I_{ref} star or the reference current. I will call this waveform as the reference current. Then I will take a small band, an upper band which is shown in this dotted line which is the i_u star, an upper band and a lower band i_L star.

Now, it is approximately sinusoid, isn't it? If I control the current within the hysteresis band, at any given time if the current is within this hysteresis band, I can say that inductor current is approximately sinusoid. So see, I have controlled the current within the hysteresis band. So, this band is the lower and this may be the upper. It looks approximately, a sinusoid, approximately a sinusoid.

So, what do I need to do? Take a reference sinusoid of desired magnitude. How to choose the magnitude? I will address that issue. Take upper band, i_u and a lower band. Measure the inductor current and control it in such a way that this inductor current always lies in within i upper and i lower. How do I control the inductor current? You know that when I close the switch S, current through the inductor increases and when I open the switch, current through the inductor decreases. So, what I will do is when the current touches the lower band, I will close the switch. Current starts increasing. When the current touches the upper band, I will open the switch, current starts decreasing and I will continue this process.

So therefore, I have a current, I am controlling the current flowing through the inductor. Hence, the name current controlled switch mode rectifier. I have taken a hysteresis band, so this technique is also known as hysteresis current control technique. Current is controlled within the hysteresis band and it looks the inductor current is the rectified sine wave. This inductor current is the same as the source current. See in the circuit, inductor current is same as the source current, whatever the current flowing through the inductor should come from the source.

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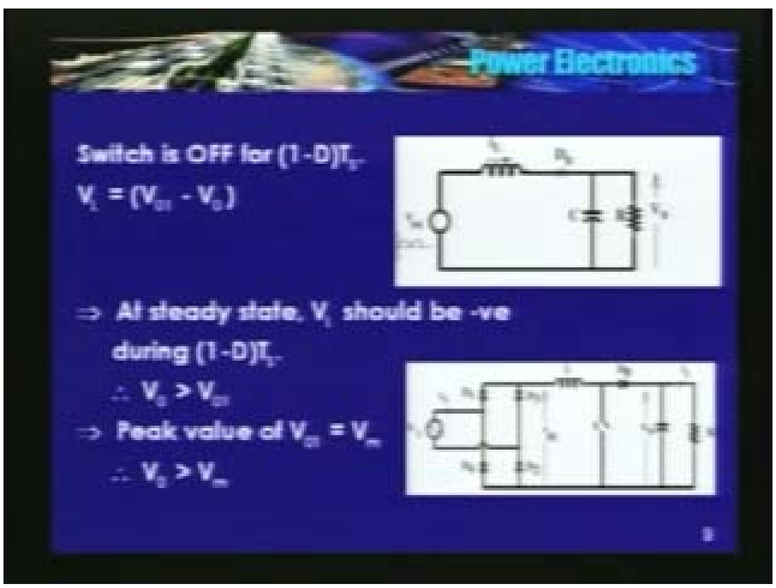

So, if it is a rectified sine, source current is a sinusoid. So, this I_S is in phase with V_i, therefore, displacement factor is unity. Current is a sinusoid, therefore, RMS value is same as the fundamental component. So, the power factor becomes approximately equal to one 1. So, the entire bridge along this resistor load appears like a resistive load to the source. Since, I_S is the sinusoid and is in phase with V_i.

In both the cases, even when I used a duty fixed duty cycle, the peak value of the current follows a sinusoid, even in fixed d strategy. But then it may have a higher frequency components, now these higher frequency components can be filtered using a very small L and C. Now, let me tell you one thing, the frequency of the component that of that are present in the source current are proportional to the switching frequency and the switching frequency is much higher than the input source. So, I require a very small L and C to filter out this higher frequency current. So, source current is approximately a sinusoid and it is in phase with the input voltage.

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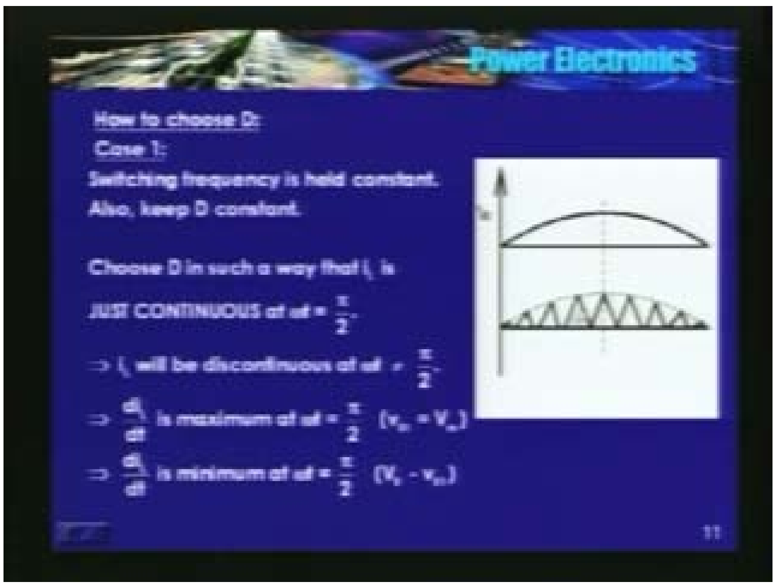

See in this, this is the fundamental component is a sinusoid, may have a higher frequency component, they get filtered out. So, I have almost a sinusoid which is in phase with the input voltage. The power factor is 1. So, the entire unit looks like, as if the source is feeding a resistive load.

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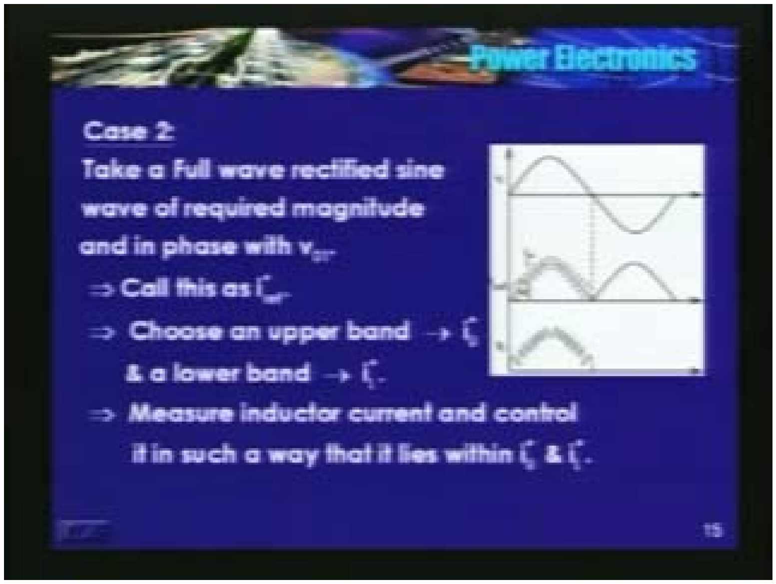

Now, if you see in the circuit, smaller the band better is the source current waveform. Smaller the band, it looks as if the current is a sinusoid itself. Now, this band is very small then the current may look like a sinusoid. But then if I reduce the band, I may have to switch at a much higher frequency because small band, current touch the lower band, I close the switch, current increases, the moment it touches the upper band, I have to open the switch. Since, this band is very small device is switched on, off at a much higher rate.

In other words, the switching frequency depends on height of this band. Smaller the band, higher is the switching frequency. Smaller the band, better is the source current waveform. So, there is a trade off. If you want to have a superior current waveform, switch it at a, reduce this band. But then switch S is switched at a much higher frequency, may be, converter efficiency comes down, temperature may increase.