Power Electronics

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Lecture No - 8

Four Quadrant Dc to Dc Converter

Last class, we talked about PWM converter using ac to dc converter that is using thyristors and phase control converters. There we required, for turn on and turn off of the thyristor, especially turn off; turn on, we can give gate pulse, to turn off, we have to give forced commutation. So, we will study a very popular forced commutation of thyristor and this forced commutation, we will study in the context of a dc to dc converter that is a chopper. So, let us talk about dc to dc converter. It is a very popular scheme used before by thyristors, for thyristors for commutation.

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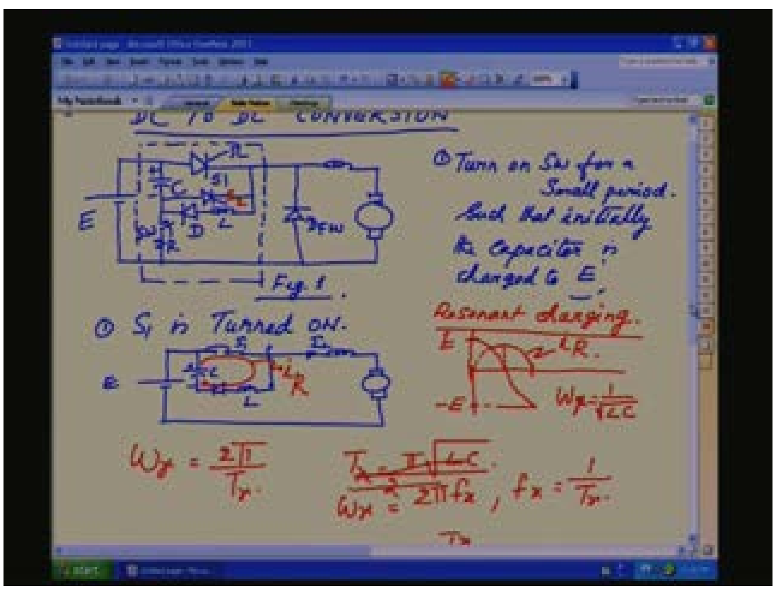

So, dc to dc conversion: here, the circuit, let us say this is our input, let us say this is our battery. Then you have the thyristor, main thyristor to be commutated, this a basic buck converter configuration, this is your freewheeling diode DFW freewheeling, then you have the motor load here. For forced commutation, for turn on this device, we can give a gate pulse here. Thyristor will be turned on. So, this we will talk about switch 1 S_1.

Now, to turn off this thyristor, we will give a reverse bias across the thyristor from a charged capacitor. So, this is the capacitor to give. Initially, this capacitor should be charged, it will be charged through a resistance. This is the switch, then a resistance. So, during turn on of the chopper circuit or dc to dc converter, first thing is you have to turn on this switch S_1 SW such that the capacitor will be charged to input voltage E. Let us say, this is E. So, knowing the R and C, we know the approximate time constant. So, through a monoshot, we can turn on this switch and after that we can switch off it. By the time, capacitor will be charged to this voltage here.

Now, but this is not the voltage we have to apply across the thyristor. For thyristor to turn off, you have to apply or we have to reverse bias that means anode should be negative compared to cathode. That means we have to reverse the capacitor voltage before the thyristor can be turned off. So, there is an auxiliary resonance circuit we will be using here. This is the resonance circuit, it constitute one diode, then L, there is a resonance circuit comes across this one. This diode is given, this LC will act as the resonance circuit such that the diode is given such that once the capacitor charge in the opposite direction due to LC, it should not discharge. So, there is no reverse conduction. To block the reverse conduction, we have given this diode D. So, this capacitor C will be charged. So, L and C will act as the resonance circuit.

Now, there is another auxiliary thyristor is there. This is this one, this we will call as S_2; this is S_1, this is S_2, S_2 we will mark with a different colour so that it is visible, this is S_2. Now, how the chopper works? This is a buck converter that means we can have voltage less than, dc voltage less than the input E voltage, variable voltage. So, this is a dc to converter, buck converter. So, this whole thing will act as the commutation circuit including the switch S_1.

So, as I told, the first thing is one to start on; turn on SW for a small period. This period depends on the time constant RC of the system so that capacitor will be such that the capacitor is charged to E such that initially, the capacitor is charged as shown in figure. Capacitor is charged to E as shown in figure 1. So, let us talk about this is figure 1. Now, capacitor is charged. Now, we are ready for turning on this chopper. So now, you are turning on the chopper. First, this is only the initial charging process.

Now, once the capacitor is charged to E here; the chopper is ready for action. Now, S_1 is turned on, S_1 is turned on. S_1 is turned on; what will happen? Immediately, this E will come across the DF. So, DF is reverse biased and E will come across the load side. This E which is coming across the load depends on when we are the duration, depends on when we are turning off S_1. So, first let us say, we are turning on S_1. So, how the circuit will be? See, the circuit, I will draw here.

We have E here that is E here, thyristor is turned on. So, this we will say, this is a turned on switch. This is off S_1 is on, diode is reversed biased so that will not come into picture, we have this load. Now, there is a capacitor here, charged capacitor in this direction and there is this diode and L. So, moment it is turned on, the load with, load is, we want the load, as a dc circuit, so load because of the high inductance, the load will flow here, I_L dc. But because of this L and C, there is a resonant discharge of C or resonant charge of C in the opposite direction through which path the L and C. So, we will mark that one with a different colour so that it will be visible. So, apart from the load, there is a resonant current here. This resonant current, we will mark it as I_R.

So, how long it will… because of the LC resonance, this capacitor will charge in the opposite direction. So, how the waveform will be? So, the resonant charging, the capacitor with the whole voltage and camp waveform will look like this. So, the capacitor, initially charged to E here; with resonant charging, it will go like this and come to minus E here, it is a part of a sinusoidal that is it will charge in the opposite direction. So, what will happen to the current? Current if you see here that is I_R current. It will slowly increase, at this point, current is maximum, so di by dt is minimum. Then it will go like this, this is our I_R. The moment the current is 0; assuming ideal LC circuit, the capacitor will charge to the minus V here. So, this is our I_R. Once the capacitor is charged, the other direction; this capacitor is ready for commutation of S_1 at any time.

Now, this capacitor can whenever the turn on this S_2 here, whenever turn on this S_2; now the capacitor is charged in the opposite direction, it will apply a reverse voltage across the thyristor and thyristor will switch off immediately. Now, this period, we should note this one, this is the resonant half period, this resonant half period if you see what the period; the omega r, the resonant frequency omega r is equal to 1 by this standard circuit, 1 by root LC, 1 by root LC.

Now, this is the omega r; so what is a period, half resonant period? Omega r is equal to omega r is equal to if T_r is the half resonant period, it will be 2 pi by T_r, this is the half resonant period. So, 2 pi by omega r, so T_r will be equal to we can find out pi into root LC because we know it is omega r is equal to omega r is equal to 2 pi into F_r and F_r is equal to 1 by T_r. Now, why this period is very important? So, during the turn on process, this period half T_r, we are using for resonant charging of the capacitor in the opposite direction. So, what it means? This means sorry this is T_r is equal to 2 pi, T_r is equal to sorry I will again mark this one; T_r is equal to here, T_r is equal to T_r is equal to 2 pi into root LC, this is the one.

Now, this is very important so this much period, we require for capacitor to resonant charging. So, once the capacitor is ready for commutation that means capacitor is charging the opposite direction, then only it will be ready for commutation, commutating the main thyristor S_1that is this S_1 here, here is the S_1, this S_1. Now, so this period, resonant period is as small as possible. How much small? That we will come to that one later for designing L and C; so, assuming the capacitor is charged now, it is ready for commutation.

Now, let us take the condition when we turn on S_2 that means we are ready for the commutation and now we are turning on S_2 to turn off S_1. So, let us go to the next page. Here, what will happen? S_1 is turned on immediately. So, let us draw the circuit during commutation.

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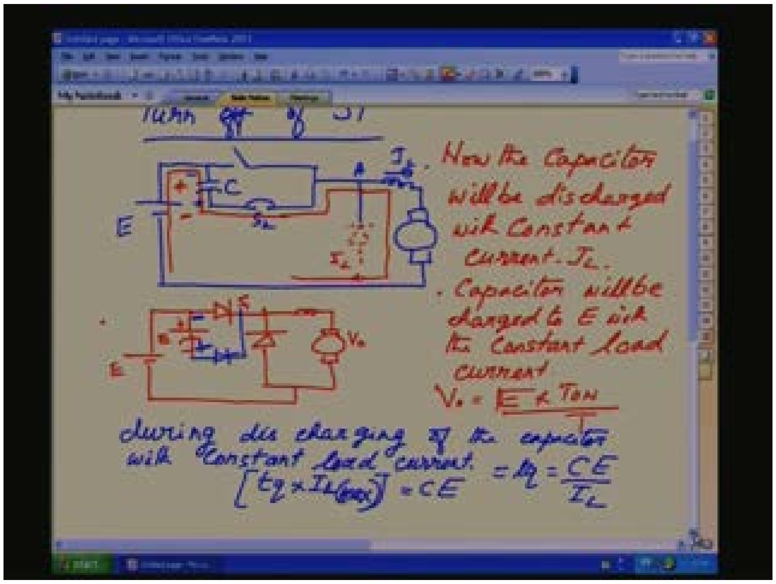

Now, turn off period that is turn off of S_1 that is a main thyristor. Now, how the circuit looks? We have E here, S_1 is turned on when S_2 is turned on. So, the capacitor, the condition immediately S_1 is turned on, it will look like this. Capacitor is in this direction charged; now S_2 is turned on. So, S_2 turned on, we will make it like this, the circuit is like this. We have the diode, see diode is not yet turned on. Why? when S_1 is turned on, the capacitor voltage C that is also equal to E, the capacitor voltage, the capacitor C, the voltage across the capacitor is E. Then E, this 2 E will come here at this point, let us say this is A, at this A point and diode is reverse biased, diode will not conduct now.

So, still load is highly inductive and load should get the full dc current. So, current cannot changes in this inductance. So still, this dc I_L will flow that means this I_L will come through C_1 S_2 and through L and go to the load. So, the current path, we will mark now. The current path is like this and returns; this is our I_L dc current. So, what it means is the capacitor will slowly discharged, capacitor will be charged by a constant current I_L or the capacitor will discharge, discharge and then charge in the opposite direction.

Now, the capacitor will be discharged with a constant current equal to I_L, discharged with a constant current, current that depends on the load that is I_L. So, capacitor will slowly discharge and again see, till the diode is turned on, load cannot free freewheel. Once the load freewheels, the commutation circuit is totally isolated. So, for the diode to be this diode to be forward biased, this capacitor should charge in the opposite direction that is in this direction to E through using I_L.

So, when it becomes E, it will oppose the input voltage E and any slight overcharge, diode will be forward biased due to the capacitor. Then the diode will discharge. So, what will happen? Here, now the capacitor will be discharged with constant current I_L, then after that capacitor is discharged, again capacitor is charged to capacitor will be charged to E; capacitor will be charged to E with the constant load current. So, then what happens? Once the capacitor charged to this point that is this, this way, it will oppose E and the diode assuming very small difference voltage, diode forward bios very small voltage only required; so diode will turn on and the load will freewheel, load will freewheel through this path. Now, the commutation is completed.

What happens to the capacitor voltage at this point? Capacitor voltage again, it charges in the opposite direction. Now, you do not require the initial original that turn on circuit to charge the capacitor that is this switch SW and R is not required to turn on the capacitor. Now, the capacitor itself will take care of the thing. How? If you see here, because of this load current; now, how the capacitor condition will be? So, diode is this is switched off, this is S_1 here, capacitor is charged to in the opposite direction E, then you have the E here, this is E, this is also E. So, this is the circuit, it is ready. Capacitor is charged and again as when S_1 is turned on, it will through resonance charging, it will charge in the opposite direction and is ready for commutation.

Now, what is more important thing is how to find out this L and C so that the resonant charging period is as small as possible compared to the T_{on} time of the S_1. Why? The output voltage depends on V_0; from the buck converter, we know. V_0 is equal to input E into T_{on} divide by the total period T. So, this is the way. So, this T_{on} for a variable voltage, the output voltage depends on the T_{on}. So, the minimum duty cycle, so our resonant, half resonant period T_r should be much much less than the minimum T_{on} period; so one condition.

So, one condition only there, now we have two values to find out L and C. So, two conditions are required. So, how to find out the C? Let us start with, the C, we have introduced the C in the circuit so that we can give a voltage, a force. We can force a voltage across the thyristor to switch off that is forced commutation and we assume during the previous analysis that the S_1, switch S_1 will commutate, switch out immediately. But in all, on all practical circuit, in all practical circuit, the thyristor will take some finite turn on time turn off time. So, this we can find out from the datasheet. So, that means any thyristor will have a minimum t_{off} time. So, during the full t_{off} period, till the thyristor is turned off that is during the full t_{off} period, we have to apply the reverse voltage across the thyristor C. So, from this circuit when T_1 is turned on, the voltage across the C was this one, plus and minus here.

Now, due to the resonant charging, it will come to the negative voltage here. With resonant charging, this negative voltage will come here. Now, when S_2 is turned on when S_2 is turned on, this negative voltage which is marked with blue colour will come across the thyristor and the thyristor will discharge due to the load current. So, this diode S_1 will be reverse biased till this diode, till this thyristor discharge from, it will come from E to 0 through the constant dc current. So, this much time, we will be reverse biasing the thyristor. So, for a circuit, the load current can vary. So, if the load current is maximum, high; the capacitor discharge will be fast.

So, for a maximum load current also, the discharge time should be more than the T_{off} minimum of the thyristor. That means during discharging of the capacitor, during discharging of the capacitor, capacitor with constant load current; the discharge period that means it is completely discharged to zero period that should be more than the T_{off} minimum of the thyristor. So, it will be capacitor is assuming, this is the discharge period; let us take the discharge period is equal to t_q.

So, t_q into I load maximum that is for any circuit; what is the maximum I load current? This is the total charge; this will be equal to C into E. So, I will say this is the I load maximum current that depends on the load. So, this is the equation. From this one, the t_q, the time required for the capacitor discharge fully from E to zero voltage is equal to t_q is equal to CE, CE divide by I_L, CE divide by I_L. So, from this one and the t_q, t_q should be more than the T_{off} minimum; so from that one, let us go to the next page so that we can make it clear.

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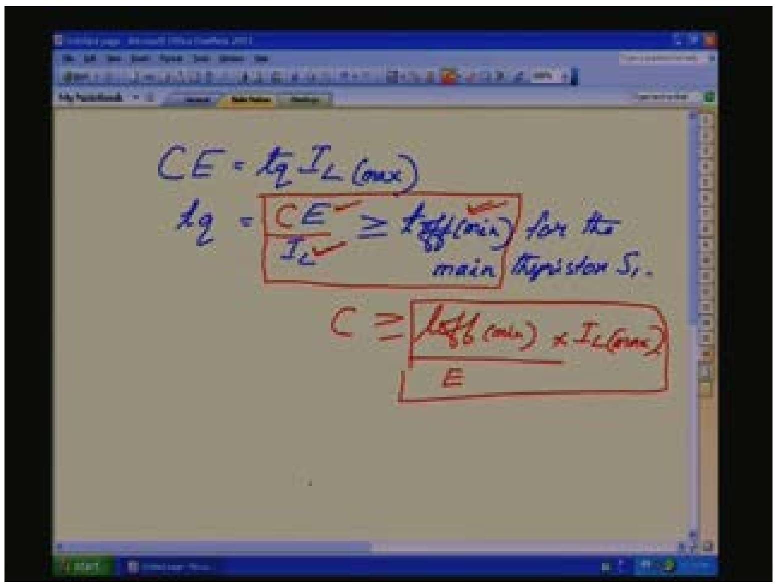

So, from the CE, CE is equal to t_q, the discharge period t_q into I_L maximum, maximum load current. Load current can vary; we know the circuit, we know the load, maximum, we know load, current should be known. So, for the maximum current, this t_q, t_q should be; what is t_q? t_q is equal to CE divided by I_L. This t_q should be greater than or equal? So, greater: how much greater? That depends on your design. You have to go back and forth and decide; 10% more of the t_q minimum, so depending on your design.

So, there is not; here, we cannot say, exactly this one. This depends on the designer's capability how to give a cause effective solution but this is the approach. So, it should be greater than T_{off} minimum, T_{off} minimum that will be specified in the datasheet; T_{off} minimum for the main thyristor, for the main thyristor S_1. From this equation, we can find out t_q, this is C. So, from this equation, we can find out, from this, E is known, I_L is known, T_{off} minimum is known; from this equation, we can find out C. How? From this inequality, C will be greater than or equal to T_{off} greater than or equal to T_{off} minimum, there is a thyristor turn off time divided by E into I_L load, I load maximum.

So, first you compute this value and the value C chosen should be greater than this value, this will ensure your commutation. Now, there is another thing. Capacitor we have found out, there is one more component, L we have to find out. So, how we will find out L? Let us go back to our original circuit again. Let us go to the next page. See, during turn on, the moment S_1 is turned on, the load current will flow, also the resonant current will be flowing through the main switch S_1.

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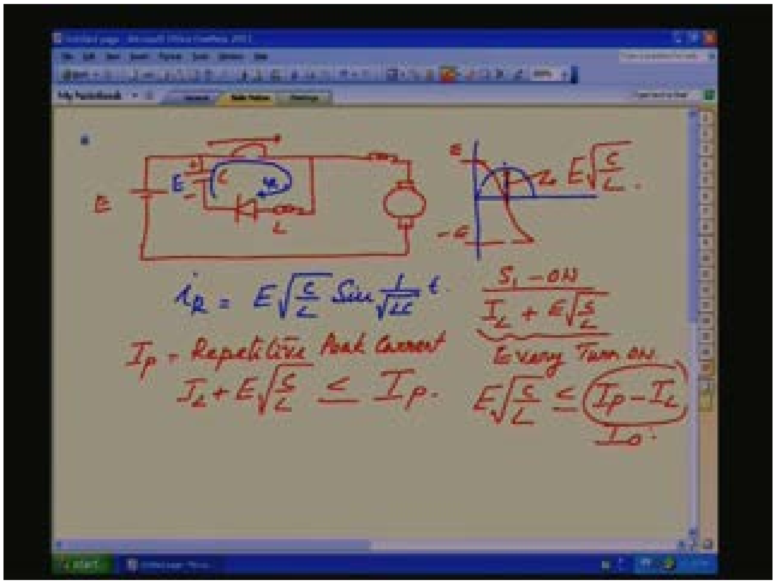

That is this is our E, main switch is turned on that is this is our main switch, capacitor initially charged to this value, then you have the diode L. Here, you have the load circuit. So, the resonant current which flows through C and L, so we will mark it like this that is this current I_R; what is the equation for the resonant current for the LC circuit? This I_R, we know it, I_R is equal to voltage across the capacitor is E. So, E into root C by L into sin omega resonant frequency that is 1 by root LC into t.

So, this resonant peak current that which we have drawn before, the current which go and the capacitor and charge the capacitor in the opposite direction that is this one - plus E and minus E; this resonant current that is this peak value is equal to E into root C by L, this value will go through the S_1.

So, during S_1 on, the current flowing through the S_1 are I_L plus the peak current E into root C by L, this is the peak current. This much peak current, every turn on; this will happen for every turn on, every turn on, so load current that is a maximum load current plus E into root C L will go through the thyristor. So, this current, it is a, this E into root C by L is a small duration. So, any thyristor will have a repetitive peak current that is repetitive peak current. Let us see that we will make it as I_p I_p or repetitive peak current. Any thyristor datasheet will give this one.

So, this data, so we should ensure that any time this repetitive peak current should be our I_L plus is I_L plus E into root C by L that is I_L plus E into root C by L should be always less than or equal to the repetitive peak current or the resonant current E into root C by L should be less than or equal to I_p minus I_L maximum, load maximum current. Let us represent this as I_0.

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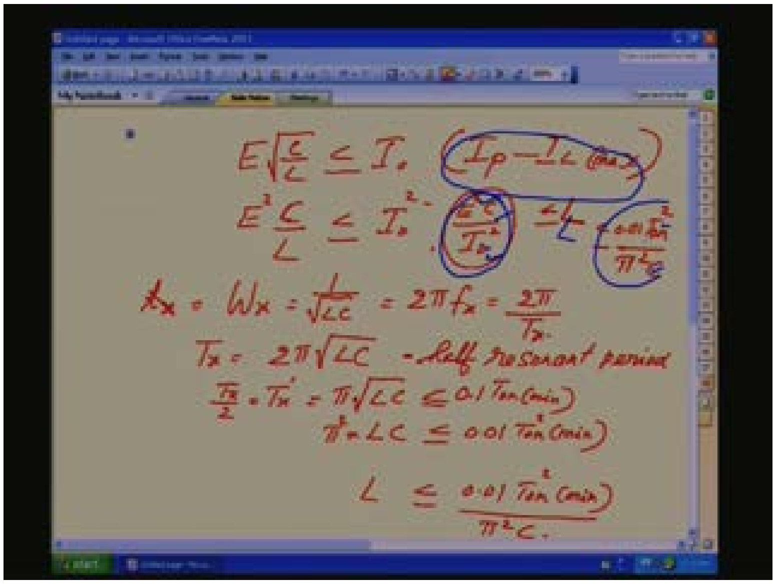

So, this condition shows that the condition what you have written here; E into root C by L should be less than or equal to I_0. What is I_0? I_0 is equal to repetitive maximum I_p minus I load maximum, I load maximum. This is equal to E into E square into C by L should be less than or equal to I_0 square. That means L should be less than or equal to E square C by I_0 square; one condition. So, from here, we found L should be or E_0 square E_0 square C by I_0 square should be less than or equal or else should be greater than or equal to this value.

But there is not sufficient, there is one more condition; we want to do it. From the resonance circuit, we found that omega r is equal to 1 by root LC. This is equal to 2 pi into f_r or 2 pi by T_r where T_r is the T_r is the resonant period. So, T_r is equal to 2 pi into root LC. But what we are talking about the half resonant period because we are not allowing the current to because of the diode, we are not allowing the current to flow in the negative direction. The half resonant period, so the half resonant period, half period is equal to T_r by 2; we will mark as T_r dash is equal to pi root LC and we want this half resonant period pi root LC should be smaller than the T_{off} minimum much smaller than or the condition T_{off} minimum required.

So, to ensure we will say 10%, so these are all design criteria, 10% of the duty cycle, minimum duty cycle; so 10% 0.1 of T_{on} minimum. Let us square this one that means pi square into L into C less than or equal to zero point squaring 0.01 into T_{on} square minimum. This implies, from this inequality; what we can find out? L should be less than or equal to 0.01 T_{on} square minimum divided by pi square C.

So, let us go back to the equality that means L, this should be 0.01 T_{on} square divide by pi square C, this is the condition. So, we can compute this value; E is known, C is known, I_0 known, I_0 is equal to Ip minus I_L, I_0 is equal to this value. Then the T_{on} minimum is known that is this one depending on the variable duty cycle, minimum chopper. Capacitor value we have initially found out from the T_{off} minimum required to switch off the thyristor. So, from this value, we can find out the maximum range of L and the minimum range of L; we have to choose L in between. So, commutation will be pakka.

So, using simple rules, using engineering approximation; one we said, the load is highly inductive, so load is linear. So, from the linear charging of discharging period, we have found out the T_{off} maximum or T_{off} minimum required for the capacitor to discharge fully so that the thyristor will be reverse biased, we found out the C. Then from the repetitive peak, there is known the resonant peak and the load current; one condition for L, one range of L we have found, the lower range. Then the upper range, we found out the minimum resonant period, resonant period. That should be much less than T_{on} duty cycle minimum of the circuit. From this one, we can find out the L and C and the computation is complete.

So, with this, that force commutation; we are only talking about the dc to dc converter, just to introduce the dc to dc converter we introduce this commutation, very widely used commutation circuit, popular commutation circuit. Now, what we want to do? The purpose of this introducing this force commutation; what we want? We want a PWM operation of the thyristor so that we can have unity power factor from the mains. So, unity power factor, at the same time, the converter should be able to work in the four quadrant region so that power flow can be from the input to the load from load to the mains.

So, how and what is the basic configuration for a four quadrant converter? Let us start. Let us talk about the converter; a front end ac to dc converter with unity power factor, at the same time four quadrant operations is also possible. Let us talk about how we can have a converter with four quadrant operation.

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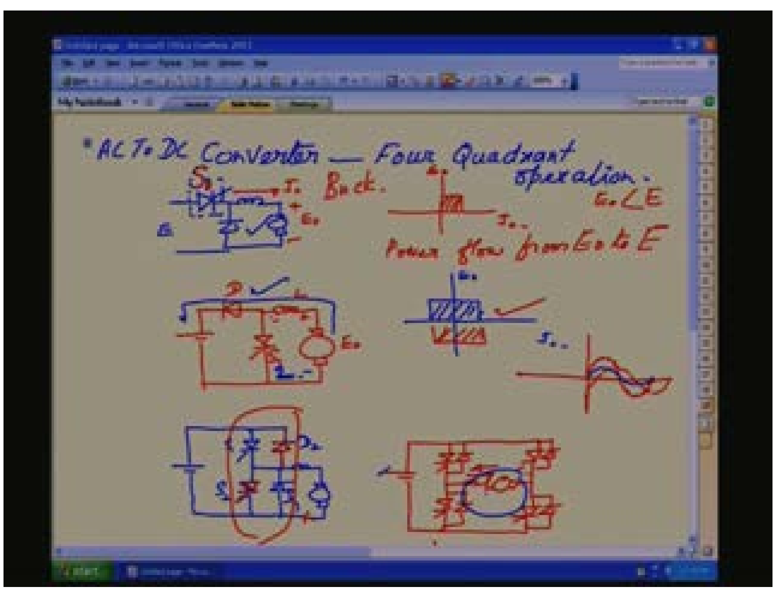

Converter; it can be used that is converter ac to dc converter; so for we are talking about ac to dc converter with four quadrant operation. We talked about our basic dc to converter previously that is the buck converter, the configuration is like this; we have this one, then the inductance, we have the load, freewheeling diode d here. This is our E. Now, we are not showing the commutation circuit; commutation circuit is inside it is there. Here if you see here because of the thyristor main thyristor S_1, we will do with a different colour, because of this thyristor S_1, the load current can conduct only in one direction. That means this output voltage can vary from zero to positive only and current only one direction.

So, if you see the power diagram that is E_0 versus I_0 let us say load current I_0, E_0 versus I_0; only one quadrant is only possible, single quadrant operation. This is E_0 and this is I_0. Now, we want a power flow from load side to the, load side to the source side. So, from the buck converter, we know that E_0 will be less that E always, E_0 will be less than E. Now, to want a power flow from E_0 side to E that is power flow from E_0 to E; what is the configuration? We know the boost configuration; this is buck, this is buck, you know the boost configuration. So, how do you draw the boost configuration? Now, the source is our E_0, the power flow is from the load side to the E.

So, let us draw our load side like this. So, how do you boost it? First, any boost circuit, we know that inductor is charged first. So, here is our thyristor. So, we are using thyristor here or IGBT or MOSFET, whatever you can use it. So, since so far we are talking about thyristor, we will talk about the thyristor now.

So, this one; so you initially, this is the main switch S_1 is turned on. When S_1 is turned on, full E_0 will come across L then S_1 is turned off; what will happen? We will put a diode here. This is our E. When S_1 is turned off, the current will flow through L and D that means the current flow when S_1 is turned on, S_1 is turned on, the current flow will be it will flow from because of that stored energy in the inductor, it will show from this side to this way. So, what you mean by that one? Here, we are not changing the polarity of the voltage, current direction we have changed. So, we can have two quadrant operations. Voltage is still positive, only positive.

So, we can have two quadrant operations. Now, so for one quadrant, we use buck converter; for the two quadrants, we use other converter. Can we combine these two so that the circuit can be buck as well as boost? That mean or from the power flow point, we can have power can flow in both direction. So, let us draw that one. See here, so now, we are going to combine these two. So, what we want is the numbers we will change it, this one we will make it S_2. See, our mains, another one is S_0.

So, how the circuit will be? So, E is still E here, this is our E, this is our old S_1, S_1 comes here, this is our load, the freewheeling diode. This freewheeling diode is this one. Now, for boosting, S_2 is connected between inductant this side and the load, so this is here. Same way, we can use it here, S_2 and the diode, this diode will come here, this will make it D_2, this make D_1. So, if you see here, to make the buck and boost independently, we will colour it here; this is S_1 sorry we will colour the different colour, this is S_1, this is the D_2, these two are for boosting action.

So, we can have two quadrant operations. So, if you repeat the same thing other side, we can have four quadrant operations. So, the circuit here will be final circuit will be see, I will connect the diode like this; this side also it is there, now this point, we will remove and connect it here. So, the load will be like this. So, what it shows the quadrant operation here? We can have any operation from this side, we can have negative operation also. So, we can all four quadrant operation is possible that means both the voltage and current as far as the load is concerned, both the voltage and current can be positive as well as negative. So, this can be used, this configuration is called a four quadrant chopper. So, if you know this is a single phase inverter configuration; see, as now the load, we want both positive and negative, so load will have alternating current and voltage.

So, if you say positive and negative means PWM operation is possible. So, if you go to the next page here sorry we want the load positive and negative; so positive waveform and negative waveform, so I put sinusoidal voltage. Is it possible? See, with duty cycle control, I can have variable voltage. At many instant, I can have different voltage so that I can have, I can have a sinusoidal voltage. At the same time I can have a sinusoidal current also that means both positive and negative is possible; a current something like this is possible.

Now, for unity power factor, for unity power factor, the current here should be like this; unity power factor. So, ac to dc converter, we are talking about ac to dc converter; so this is the dc, this is the ac part, ac to dc with unity power factor. Is it possible? We will try to study that part in the next class.