# Power Electronics

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Lecture - 22

Last lecture we discussed the operation of a switch mode rectifier and a bidirectional power converter. In both this converters, the magnitude of output voltage should be higher than the peak of the input voltage and second point is in the case of SMR with the fixed hysteresis current control, switching frequency is a function of load. Switching frequency varies with the load, whereas, this switching frequency remains constant in the duty cycle control. But then in the current control, inductor current is always continuous. There is always current flowing through the inductor. Current control is within a hysteresis band, whereas, inductor current is discontinuous in the case of fixed duty cycle control.

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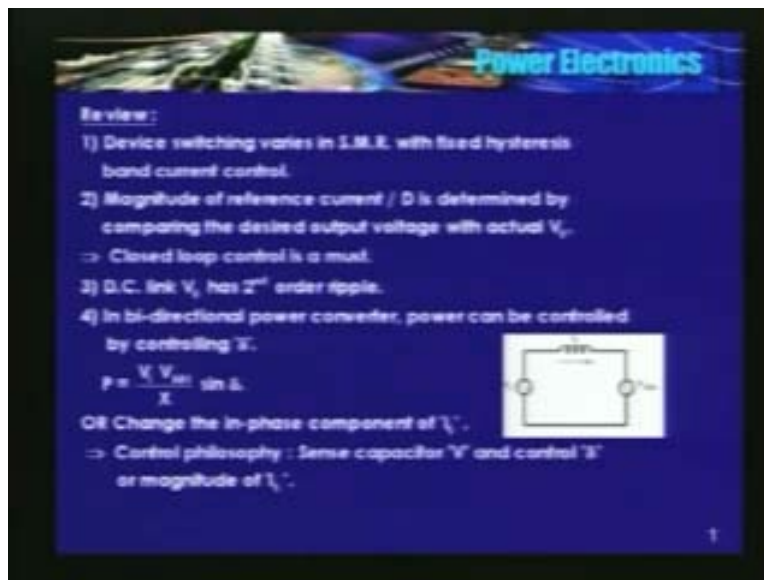
I told you that the magnitude of the reference current or the duty cycle is determined by comparing the actual output voltage with the desired. Basically, what are we doing? We are storing the energy in the inductor and transferring it to the output. So, if there is a power balance, in other words, if the input power is equal to the output power, capacitor voltage will remain constant.

Now, assume that you had connected some load, remember, load is always an independent variable. You can go on changing the load and there is no information about the change in load at the output. In other words, the system is operating in open loop and you have not changed the magnitude of the current or the duty cycle. There is going to be a miss match in the input, output. Now, if it happens that out load has decreased and source input power remains constant,

capacitor voltage goes on building up. So, all the equipments, all the components have their own voltage ratings. So, if the voltage increases above the rated, capacitor may get punctured. The same output voltage appears across the switch as well as the diode, the blocking diode. So, they may get damaged.

Therefore, all this boost converters; SMR or bidirectional power converters, close loop control is a must, remember. Close loop control is a must in SMR as well as boost converters, any boost converters close loop control is a must because input condition, input quantities are derived by measuring the output. So, open loop control is not possible. The other point that we discussed was in a single phase, SMR, even if the source current is sinusoidal, the input power has a pulsating component. Input power pulsates at twice a supply frequency. Therefore, if the power, input power pulsates, capacitor voltage also will pulsate. Therefore, it will have a second harmonic ripple.

So relatively, size of the capacitor is bigger to reduce this ripple. So, second order ripple is invariantly present in a single phase SMR or a bidirectional power converter. What will happen in a 3 phase? We know that if the 3 phase system, if the current is sinusoidal and voltage is also sinusoidal, instantaneous power is always constant, I hope you remember. Instantaneous power in a 3 phase system when both voltage and current are sinusoidal, power is constant. So, if the input power is constant, capacitor voltage will remain constant. So, there is no lower order harmonic.

In other words, 6F, minimum ripple in a 3 phase is 6F is not there because power is constant. So, I need to have a very small filter in the case of 3 phase to eliminate high frequency ripple. So, there is no 6 time the supply ripple in the output in the case of a 3 phase SMR with sinusoidal current or 3 phase bidirectional power converter with sinusoidal current, remember.

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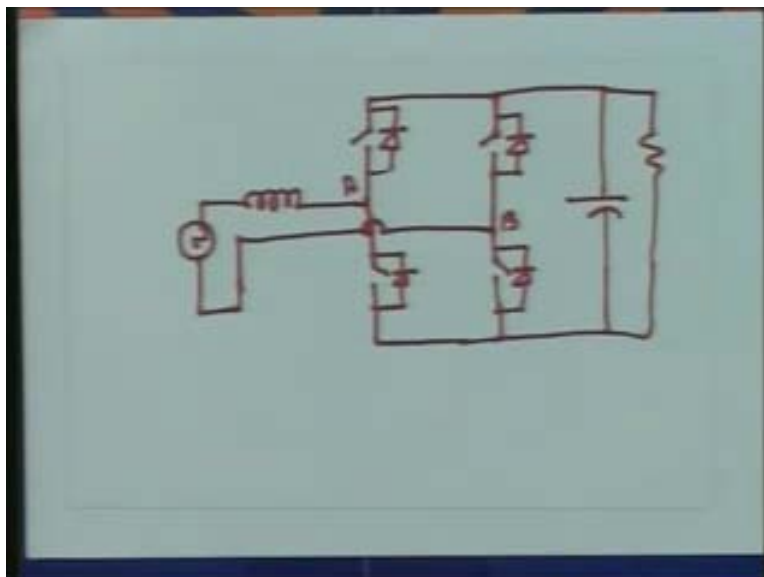
So, we were discussing bidirectional power converter. So, though the source voltage is sinusoidal, input voltage to the bridge is the voltage at the input terminals is non sinusoidal. It is the stepped wave. So, this stepped wave has its own fundamental component.

So, in other words, there is a voltage source here, an inductor, another voltage source. So, 2 voltage sources are 2 AC voltage sources are connected through an inductor. Therefore, power transferred can be controlled by controlling delta where delta is angle between these 2 voltage sources. So, one way to control power is by the controlling the angle between these 2 voltages or by varying the in phase component of the source current. After all power transport is V_1 V_{AB} X divided by X into sin delta or Vi into i into cos theta where i cos theta is angle between V and i. So, by changing the in phase component of the source current, you can change control the power transfer to the bridge.

So, control philosophy here is sense the capacitor voltage that has to be controlled and if it remains constant, there is a balance of input and output power. So, if it changes, either change delta or the magnitude of in phase component that is the philosophy.

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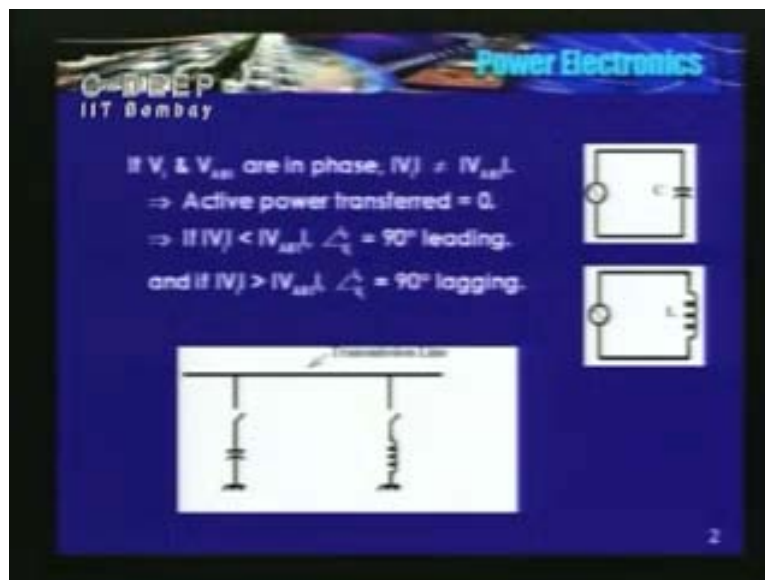
But then if these 2 voltage source are in phase and magnitudes are not the same, power transfer is 0. In other words, this can happen only when if I neglect the total losses. This can happen, remember, if both the voltage sources are in phase and magnitudes are not the same, in that case, power transferred from the source to the inverter system is 0. This can happen only when inverter is lossless and at the output, capacitor, it is not supplying any load. In other words, the output terminals of the bridge, there is only a capacitor. There is no resistor. All this time, I connected a resistor there and I also told you that this resistor is not a must. This may be an input stage for other power electronic equipments.

So, if this both the voltages are in phase and if the magnitudes are not the same, power transfer is 0 and the system can work only if this inverter is lossless which I can, may be, fairly a good

assumptions for the simple reason that losses in a inverters are very small, efficiency is fairly high and at the output there is only a capacitor, there are no lossy elements.

Now, since voltages at 2 voltages at the 2 terminals of the inductor are not the same, current has to flow and we found that if the magnitude of the voltage at the input terminals of the bridge, in other words, V_{AB}, V_{AB1} is higher than V_i, angle between the input voltage, input source voltage V_i and the source current is 90 degrees leading.

So, this is equivalent to a source and a capacitor connecting a capacitor. Entire system; the inverter along with the inductor looks as if there is a capacitor and if V_i is greater than the voltage at the input terminals of the bridge that is V_{AB1} is a fundamental component, then we found that angle between V_i and the source current is 90 degrees, current lags the voltage. So, this is equivalent to a source and purely an inductor. The entire system, we connected a series inductor, 4 switches, capacitor, only capacitor, looks as if there is a L here. So, just by controlling the magnitude of the voltage at the input terminals of the bridge, as of now, I am calling these are the input terminals of the bridge, the V_{AB}, I can make the entire system to appear like either like a capacitor or like an inductor.

By the way, I have not told you how to control the magnitude of this V_{AB1}. I am not going to tell you right now, sometime later in the course, I will come back and I will tell you because right now if I try to explain, you may get confused. Later in the course, I will tell you how to control the voltage magnitude of V_{AB1}. Take it from me. It is possible because the essential condition here is magnitude of capacitor voltage is should be much higher than the input source voltage. If that is a case, I can have a higher or lower component at the input terminals of the bridge. It is possible. I am not going to tell you right now, some time later in the course, I will tell you.

Where will I use this system - a bridge, an inductor and at the output side just a capacitor, where will I use? Because, if they were, if the both the voltages are in phase under ideal condition, it is either a capacitor or inductor. In non ideal condition, what will happen? Losses are very small, so what do I need to do? Instead of these 2 voltages having in phase, I need to have a very small angle, delta or a small in phase component of the source current.

I will repeat; under non ideal condition, inverter losses are, inverter switching losses are finite. Then I have a non ideal inductor also, I have a non ideal inductor, this is a non ideal inductor, losses are finite, but then they are very small.

So, what do I need to do? The angle between input voltage and voltage at these 2 terminals, delta should be very small, may approach del 0 or I need to have a small in phase component of the source current. V_i into I_s cos 5 should be equal to the power that is dissipated in the internal resistance of the inductor and the losses. Under that condition, of course, we should not have this resistor.

Now, where will I use this system? This entire system, where will I use? Now, I will just divert and take back to power transmission. We know that most of the loads are inductive in nature. So therefore, we need to have, if the load is, if you are a bulk consumer, your power factor cannot follow a certain value. If it falls below a certain value, power tariff is going to change, plus, if the

power factor deteriorates, there is going to be a voltage drop at the load terminals. Generation is usually at a constant voltage, so, for a given power if the power factor deteriorates, the magnitude of the source current increases. PE same, power factor angle increases, cos pi decreases. So therefore, i has to increase, so there is going to be a line drop. Voltage at the low terminals decreases. All this factors, you have studied in a circuit course.

So, what do we do? General practice is to have a capacitor at the load terminal to improve the power factor. You connect the capacitor at the load terminals to improve the power factor or in other words, may be, voltage support are supplying the reactive power to the load and I do not know whether you have encountered this situation or not when this when the transmission line is lightly loaded, voltage at the far end of the transmission line may be higher than higher than the input voltage, the so called ferranti effect.

Now, at that time I need to connect an inductor in parallel, just to bring down these voltages. So, in power factor improvement there may be a cases where you have to connect a capacitor across the load or in a transmission line, you may have to connect an inductor when the system is lightly loaded in order to bring down the over voltages. So, can I have or can I implement these 2 schemes using the bridge that I showed you just now and I told you that this bridge can either work as a capacitor or it can work as an inductor. In principle, you can use this.

I will just give you an example to how to use this as a capacitor or how to use this to improve the power factor.

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See consider a case, source supplying a load here. If it is a passive RL load, fine, current is just lagging. Now, if I have a non linear load, assume that this load is nothing but a SCR bridge feeding some other load, a DC motor or whatever, in other words, some non linear load. The moment, this is a non linear load, this current is lagging. I told you that if there is a SCR bridge, power factor is a function of alpha and if I had assumed the source current to be constant and

==ripple free, sorry, load current is constant and ripple free== then source current is going to be a square wave.

In a single phase case, predominant harmonic is third, fifth, seventh and in a 3 phase case, it is 6 and plus or minus 1, fifth, seventh, eleventh, thirteenth and I also told you that ==there is going to be,== there are various standards, wherein, you cannot pollute the voltage at the point of common coupling, point of PCC because if you start drawing a non sinusoidal current because of the line inductance, voltage at the load terminals or voltage where the other loads are connected is going to be a non sinusoidal, recall. I have explained all these.

So now, load is a non linear that is determined by the nature of your system. So, it will draw a harmonic current that should not flow into the system and pollute your voltage at the point of common coupling. So, what will I do? Now, I will connect a bridge, a capacitor and inductor, whatever the system that I discussed just now, across the load. Now, if I make voltage at this terminals higher than this, ==this can supply, this is a appear==, this system appears as if like an entire system, this entire system appears like a capacitor. If voltage at this terminal is less than voltage at this terminal, this entire system appears like a capacitor.

In other words, I am connecting a capacitor across the load. ==So, by connecting a capacitor== we know that by connecting a capacitor, it can supply, it can compensate the load. So, I will control now, the source current, IP which is sinusoidal and in phase with the input voltage. I said load is non sinusoidal, load current is non sinusoidal and it is lagging. I am connecting this unit which appears like a capacitor, now a capacitor can supply the lagging component of current to the load. So, if I choose this value of the quadrature component of current, the source will supply just the active component. But I have also told that in addition to the quadrature component of current there are harmonics present in the load current. This harmonics source should not supply or this harmonic should not flow back to the source.

So, I should have some sort of a harmonic generator which generates harmonics in the opposite sense. ==If the source==, if the load has a third harmonic current of magnitude X, I need to have a harmonic generator. We should generate third harmonic whose magnitude is minus X. So, this unit should not only supply the quadrature component of current, it also should supply whatever the harmonics that are present in the load current. So, this load is a non linear load, has a lagging component as well as harmonic current. Source should supply only the active component of current, this bridge should supply the harmonics as well as the quadrature component of current. Is it possible? In principle, yes, it is possible. There are systems like this, I will just explain you very briefly the principle of operations.

In SMR, in a current control, what did we do? We controlled the source current in such a way that it is in phase with the source voltage and it is sinusoidal. I will repeat; in SMR with current control, we controlled the source current with a hysteresis band. Therefore, it looks like a sinusoidal and it is in phase with the input voltage. In other words, in this scheme, source supplies only the active power. I may say that it is not a pure sinusoidal, agreed. But then if the hysteresis band is very small, the frequency of the harmonic that is present is also is very high and they can be easily filtered out, a very small filter that is not a problem or they may eventually get filtered out by the line inductance itself.

So, if I make or if I control the source current, even in this case which is sinusoidal and in phase with the input voltage, source is as if it is feeding a purely a resistive load. Whether the load is lagging or whether there are harmonics in the load current, it does not matter to the source. I will repeat; if you make the source current a sinusoid and in phase with the input voltage V_i then source is as if to the entire system, load with whatever the compensate that I was talking, as if it is feeding to a resistive load. It is feeding just a resistive load but actual load is may be, a lagging load or it can have lagging as well as the harmonic load, does not matter.

Who supplies this harmonics? At any given point, KVL has to hold good. At any given point, KVL and KCL, has to they have to hold good. Kirchhoff's current law and voltage law, they have to hold good whether you are doing power electronics or whether you are doing some other electronics, does not matter. So, if I apply KCL at this node, I_P plus J into whatever current, I will not call it as quadrature component now, I will not call it as a quadrature component. Some I_C, I_P plus I_C should be equal to I_L. So, if I told you that source current and voltage are in phase, this I_L has the reactive component as well as the harmonics. So, the reactive component and the all the other harmonics should come from the compensator.

So, if the load is non linear and if I use this system and control the source current in such a way that the current supplied with the source is in phase with the input voltage, all the remaining things including the reactive power is being supplied by the compensator. Now, how do I control this I_P? by switching these devices. Very simple, control I_P by switching these devices such a way that this current is in phase with the input voltage.

So, whether source has harmonic or reactive power, it does not matter. Everything is being compensated by this, hence the name, VAR compensator. It supplies VARs to the load as well as it is filtering or as well as it is supplying all the harmonics that are present in the load. In other words, it is an active filter not a passive filter. Why active? As the load current changes harmonics also may change. Harmonics also may change or the harmonic will change but the source current is just applying the active component of current.

So, as the load changes, as this output condition change, compensator has to change the current that is being supplied by it. I am not calling this as a JI_Q. Now, it can it will supply JI_Q only if a quadrature component of current, only if the load is passive and linear, no harmonics. If it has harmonics, the load has harmonics, compensator should supply the quadrature component of current as well as the harmonic current. So, this unit is known as VAR compensator and active power filter. There are lot of literature is available in the papers. I encourage you to read in the library. I will stop here and go to another topic.

In the previous case, for the same bridge, what do you do in the positive half? We closed S_4 only, we closed S_4 only.

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So, current flowing from A, S_4, D_2, back to source and in the negative half we closed only S_2. The current was flowing S_2, D_4, back to source. So, we wrote the Kirchhoff's voltage equation when I close the switch, di by dt is V_i divided by L and V_i is the instantaneous value of the input voltage. But then instantaneous value of the input voltage itself is changing and near the 0 crossing, V_i is very small. Near the 0 crossing, positive or negative both <mark>...</mark> theta, sine function is 0. So, forcing function itself is 0.

Since, the forcing function is itself is 0, there is an inductor connected in series, rate of rise of current is going to be very small. So in other words, it may not be possible to control the current within a hysteresis band or in the fixed duty cycle there will be a very small current, most of the time you have a discontinued period. Remember, we fixed the duty cycle in such a way that current is just continuous near pi by 2. So, most the cases, most of the periods, the remaining period, current is discontinuous and the periods for which the source current is 0, increases as you go towards 0 or 180. At pi by 2, it is just continuous, as you go towards other direction 0 or 180, <mark>0 voltage</mark> 0 current period goes on increasing.

So, near the 0 crossing, if it is in duty cycle, most of the times it is 0. It is discontinues period and if it is a hysteresis control, may not be able to force the current or most of the times you have to close the <mark>...</mark> So, you may have hysteresis control something like this. It may not be able to control, force the current but then the bridge has 4 switches. We have not told you anything about the upper S_1 and S_3 because when I close, I close either S_4 or S_2 and I just open S_4 S_2, current was flowing through the diodes.

Now, the question is can I close these switches or can I use these switches and try to overcome this problem, the problem of making a current sinusoidal even <mark>during the</mark> near the 0 crossing? Yes, it is possible. Now, instead of closing S_4 only in the positive half, you close S_4 as well as S_3 in the positive half. You close both S_4 and S_3. How does the equivalent circuit look like?

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See here, I close both S_4, S_3, current is flowing positive half, flowing in this direction. This through the capacitor, negative, positive, once like this, flows in this fashion in S_3, back to source. See, I will just show you S_3 is in this direction, so when I if I close this 3, current will flow this way.

So, what does the KVL says? It is di by dt now, Ldi by dt is V_i. This is plus, this is aiding, this 2 voltage sources are aiding now, V_i plus V_0 divided by L. V_i plus V_0 divided by L. So, even if V_i is very low, V_0, I told you, generally it is held constant. So, rate of rise is higher now. So, even near the 0 crossing, I can have a fairly high dr by dt. Now, you may say that sir, V_i will attain a peak value, at that time, what will happen? Yes, rate of change is much faster. So, switching frequency will increase.

So, that is what, whatever you do in life, you have to pay a price, nothing comes for free. So, if you want to improve the source current wave form, use 2 switches, use the capacitor voltage to aid the source current di by dt, current wave form becomes superior. But then switching frequency increases because now, di by dt positive di by dt is V_i plus V_0 divided by L. V_0 is held constant and magnitude of V_0 is much higher than the peak of V_i. So, if V_i is low, things are not all the but, but V_i can attain V_i, will attain its peak value. So, di by dt is is higher than 2 V_m by L because V_0 is much higher than V_m.

So, di by dt is much faster as V_m increases. So, we do have a problem. Switching frequency will increase but then current wave form is superior, can have fairly a good current wave form. By switching, closing S_4 and S_3 in the positive half, switching frequency increases, current wave form improves.

What happens to the voltage at the input terminals of the bridge that is V_{AB}? Will it remain the same? Wave form will remain the same or it is different? It has to be different, let us see. When I close only S_4, V_{AB} has 0 because current started flowing S_4, D_2, back to source. So, voltage at

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these 2 points is 0, isn't it, when S_4 is closed. There is a short here, diode is conducting, so V_{AB} is 0. Now, when I am closing S_4 and S_3, point A is connected to the negative polarity of the capacitor voltage at this point. V is this, it is connected here, so V_{AB} is minus V_0. In the first case it is 0, in this case it is minus V_0 and when I open the switch, what happens? Current starts flowing through the same D_1 and D_2 in the positive half and V_{AB} is V_0.

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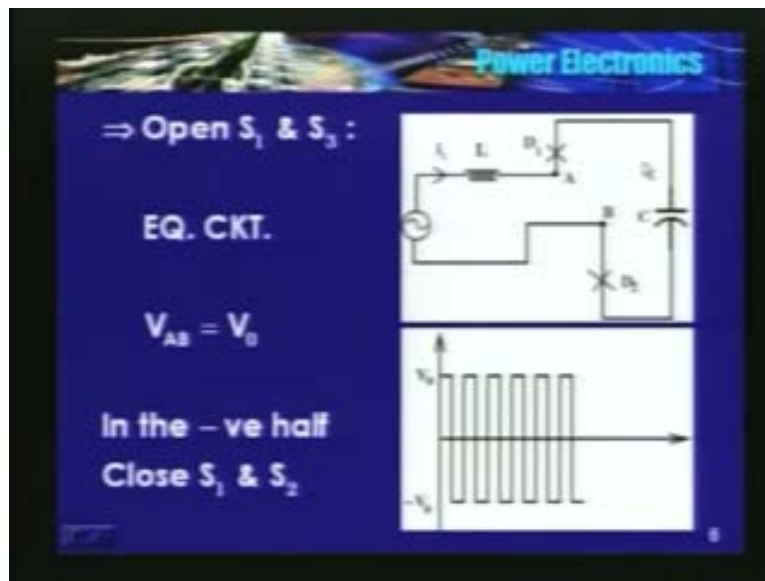
So, voltage wave form now varies from V_0 to minus V_0. See the transition, it is quite fast, minus V_0 to V_0 at this terminals. This is the change in the voltage wave form.

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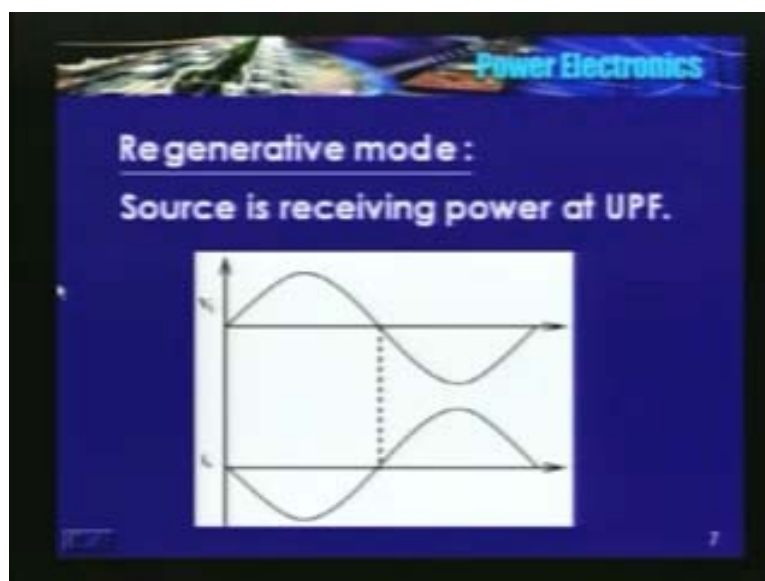
Now, all this time we studied about source supplying power, only active power. If the current angle between the source current and the voltage is 0, source is a purely resistive load. If in a bidirectional power converter, if the source voltage and the voltage at the input terminals of the bridge that is V_{AB}, they are in phase under ideal condition and magnitudes are different, source is either an ideal capacitor or an ideal inductor. I called in the beginning, it is a bidirectional power transfer.

Can I transfer the power back to the source at unity power factor? There are 4 switches, I told you that. Now, current can reverse, I have bidirectional switches but I have connected, since I connected capacitor at the output, voltage cannot reverse. So, in other words, if I connect a battery here, now you have to remove this resistor.

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I need to have an active load. Only active load will supply the power back to the source. So, if I have a battery here, battery can supply power back to the source. Current can flow through these switches back to the source. No, R here, resistor cannot supply the power. It can just dissipate it or any other system, if I have a capacitor and continuously power is being coming from this side, it can flow back to the source and that too at unity power factor. What should I do it?

See in this, at unity power factor, it receives, it supplies angle between them is 0, it receives, at unity power factor, angle between them is 180. I take the current which is out of phase with the input voltage, control the switches such that this current is within the hysteresis band because there are other control techniques also, is not you cannot you can make the source current out of phase by 180 degrees you can using other techniques also. Simple control technique is using current control, is out of phase with the voltage by 180 degrees, control it within hysteresis band by turning on and off these switches, simple.

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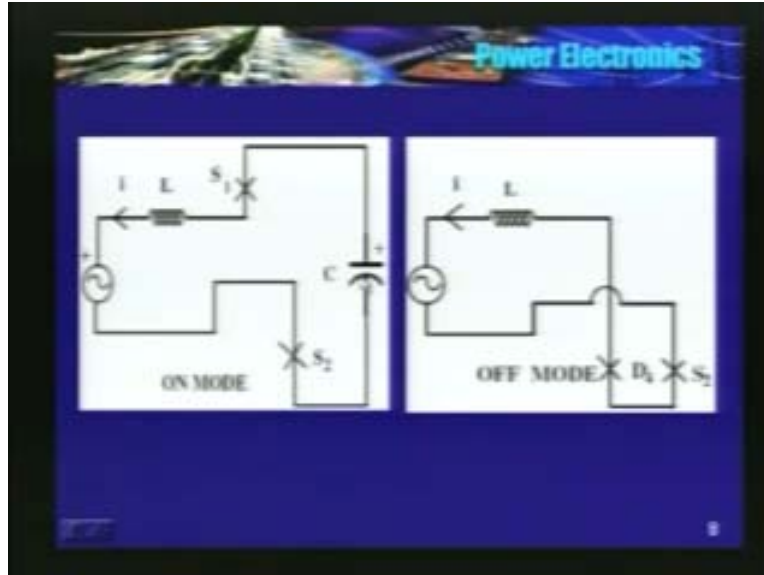
So, it is like this, close S_1S_2. What will happen? C or in this case, I am assuming, I have connected a C assuming that power is capacitor is continuously charged by other source, other source that is connected at these 2 terminals or I need to have a battery here. So, assuming that power is being coming from these 2 terminals, it can flow back to the source this way. Same philosophy, I will if I keep the voltage, if a capacitor voltage remains constant, there has to be a power balance and voltage and current are out of phase by 180 degrees, source receives power at unity power factor. So, those that power has to come from other source which is connected to these 2 terminals. Or if I have a battery, battery supplying power and this voltage is higher than this, conditions remain the same.

Open S, what will happen? Current this direction of current should remain the same. So, it starts flowing through D_4. So, this is the path. So, this converter can act like a bidirectional power converter, source can receive, even at, source power at unity power factor. So, almost all the possible functions are possible, we are almost through.

In other words, we have completed AC to DC conversion, a major part in power electronics course. I have those, we can have more than 1 course in AC to DC conversion. I try to cover in around 12 to 13 lectures, just to try, to give just an overview. I started with half wave rectification then we did half controlled, we did fully controlled bridge, both single and 3 phase, we found that power factor and harmonic spectrum, they both are poor, in half wave there is a DC component also, if the bridge is excited by a single phase supply, there is only 1 pulse per half a cycle, the ripple in the output voltage, there are only 2 pulses per 180 360 degrees or 1 pulse in half a cycle.

In a single phase case, ripple frequency is twice the supply frequency, whereas, 6 pulses in 3 phase bridge, so ripple frequency is 6 times the supply frequency. So, something like this.

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I hope you remember, for alpha is equal to 0, a 3 phase uncontrolled bridge. This is for alpha is equal to 0 for a single phase bridge. So, if I want to have a constant DC, I need to have a very small capacitor here because this voltage approximately constant. This is root 3 times, this is 1.5 times, approximately comes 1.5 to 1.713, whereas, this varies from 0 to V_m and I want a constant value. So definitely, filtering in this case is minimum, is much more than this.

So, what did we study after that? In the sense, as the number of pulses in the output voltage wave form or as the number of pulses in the source current increases, harmonic spectrum increases. Power factor also becomes unity, power factor also improves. So, that is nothing but a PWM converter. How did we control the output voltage in PWM converter? by changing the modulation index. In a sinusoidal PWM technique, there are large number of other PWM techniques and in PWM converter, what happens is magnitude of output voltage is less than or equal to or is less than the input voltage?

Then we studied switched mode rectifier. They are also known as the boost converters. We control the SMR with fixed duty cycle and controlling the inductor current. That is same as the source current also, rectified. Source current is the inductor current, there power factor is unity but then output voltage of switched mode rectifier or the boost converter should be higher than the peak of the input voltage. It is almost an essential condition.

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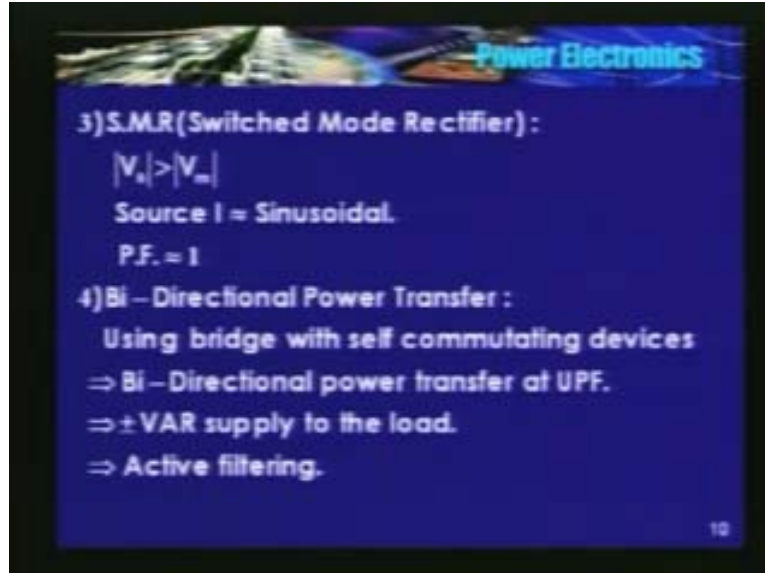
Other essential condition is these converters should be working only under closed loop condition. Closed loop is a must in switch mode rectifier as well as the bidirectional power bridges or if I use this bridge to improve the power factor or if I use this bridge as a VAR compensator or active filter, close loop control is a must. Bidirectional power transfer at unity power factor is possible, plus or minus VAR, leading or lagging VAR supply is also possible, on line correction of harmonics is also possible using a single phase or a 3 phase bridge with self commutating devices, 6 self commutating devices, all these things are possible.

So, we are almost through or completed AC to DC conversion, lot of things are still left. If you have followed whatever that I have covered, you can open any text book or you can open any papers and try to understand that. I just try to give you the principle of operation that remains same for other power topologies also. There are large numbers of topologies in SMR, I just or I just did replace the inductor, you can replace the switches also. I use only 1 switch in the DC link, in the DC side. You can put that device or put that replace that switch or you can transfer it to the AC side, have an inductor and … There are large number of topologies.

So, principle of operation is the same. Close the switch, load the energy, open the switch, transfer it to the output, this is the principle. There is no much difference. There are various control schemes also to control the active filter or to control the VAR compensator, VAR supplier.

Now, we will do another topic, an important topic in power electronics, DC to DC converter. These DC to DC converters, where are they used? These are also known as switched mode power supplies, SMPS - switched mode power supplies. Generally, this terminology used for low power application. The same concept is used in high power, they are known as choppers, they are known as choppers. Chop of a DC machine, an important application. Where it is being used? Have an input DC and I want an output DC. Why output DC? Variable output DC? To

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control the speed of a DC machine, to reduce speed from base to 0 or to increase the speed from 0 to base, I need to increase the voltage applied to the armature.

I have a fixed DC. Do not ask me how did you get this fixed DC? There are various ways, in the sense, one of them may be whatever that I have studied, whatever that we studied in AC to DC conversion or I have a fixed bank of batteries. So, battery's voltage ==is the voltage is voltage== remains constant. Now, I want to have a variable output voltage or take for example, ==in metro DC,== in Calcutta metro, you have 750 volt DC, Bombay to Igatpuri is 1500 volt DC, over head traction and if I want to vary the voltage applied to the armature of a DC motor which is used, I have to control it. So, these all come under high power application. So, they are known as, generally known as chopper fed, we do not say SMPS fed DC motor.

The principle may be the same in both the SMPS input is DC, output is also a variable DC. So, if the power is high, if it is a DC to DC converter is feeding a motor, we will call it as a chopper fed motor, not an SMPS fed motor and take any electronic equipment, say, a power supply in a computer, power supply in a computer or any sophisticated electronic equipment, TV, it requires a DC power supply.

Where am I getting the DC from? Input is AC, I want a controlled power supply regulator, power supply for various ICs. Power level is not very high, few 100 of watts. So, I might have converted the input AC to DC and this DC to another DC, another voltage. They are known as switched mode power supplies. If I use a DC to DC converter in computers or any electronic equipment or for low power supplies, I will call it as SMPS or if I use the scheme where DC to fixed DC and I am trying to get a variable DC, I will call it as a, in high power application, I will call it as a choppers. More about it, we will study in our next class.

Thank you.