Power Quality Improvement Technique

Prof. Avik Bhattacharya
Department of Electrical Engineering
Indian Institute of Technology, Roorkee

Lecture – 18
Three Phase Converters – III & Multipulse Converters

Welcome to our NPTEL course of Power Quality Improvement Technique. Today, we are going to discuss about Multi-pulse Converter. Now, we have already discussed 12-pulse converter. We are just left with the 18-pulse converter and thereafter we will mainly discuss the three-phase PWM rectifier.

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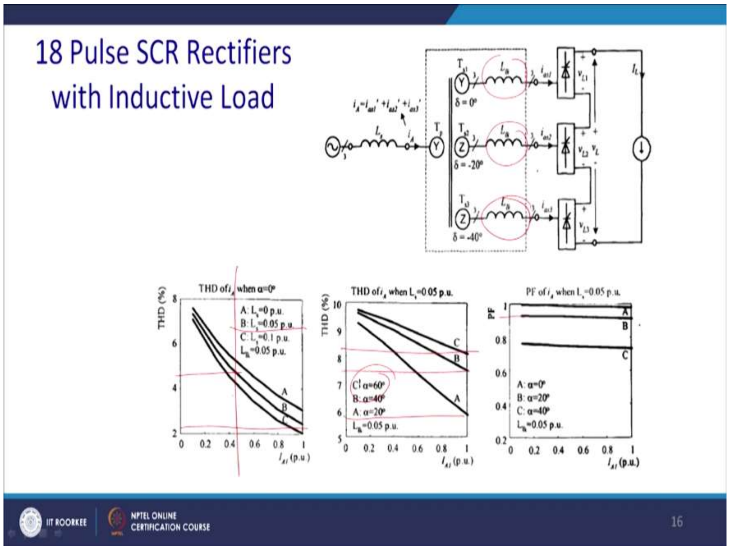
18 Pulse SCR Rectifiers with Inductive Load

Now, let us come to 18-pulse converter. Ultimately concept of this 18-pulse, same way this concept can be extended to the 24-pulse converter. So, you have a constant current source due to the highly inductive load and there is a source inductance and generally you have to give some amount of the inductance to get connected to smooth out this THD part of it. So, it will generally make this entity more continuous.

So, essentially in this case you can find that Ls for (let us that the entity 'B'), the THD for B for full load is close to 2.5-2.3 and for half of the load you can get close to 4 percent. So, it is up to some extent acceptable for this application. For this rectification where you are feeding highly inductive load, what is the problem? Problem in this case are all these multi-pulses. We required to understand that.

Ok, let us close this discussion first. For alpha equal to 60 degree again this is a ‘C’ curve and you get the THD close to 7 percent for the full load and if alpha equal to 20 degree, then you can get this curve around 6 percent and of course. Here if alpha is 20 degree, you got a displacement power factor. You get a THD close to 4 to 5 percent.

Power factor does not change much but, for the ‘C’ or the highest triggering angle alpha equal to 40 degree. So, you get close to 0.78 and for ‘B’ you get close to 0.92-.93 and for ‘A’ you get very close to 0.95-.98 something like that. So, this is the overall 18-pulse converter.

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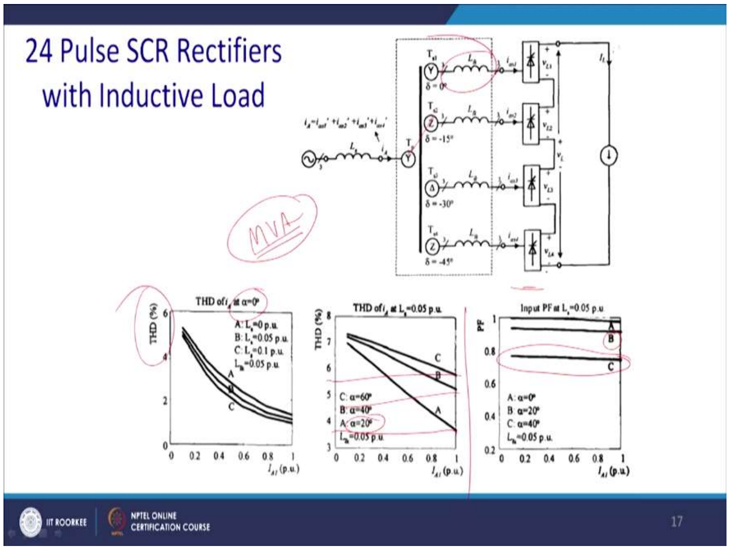

24 Pulse SCR Rectifiers with Inductive Load

And, same concept can be extended to the 24-pulse converter and let us see what is the benefit of this. One of the benefits is that in case of the ‘C’, you can see that this curve is almost same. So, there is no such benefit can be attended by connecting the extra converter, but ‘B’ you can see that it is close to the same. So, in terms of the power quality you can see there is not much difference between the 18-pulse and the 24-pulse converter.

But here there is an advantage. You can see that ‘A’ is close to less than 4 percent for alpha, 20 degree for full load. Similarly, this is ‘B’ and it is 40 percent and C that is 60 percent. Same way THD alpha, THD ‘A’ equal to alpha equal to ‘0’ that is not the case generally we prefer. Otherwise you can see that at the same variation which you will find in case of the series load. Almost very close to that variation you will get this kind of series inductive load.

Now, what are the major drawback of this multi-pulse converter? One of the major drawbacks of the multi-pulse converter is, since you are feeding a DC load and if there is a mismatch of the triggering angle of this converter, then there will be a mismatch of the DC component in the primary and also this leads to the saturation of the transformer. One problem is that.

So, you have to see that whether you have any tresses of the DC component in any of the current part of your circuit. So, accordingly you required to adjust the triggering angle and you require to eliminate the DC portion of it. Otherwise you are going to saturate the transformer core. That is the major corrective action you required to take within a regular interval of time by proper monitoring of it. Thus, you can operate it for the longer durations. Otherwise you will cause the unnecessary heating up of other transformer and ultimately it will go into the saturation.

Apart from that all those multi-pulse converters are a bulky solution. You want to have a solution with the transformer and thus solutions are quite bulky and it is applicable for those where, mostly they are thyristorize drives. Mostly you will be applying these drives for driving your vehicle, with the power rating in the range on the MVA. For the lower rating up to 3 kilo Watt, we generally prefer to have a single-phase system. We have discussed the problem of this single-phase system, THD, power quality other issues.

Now, with the three-phase system in the level of the MVA you will go for this multi-pulse converter and since the power handling capability of thyristors is quite large and it can handle this power. So, you will have this entity to be fit for thyristors.

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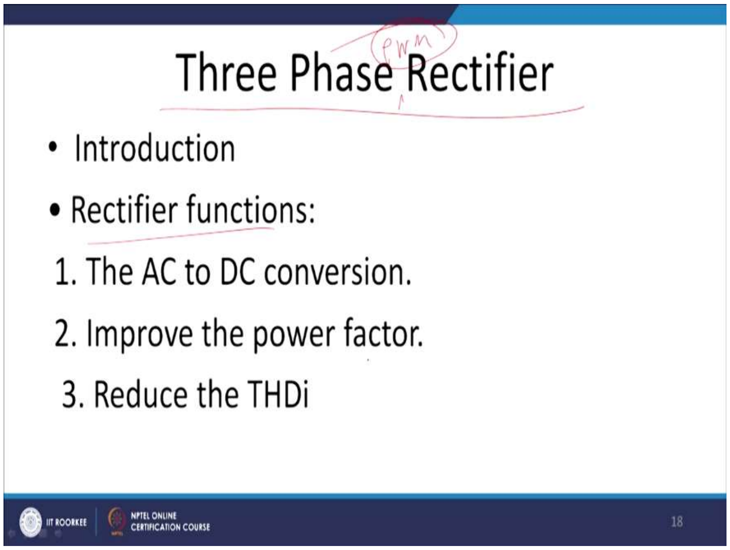

Three Phase PWM Rectifier

- Introduction
- Rectifier functions:

1. The AC to DC conversion.
2. Improve the power factor.
3. Reduce the THDi

But, if you have let us say a power rating of around 100 kilo Watt, then we shall go for the three-phase rectifier, that is three-phase PWM rectifier we will use. So, that we will have. This is something we will discuss that AC to DC conversion, improve power factor, reduction of the input current THD.

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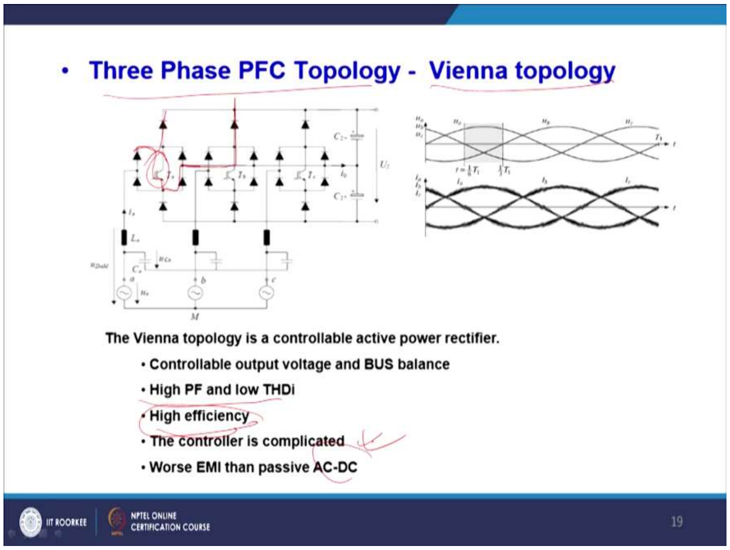

- **Three Phase PFC Topology - Vienna topology**

The Vienna topology is a controllable active power rectifier.

- **Controllable output voltage and BUS balance**
- **High PF and low THDi**
- **High efficiency**
- **The controller is complicated**
- **Worse EMI than passive AC-DC**

So, one of the applications of this is called the Vienna topology, but it consists of huge number of switches and these are the three utilities and ultimately it fit to these bi-directional switches. This essentially you know are the bi-directional switches. If you can find it out then you can find. So, current can go from this point to this point and if you want this switch to be ‘on’ then current can go this point to this point then can pass on this point and can go this way.

So, multiple connections are possible depending on the logics and ultimately this is the way, but it is quite complicated in operation and you require a large number of diodes. These are all power diodes and ultimately while current flows it accounts two diode and one switch losses. Unnecessarily. So, two diode losses will be around, it is not 0.7-volt diode. These are all high-power diode and for this reason this drop will be quiet maybe double of the 0.7 maybe 1.5 volt.

So, you got a 3 volt. Thereafter we have switch. That also gives you around 2volt. Sometime if it is high rating IGBT, then 5-volt drop will be there and if it is carrying a 100 ampere of current, so each of these set will give you 500-Watt losses you know. So, it is equivalent to run a 500-Watt motor.

Since, you are not using it as a room meter hence no purpose of having this kind of configurations. But this is one of the top primitive topologies which was developed by the switches and this is called the Vienna topology and it is controllable, active rectifier and also bi-direction action sometime was also possible with a little change in the circuit.

And, it gives you a controllable output voltage, high PF and low THD. You can see that this is the voltages and this is the current IIBIC and there is a high-power factor and low THD, high efficiency. But efficiency required to be challenged this term because of this higher, it has a high diode drop, high conduction loss for switching losses is lower. But this is one of the issues. That control is quite complicated and worse EMI for the passive AC to DC conversion than your multi-pulse converter.

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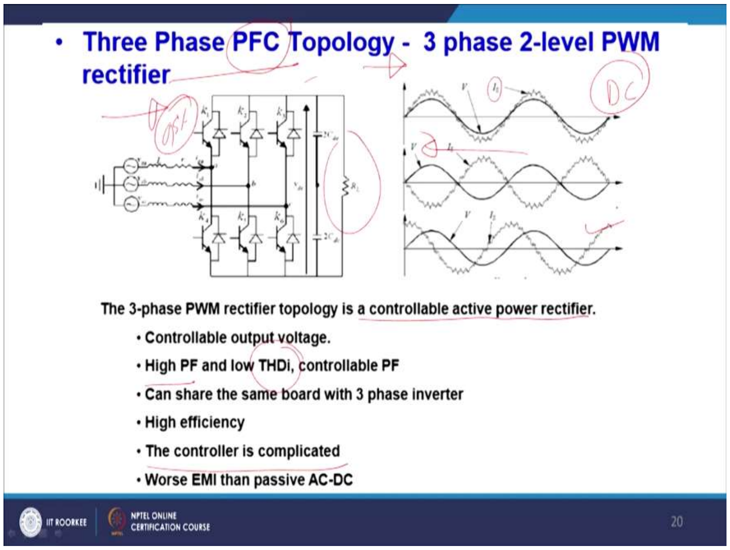

- **Three Phase PFC Topology - 3 phase 2-level PWM rectifier**

The 3-phase PWM rectifier topology is a controllable active power rectifier.

- Controllable output voltage.
- High PF and low THDi, controllable PF
- Can share the same board with 3 phase inverter
- High efficiency
- The controller is complicated
- Worse EMI than passive AC-DC

For this reason, we try to find one solution by your three-phase that is power factor correction topology. Not only power factor it is also reduces the THD and it is for the three-phase. For the low power rating it will be 2-level and if you go higher level it can go to higher level. This is the voltage. I will show you the practical current and voltages. I have worked on it. For this I can show some practical results and this is the Is and you can see that this kind of ripple is present. Switching has to be done in that pattern.

So, three-phase PWM rectifier topology is a controllable active power rectifier. Once you power flow from this point to this point, of course in case of the regenerative breaking or some other action in case of the micro gate kind of applications where you have a storage, you can feed back this power to the AC side to DC side. It has high power factor, low THD and controllable power factor. Generally, this point can be connected with the three-phase inverter and it can have an efficiency up to 95 percent and the control is little complicated. Not so complicated. Also, there is a problem of EMI, EMC because of the switching of the device.

You can see that. I have shown the wave form. Once the current goes to this, this is the DC action current goes to grid to DC and you can send power back to the grid if you have a storage element of the capacitor then voltage and current will be 180 degree out of phase and you can also have lagging or leading power factor. That is also you can do. Then, you of course, you are correcting the power factor of the system. Since you have made leading power factor in this case as I have shown. So, it may compensate the lagging power factor from other parts. So, it can act as a power factor corrector or STATCOM kind of applications.

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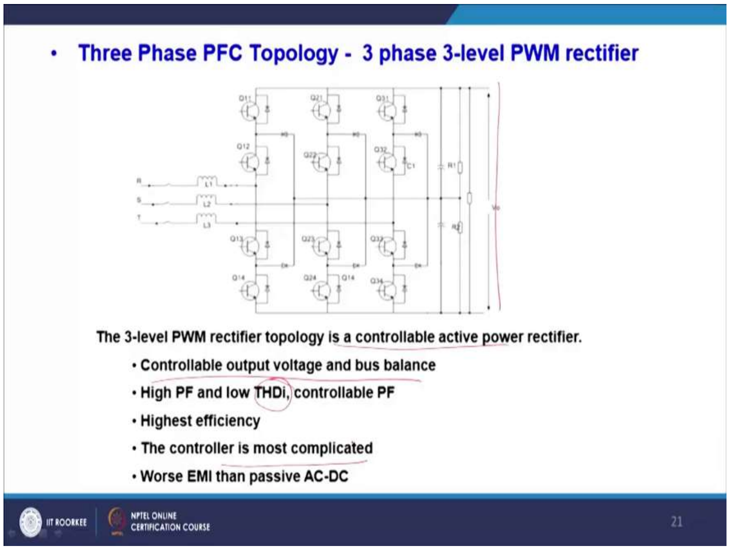

- **Three Phase PFC Topology - 3 phase 3-level PWM rectifier**

The 3-level PWM rectifier topology is a controllable active power rectifier.

- **Controllable output voltage and bus balance**
- **High PF and low THDi, controllable PF**
- **Highest efficiency**
- **The controller is most complicated**
- **Worse EMI than passive AC-DC**

And, this is its multilevel version. I have shown the three-phase 3-level diode clamp inverter for handling higher power capability. You can of course, go for multilevel depending on its power rating. But switch counts become more and this is one of the simplest multi-level inverters. 3-level PWM rectifier topology is a controllable active rectifier. Controllable output voltage and bus balance is possible.

High power factor, then low THD. Controllable power factor also possible because here you can see that not only your feeding a unity power factor but you can change the voltage and current angle. If you want to compensate the negative VAR you can inject the positive VAR by proper switching.

Then control is more complicated. We have discussed already the MLI, multilevel inverter. So, there are three kind of multilevel inverter as we have discussed. That one is your diode clamp inverter for the 3-level and its switching pattern. Please refer to that lecture and another is that it has a complicated switching technique and thus it makes that more complicated. The controller thus is more complicated and you can also have a cascade option for the flying capacitor topology.

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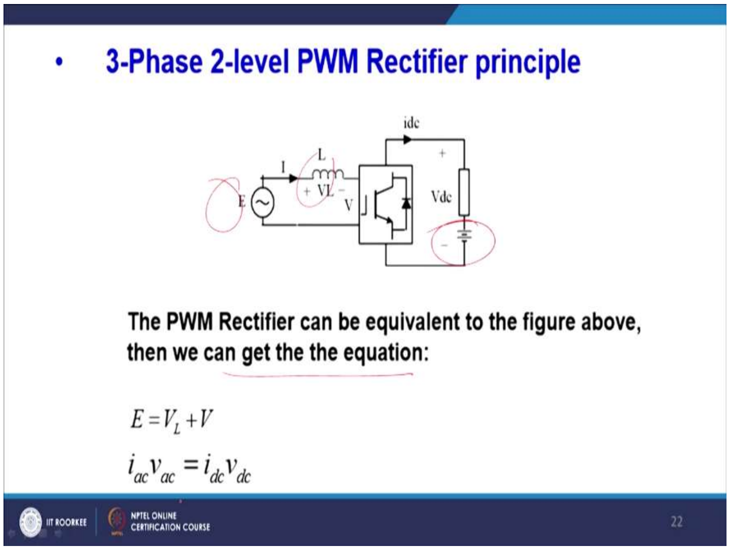

- **3-Phase 2-level PWM Rectifier principle**

The PWM Rectifier can be equivalent to the figure above, then we can get the the equation:

$$E = V_L + V$$

$$i_{ac}v_{ac} = i_{dc}v_{dc}$$

So, how does it work? So, this is the single line diagram. Generally, this is for the battery charging application. We want that to charge our battery for the '0' unity power factor. Then this will be an inductor and this is the IGBT and that can be operated as high as needed for the lower power rating which is as high as 20 kilo. I will show little data on it.

The PWM rectifier can be equivalent to the figure above and we can get this equation $E = V_L + V$ and we are assuming that there are no losses in AC to DC conversion. Thus, we can say $i_{ac}v_{ac} = i_{dc}v_{dc}$. This is the balance of power and ultimately you can have a different kind of model.

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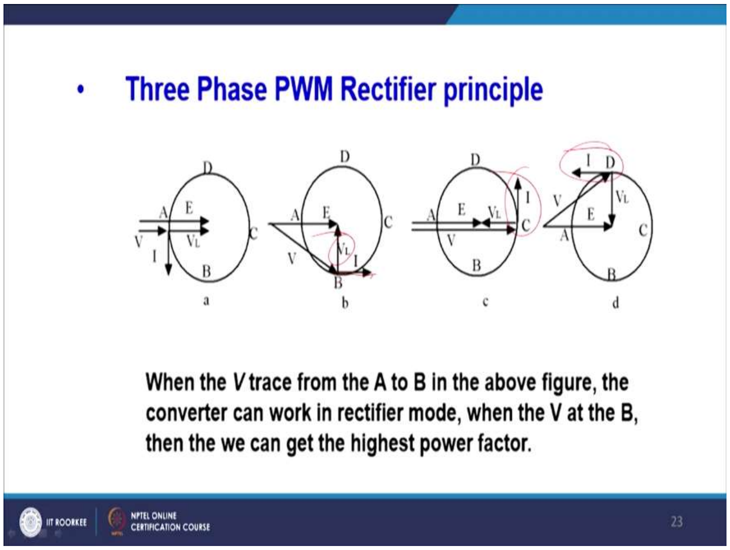

- **Three Phase PWM Rectifier principle**

When the *V* trace from the A to B in the above figure, the converter can work in rectifier mode, when the V at the B, then the we can get the highest power factor.

So, when vector ‘A’ stresses from the A to B in the above figure, the converter works in a rectifier mode. When ‘V’ at the ‘B’ then we can get the higher power factor. Then we can get the highest power factor.

Same way in ‘C’ we can give voltage back and ultimately in this case ‘I’, you can see that ‘I’ is leading in this case. ‘I’ can be lagging and you can see that ‘I’ is 180-degree phase shifted. That means you are sending back the power to the grid. Same way here I, here V_L and V are this, this gives you the lagging power factor and you have ‘I’ in a direction of the ‘E’. So various combinations are possible for a PWM rectifier and thus different function can be accomplished with this rectifier.

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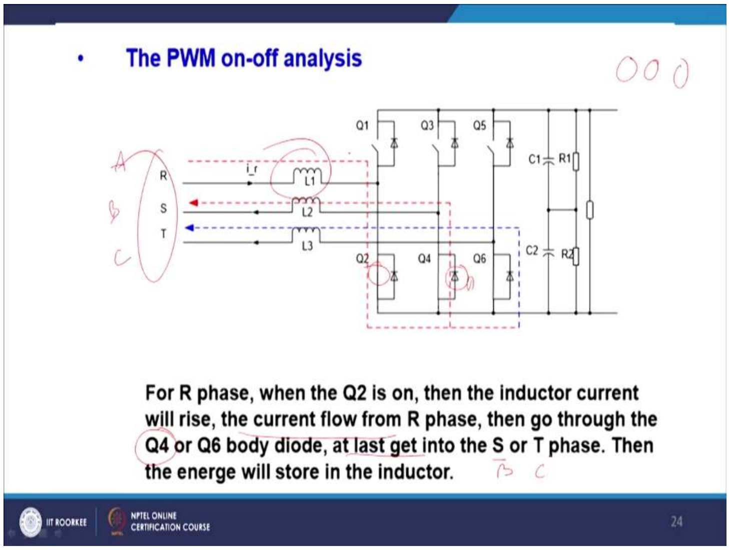

- **The PWM on-off analysis**

For R phase, when the Q2 is on, then the inductor current will rise, the current flow from R phase, then go through the Q4 or Q6 body diode, at last get into the S or T phase. Then the energe will store in the inductor.

Now, this is the principle of operation of the PWM inverter. I just go switch by switch. You can see that this is the i_r and you know this Q2 is closed. So, current will flow through it and we assume that all the upper switches open. So, you can have the logic of this upper switch is this, lower switch is closed and this is closed and this is closed. So, this is essentially a state of a space vector modulation is as 0 0 0.

So, that is what we have considered. In that case what happens? This will give you the boost mode of operation. You can see that depending on the direction of the current, because $I_a + I_b + I_c = 0$. Here current will assuming that this Ia will enter and will go back through these diode D4 and D6. Ultimately what happens? Since you have sorted the voltage, there will be a ramp on of the current.

For example, for phase R when Q2 is on then inductor current will rise. The current flow from R phase, then goes through the diode from Q4 and the Q4 body diode at least. But if you have a IGBT generally it is not body diode, manufacturer physically points this anti parallel diode at least to get the S' 'and 'T' phase. Generally, this is germen abbreviations A, B, C. So, B will be equal to S and C you will be equal to T. So, that is what the convention we are followed. So, we can write as B or C phase, then the energy will store into the inductor.

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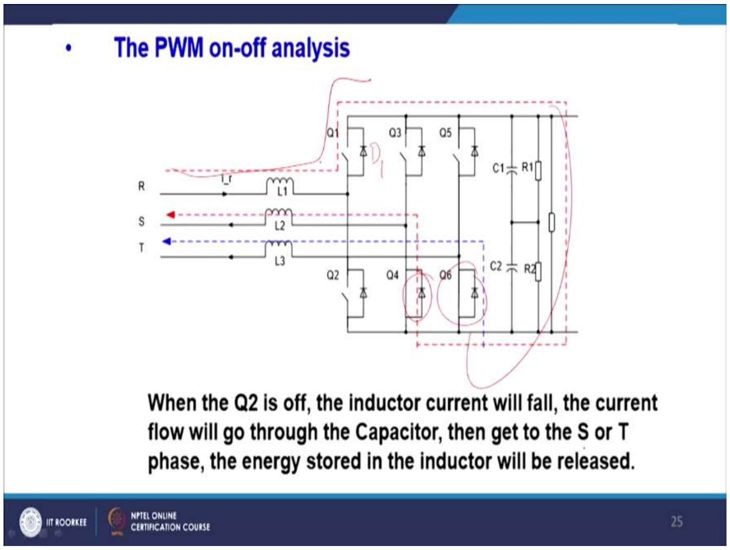

- **The PWM on-off analysis**

When the Q2 is off, the inductor current will fall, the current flow will go through the Capacitor, then get to the S or T phase, the energy stored in the inductor will be released.

Similarly, now let us consider that those switches were closed and you have opened that switch. Then what will happen? These two switches are closed. Since you have closed this switch ultimately this i_r will flow through that body diode of Q1 or this external anti parallel diode you have connected and will boost up the voltage. Ultimately it will flow through this lower switches and back. So, this is a way of the operation of this converter.

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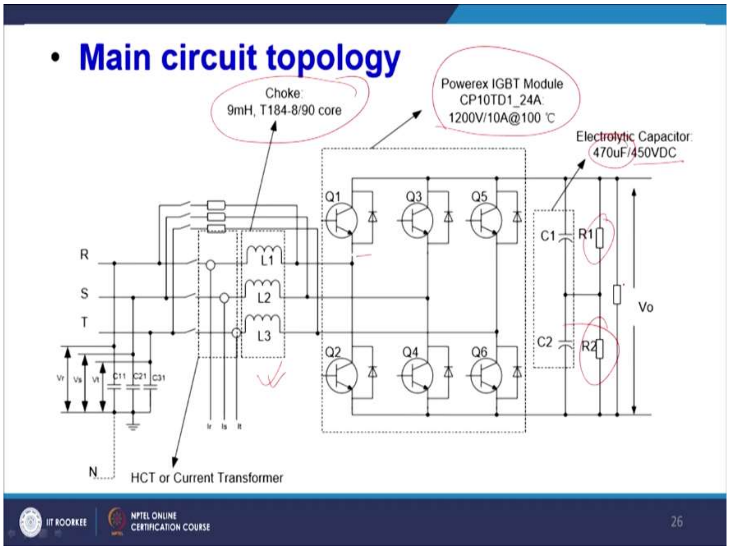

- **Main circuit topology**

Choke: 9mH, T184-8/90 core

Powerex IGBT Module CP10TD1_24A 1200V/10A@100 ℃

Electrolytic Capacitor: 470uF/450VDC

HCT or Current Transformer

Now, this is a practical circuit of this PWM converter. This is a static by pass and generally we will have an inductor and we will have a choke and you required to design the choke.

So, that will be depending on what is the value of the switching frequency for the continuous conduction mode. All those issues required to be taken care of. So, from there you can design the value of the inductor. This is something we shall discuss in the next class, like what should be the value of this inductor and how you will select this choke.

Thereafter, there will be a switch. I have ordered this board from the Texas Instrument. So, student version maybe available there. So, they used this circuit courtesy to the Texas Instrument. They have used this IGBT which has a 1200-volt 10 ampere at 100-degree centigrade rating. We are using electrolytic capacitors of 750 by 750 volt and generally it will be boosting the voltage.

Thus, you know once you rectify, it will go to the 600 volt for the 440 volt line. So, you will find that. This voltage will be around 700 volt 750 volt something like that and for this reason you will be using two capacitors of the rating of 450 volt so that 900 volt can be used. Now these are the calculations and all those aspects has to be there.

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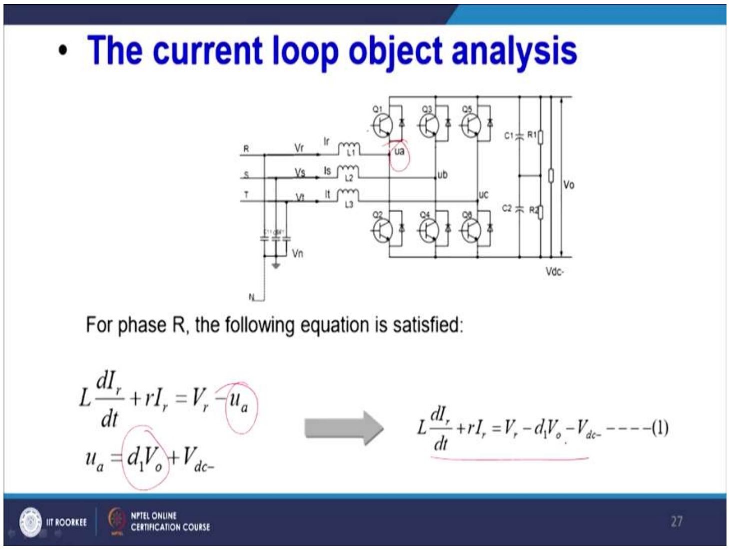

- The current loop object analysis

For phase R, the following equation is satisfied:

$$L\frac{dI_r}{dt}+rI_r=V_r-u_a$$

$$u_a=d_1V_o+V_{dc-}$$

$$\Rightarrow L\frac{dI_r}{dt}+rI_r=V_r-d_1V_o-V_{dc-}\quad ----(1)$$

So, this is the value of this. Ultimately you can write it out for the phase R or equivalent to A. So, that is $L\frac{dI_r}{dt}+rI_r=V_r-u_a$, where ‘a’ is the pole voltage of this leg ‘a’. Similarly, $u_a=d_1V_0+V_{dc-}$ because here one switch is on. So, from there you can balance. This is your equation number one $L\frac{dI_r}{dt}+rI_r=V_r-d_1V_0+V_{dc}$.

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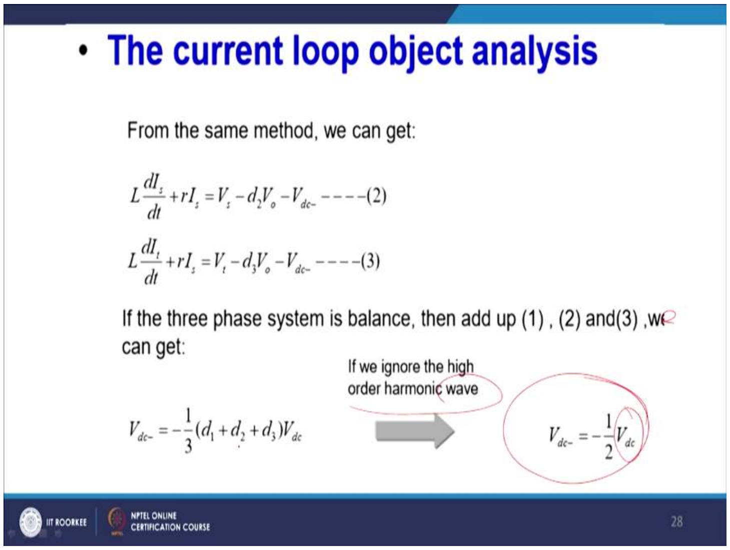

- **The current loop object analysis**

From the same method, we can get:

$$L\frac{dI_s}{dt}+rI_s=V_s-d_2V_o-V_{dc-}----(2)$$

$$L\frac{dI_t}{dt}+rI_s=V_t-d_3V_o-V_{dc-}----(3)$$

If the three phase system is balance, then add up (1) , (2) and(3) ,we can get:

If we ignore the high order harmonic wave

$$V_{dc-}=-\frac{1}{3}(d_1+d_2+d_3)V_{dc} \longrightarrow V_{dc-}=-\frac{1}{2}V_{dc}$$

Using same method, we can write it for the other phases. That is ‘S’ and ‘T’ and ultimately we know that we can get $V_{dc-}=-\frac{1}{3}(d_1+d_2+d_3)V_{dc}$ and we can ignore the higher order harmonics and thus what essentially you get? $V_{dc-}=-\frac{1}{2}V_{dc}$ from here this is the constant value of it and this the variable value of it.

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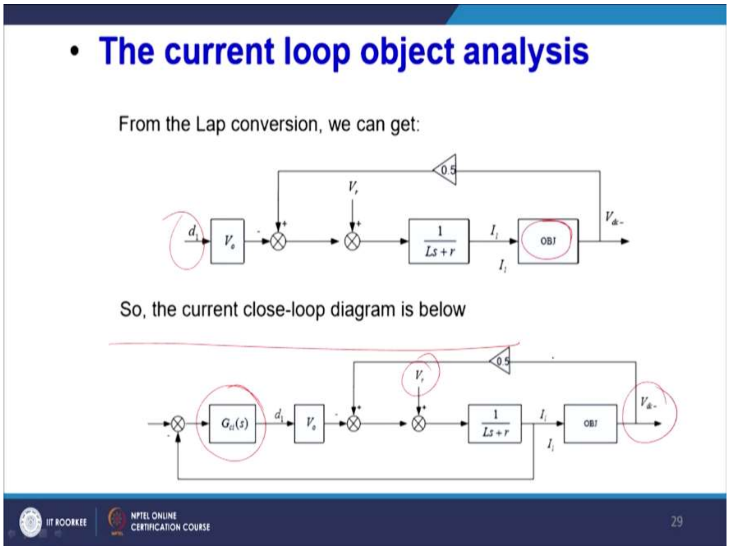

- **The current loop object analysis**

From the Lap conversion, we can get:

So, the current close-loop diagram is below

Thus, this is a control loop you require to control. This is the duty cycle of V_0 and you are giving a feedback through this inductor and this is your objective function, nothing but an inverter. So, you are controlling this controller. So, into the control loop, what you have essentially? You have the inverter from there you have multiplied it with the d_1 and the duty cycle is coming that will be multiplied by V_0.

Same way you get it divided by the phase voltage Vr and this is your inductor and there after essentially you get I_1 and that gives you the V_{dc}. You required to control this control block of this current control loop.

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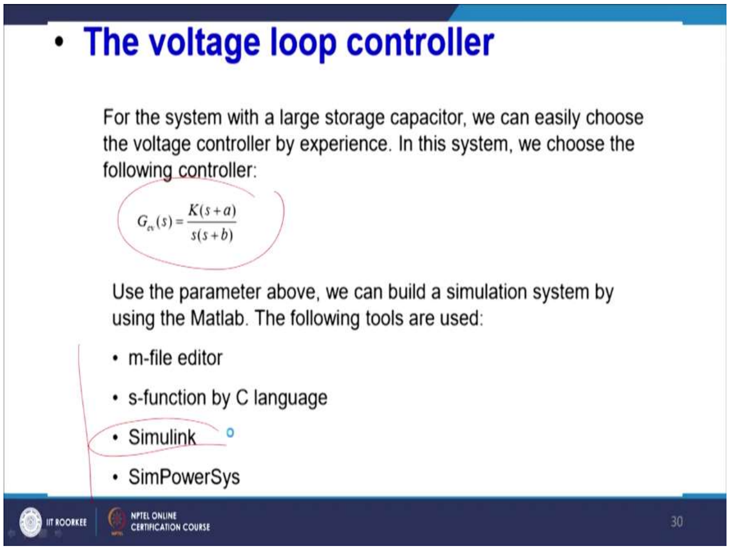

- **The voltage loop controller**

For the system with a large storage capacitor, we can easily choose the voltage controller by experience. In this system, we choose the following controller:

$$G_{cv}(s) = \frac{K(s+a)}{s(s+b)}$$

Use the parameter above, we can build a simulation system by using the Matlab. The following tools are used:

- m-file editor
- s-function by C language
- Simulink
- SimPowerSys

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Essentially for the system of the large capacitor, we can choose the voltage controller by experience and this 'C' system can be chosen like this and using the above parameter it can be built by the Simulink MATLAB and you can do it by either of this thing. We generally prefer the Simulink for the sake of the simplicity.

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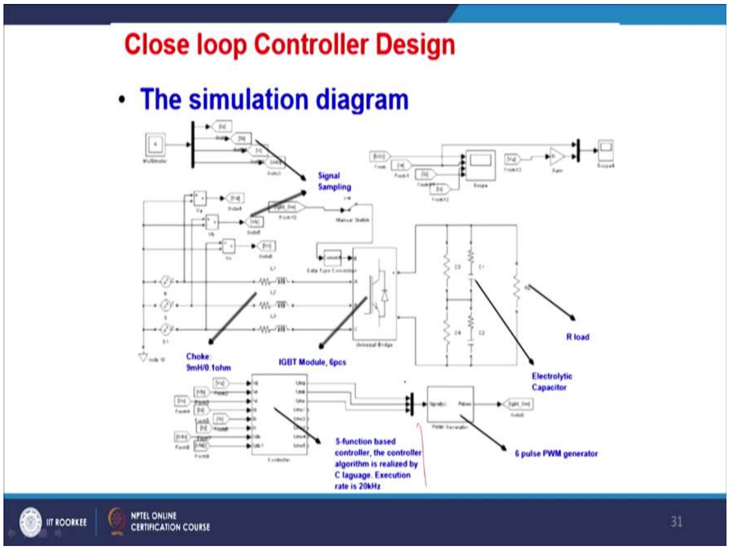

Close loop Controller Design

- The simulation diagram

I am showing you the Simulink model this way. So, you can use the controller and the choke. This is the capacitor and you can have a switching logic based on the S-function block or you can use any other way which you prefer. So, this will be switching.

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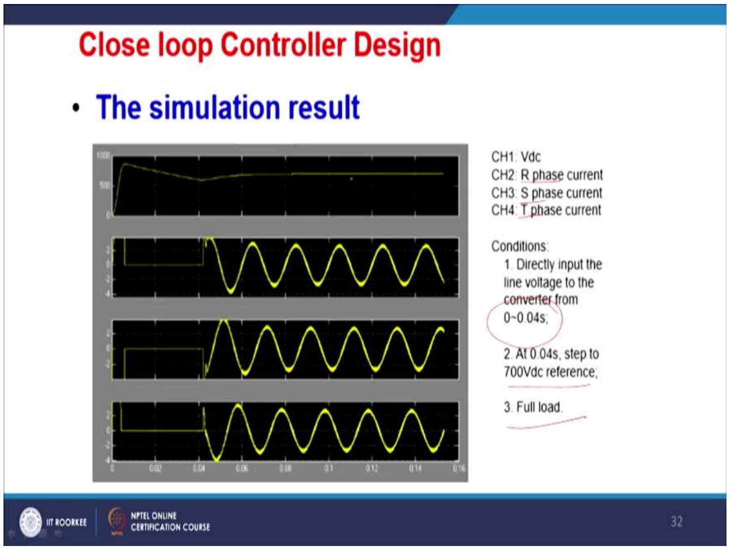

Close loop Controller Design

- The simulation result

CH1: Vdc
CH2: R phase current
CH3: S phase current
CH4: T phase current

Conditions:
1. Directly input the line voltage to the converter from 0~0.04s;
2. At 0.04s, step to 700Vdc reference;
3. Full load.

I am giving you this just for your interest. This is the DC bus voltage. These are the currents. Once it starts, its spikes, thereafter it will be stable and come down. So, this is the V_{dc} and this is the R phase, S phase and T phase and thereafter the condition of direct input for 0 to 0.4 seconds. Thereafter condition 2 at 0.04 seconds, steps reference to 700 volt and condition 3 we got a full load.

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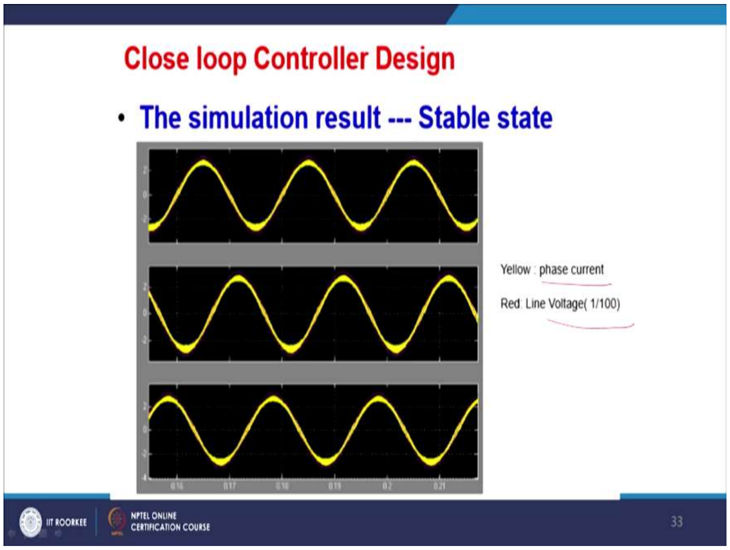

Close loop Controller Design

- The simulation result --- Stable state

Yellow : phase current

Red: Line Voltage(1/100)

This is the yellow one. You can see clearly because of the switching. There is a ripple and this one is a phase current and with that there is a small red portion of the pink line. So, this is a voltage which has been scaled down by 100 times to show in a same scale. So, this will be your voltage and they are in a same phase. That is what we have simulated. Of course, you can have a phase lead, phase lag. Other options are also possible.

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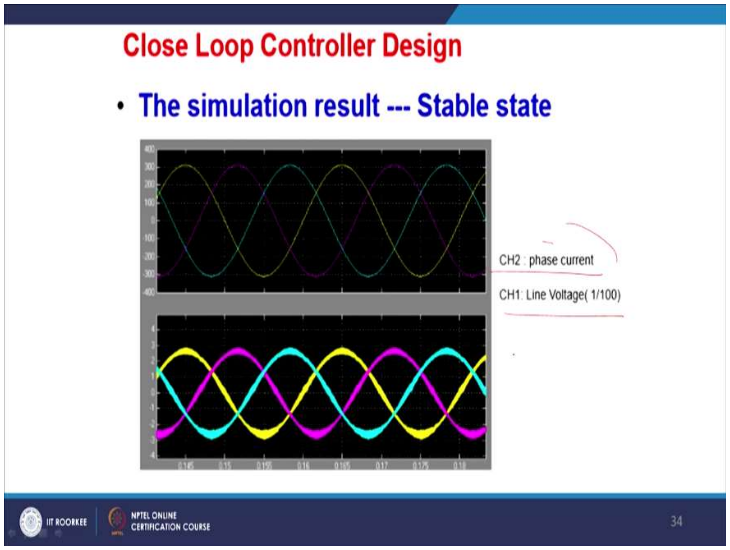

Close Loop Controller Design

- The simulation result --- Stable state

CH2 : phase current

CH1: Line Voltage(1/100)

So, this is a three-phase phase current and this is corresponding to that. Upper one is the phase voltage and lower one is a phase current.

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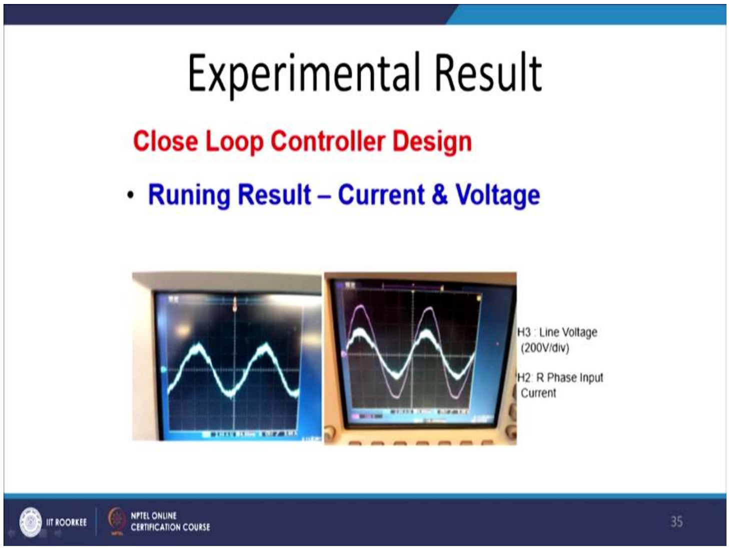

Experimental Result

Close Loop Controller Design

- **Runing Result – Current & Voltage**

H3 : Line Voltage (200V/div)

H2: R Phase Input Current

This is some simulation and experimental results. This is a current waveform and this is the voltage and current waveform. You can see that they are in co-phases.

Thank you for the attentions. I just completed some fundamentals of the PWM rectifier. I shall continue some design aspect of this multi-pulse converter as well as the design of this PWM inverter in subsequent classes.

Thank you so much.