Flexible AC Transmission Systems (FACTS) Devices
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Lecture - 06
Closed Loop Control

Welcome to our 6 lectures on FACTS devices. Today we shall discuss Closed Loop Control of the FACTS Devices. To discuss it we shall first actually discuss about simplest DC to DC converter that is buck converter and it is different control technique. So, the stacks as since our understanding of the buck converter is quite familiar for this I have chosen this to discuss. Thereafter, this concept of the current loop control will be actually used in our facts devices also.

So, essentially a buck converter with the voltage mode control can be used to stabilised with the proportional of the pi gain of the compensator.

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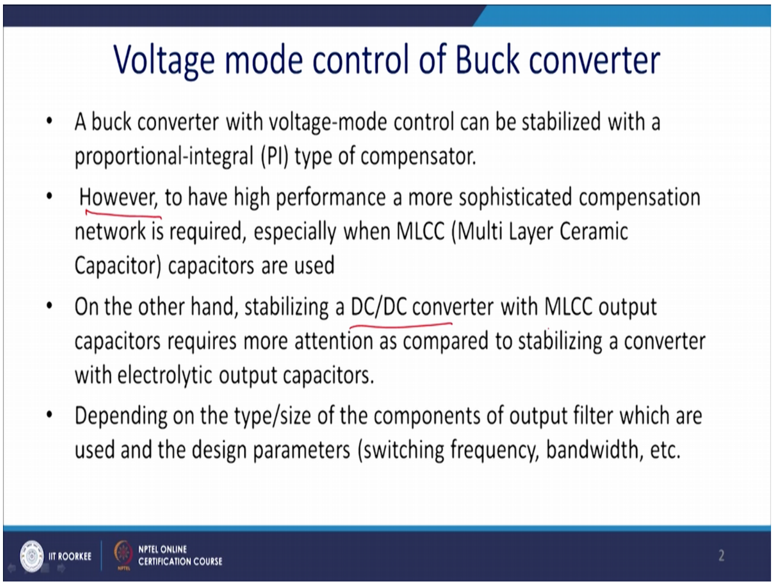

That we are familiar with it and, but problem lies we required to have few more aspects like short circuit protection stability, which can be done better with the current mode control for this reason. However, we have a high performance for the more sophisticated compensation network is required; especially multilayer ceramic capacitor is used.

And, on the other hand to stabilize the DC to DC converter with MLC the capacitor require more attention compared to the stabilizing the converter for the electrolytic 1. And depending on the size or the type of the component output filter used and switching frequency bandwidth etcetera is determined. Whatever, I am telling for the DC to DC converter same thing applicable for the facts devices also.

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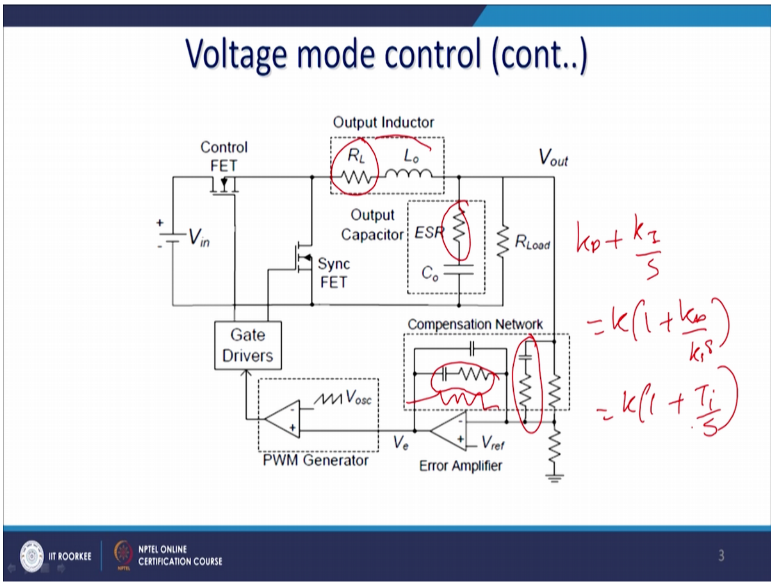

Or let us consider the operation of the voltage mode control of the simple buck converter. So, you know this is the devices and that contains the parasitic this R L is the actually parasitic resistance associated with R and this is ESR, and ultimately these will actually lead to the some kind of deviation from the actual work and we required to stabilize it is output.

Generally, what we do we have a this is actually noise subtractor noise suppressor and we required to scaling down and ultimately you require to fit the scaled output voltage, and this is going to compare with the V reference and V reference is generally made from the input site with the help of the (Refer Time: 03:00) and then we put a pi controller. Task of the pi controller you know that actually to eliminate the actually steady state error.

Now, what essentially it does and how you will actually calculate the value of this RNC and some time we will put a proportional resistant to it. What happened here this value RNC will gives you the bandwidth you can write actually kp plus k I by S, it can be rewritten k plus 1 plus kp by k I into S and you can write you know k into 1 by k by S.

Now, this T i you should require to match with this value of the RC network. And, generally it should be you know it you have to choose the op amp with the proper bandwidth and whatever will be the switching frequency of the (Refer Time: 04:04) wire, tell T i is considered around 10 times or 20 times depending on the practical application into it, and this will actually operate this actual this is the synchronous buck convertor. So, to reduce the losses of it since when MOSFET is on it is only at the on. So, losses will be very much minimized, for this is we use a synchronous buck convertor now what is instead of the normal buck converter and this is the way actually it works.

Well, disadvantage of it disadvantage of it definitely you know, it is not short circuit protection. Whenever actually if there is a drags very huge amount of load and it is what it is actually try to regulate the voltage only. And, it does not takes any information about the current for this reason we required to put extra circuitry to control all the limit to the current protection.

But, this scheme can be further modified this is actually the voltage mode control.

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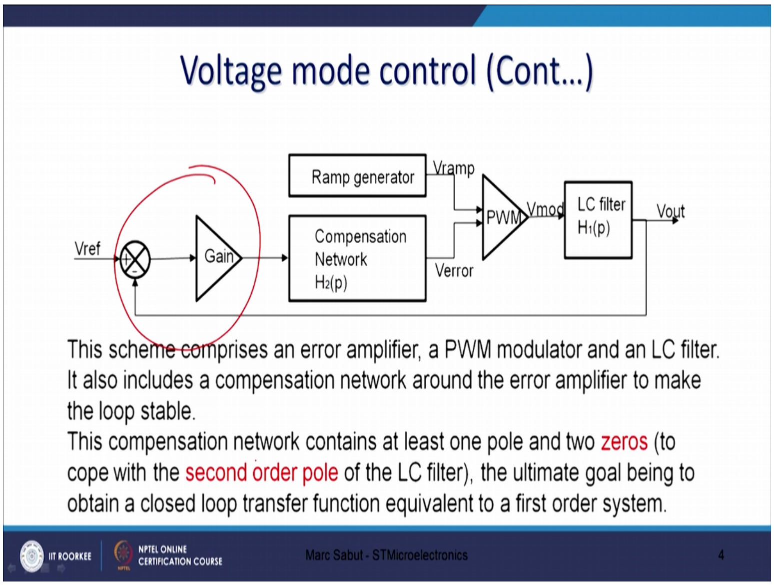

This scheme comprises of an error amplifier, this is consisting of a error amplifier and a PWM modulator and a LC filter. And this compensation network contains at least one pole and two zeros to cope with the second order pole of the LC filter. And the ultimate goal being to obtain the close loop transfer function equal to a first order system, ultimately it will be a order reduction and since a first order system inherently actually damped. So, you get a damping effect of it.

So, for this reason to work it in a finite manner next step is we require at least one pole and two zeros. These are the requirement for the working with the stability point of view for the voltage mode control.

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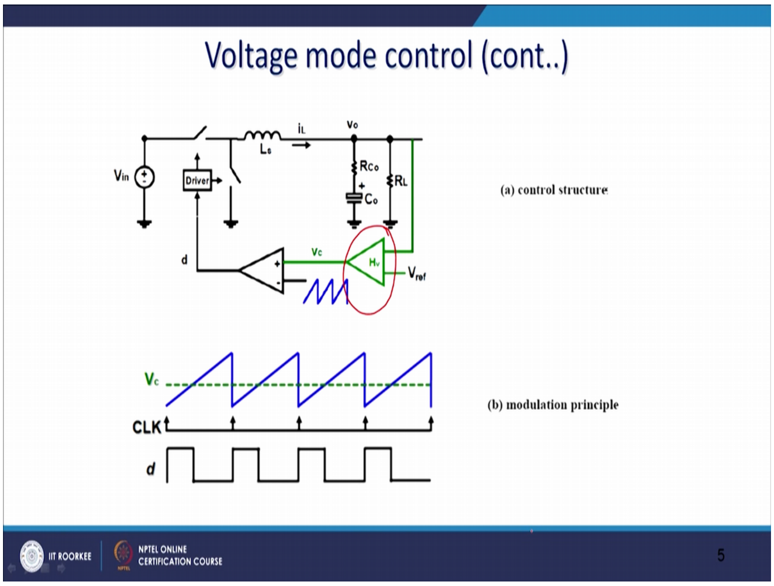

Now, this is the principle of operation of voltage mode control you got V ref there after you can compare with it and this is basically the control structures, all these pi controller has been cooperated here. And there after you will have Sawtooth wave and in Sawtooth wave will actually give you the pulses and that pulse will run this MOSFET.

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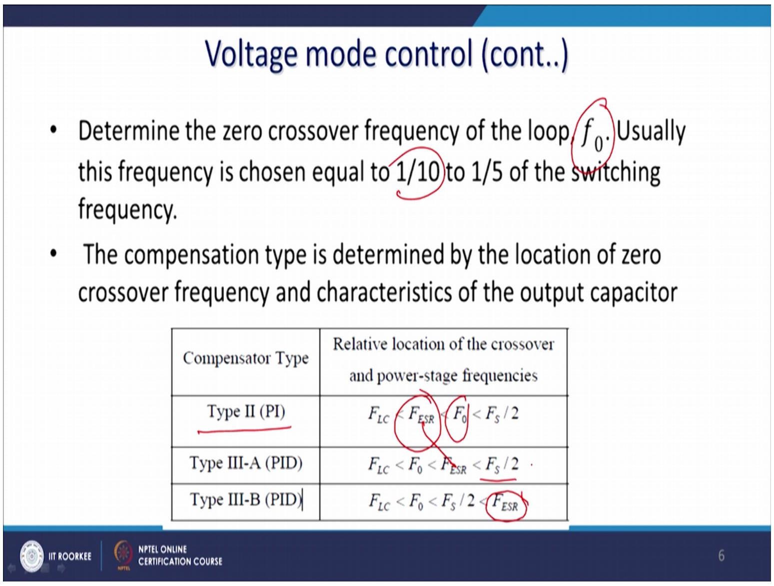

Now, there are few consideration while actually considering the close loop operations of the voltage mode control. The zero crossover frequency for f 0 usually the frequency is chosen as one-tenth or one-fifth of the switching frequency. Why I have explained because you know it is a concept of bandwidth, because what a pi controller actually to it will eliminate the study state. We expect that within the tenth of the cycle within actually 10 cycles or 5 cycle the error will be eliminated, steady state error will be eliminated.

The compensation time is determined by location of the 0 crossover frequency and characteristics of the output capacitor, but unfortunately the output capacitors value actually it is not very much known to us there is a actually it have degree of unknown, the value of ESR changes with the frequency and also what condition.

So, thus we required to take a guess something and we required to while designing we have to keep in mind few thing this. Is the compensation type and where you see that this is actually the resistance of the ESR. And where it required to be greater than F LC and F LC is required to be actually should be again it should be actually less than, the cut off frequency of display controller and that should be at least more than twice of the switching frequency as prescribed by the Nyquist criterion.

Similarly, if you take type 3 PID controller, then this is the logic now you have F LC actually is less than F 0. And here this ESR frequency of this ESR should be greater than F 0 and same characteristics will get it from the here. And, if you choose A type B PID controller I am claiming less what is type A and type B type PID controller.

So, we will find that F LC actually is less than F 0 and less than F by 2 and at last ESR value will come. Depending on the value of the ESR frequency for different combinations of the capacitor, we required to choose a particular type of the PID or the pi controller. So, see that this is a type 1.

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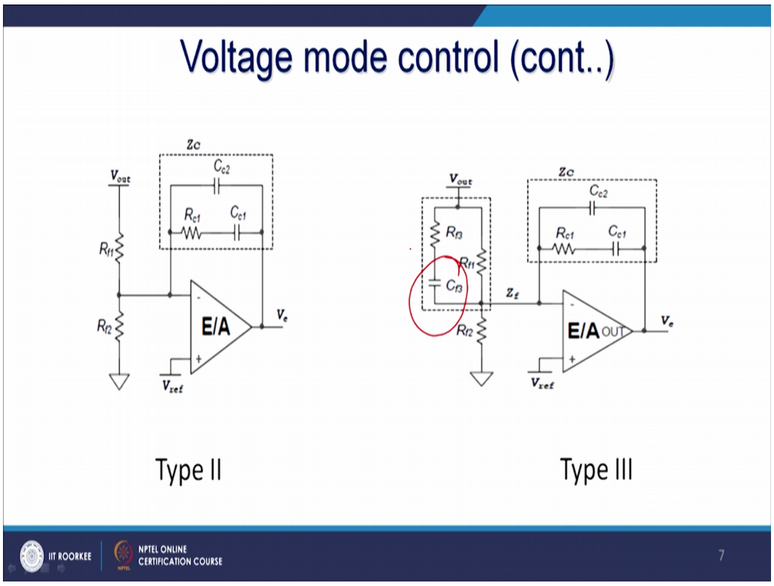

This is a pi controller.

So, this is normal pi controller of type 1, type sorry type 2. So, here you can find it out this is a normal pi controller and here you know this capacitor put into the picture and thus it has a effect on the control system. Let us go back to the previous slide and see that what is the type 1 and type 2? In type 2 actually you require F L F LC is less than F LC should be less than F ESR, and less than this cut off frequency and thereafter it should be less than of the switching frequency. So, this is the case and this is the type 3 type of circuits, then this is basically a PID controller.

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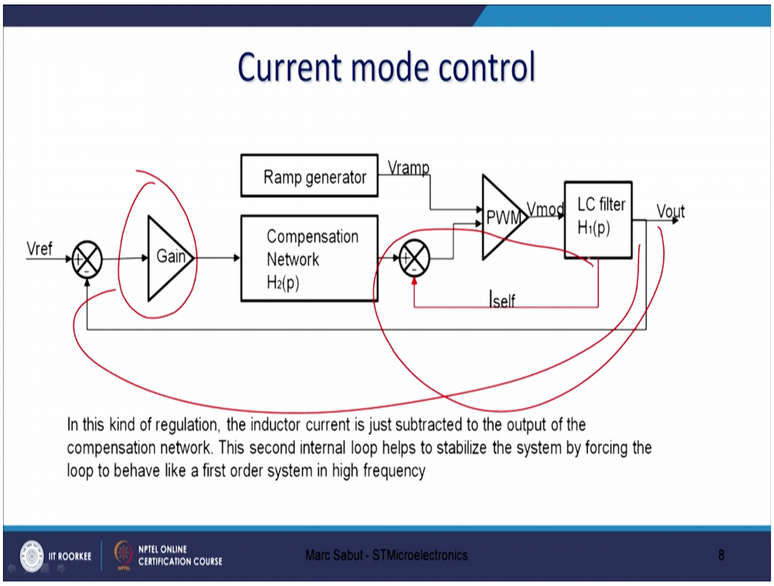

Now, this constraint in design can be simplified by using a current mode control. Where there will be a outer loop to compensate voltage and there will be a fast acting inner current loop that will give you a reduction of order of the stability. And also it will take a connective actions very fast moreover inherently since the current control it will give a short circuit protection.

So, let us see the different block diagram of the current control this part is same this is basically you can replace it any type of play controller, which has been already explained you. So, this is basically the outer voltage loop, this is basically the outer voltage loop. And there after you have a compensation network and from there you get a scale value of the error here. And you got a V ramp and ultimately use measure current value with a filter, which will eliminate the high frequency noise. And it will it will add up and ultimately it will be totally compared with the ramp and accordingly frequency will be generated.

So, here this part of it is a inner loop for the current and other is the outer loop for the current.

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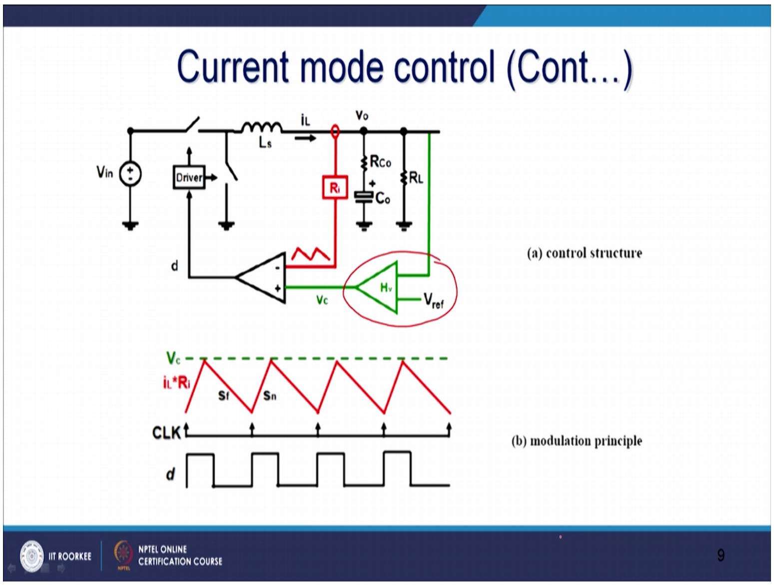

Let us see how does it work very simple way? This part was same in case of the voltage mode controller where pi controllers and all those scaling has been put into the block HP. And thereafter you will be sensing the current it can be sense by a very resistance with very low value of inductance or by all of a sensor, and that you put it and ultimately you will have a comparison.

So, you allow to current to grow and once this actually you have a scaling network and accordingly you required to scale it. So, it will be compared. So, when you have a voltage error current is allowed to grow, and thus voltage will build up when there is no voltage error. Then actually then the output of the comparator will be 0 and thus it will come down. And this is the principal of operation ultimately you have a scaled value of V c. So, once it touch V c it will come down and accordingly it will generate pulses.

There are 2 kind of current mode control one is called peak current mode control.

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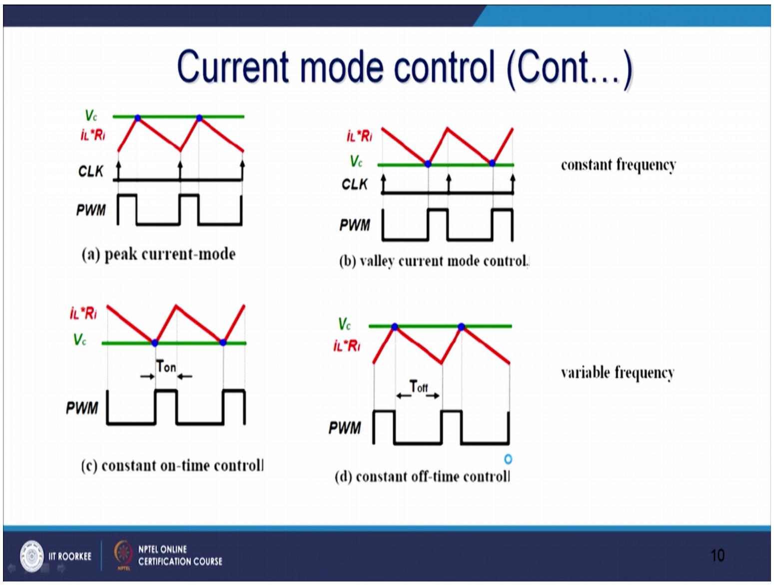

Another is called average current mode control and it can be operated in fixed frequency as well as the variable frequency. So, this is the peak current mode control whenever it touches some value of the peak current, generally it put at by a limited and that is depend on the switch stating and other devices that puts restriction on it. So, then you will get a clock pulse and you will generate the PWM and this is the peak current mode control.

This is constant on time control where frequency will change, but the value of this actually T on will be constant. And this is the constant frequency control in this case value of the T on and T off will vary, but frequency will same and similarly you can have constant of time control.

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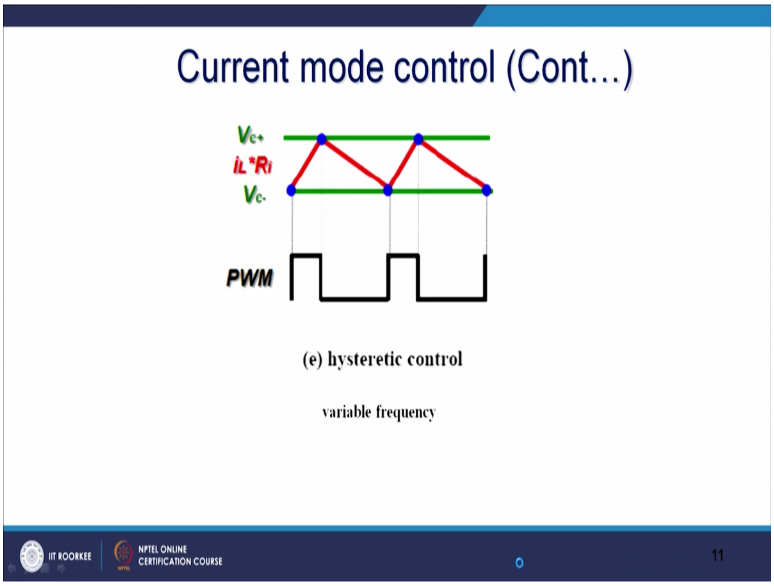

Now, we can have a hysteresis control that is a simple control and that is very frequently used for our facts devices applications. So, generally to avoid chattering we generate a band of plus minus and actually current is required to oscillate between these band. if it actually put to the higher band, then it then actually the switch which is transferring power will be off for the buck converter ultimately current will come down through the through the diode here diode been replaced by the MOSFETs again it will carry on. So, this is called a hysteresis controller.

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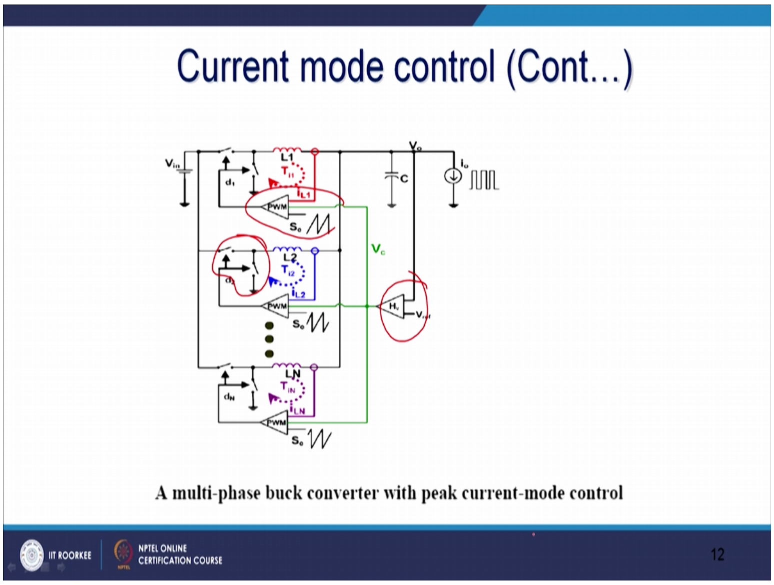

Hysteresis controller has a great usage in case of the facts devices also especially in a stack forms. So, see that current mode control, here is actually the volt upper voltage loop outer voltage loop and this is basically the inner current loop. So, what does it do you know.

So, this put an information and ultimately this operate this small switch and once this switch is operated accordingly actually current will pass and will be measured and this is basically the concept of the multiphase buck convertor. You know, if you require to increase the power density of the MOSFET power density of the convertor. Then generally we use this kind of concept called multiphase buck converter, where actually 3 buck converter multiple buck converter is connected if the same output DC bus voltage and same input DC bus voltage.

So, since you do not allow to off that much of time because of the huge amount of current required to flow. For where actually for this kind of thing is very much suitable for low voltage high power applications, and these are this what happened this most of the cases this category wave are phase shifted by some angle to accommodate. If there is a 2 such thing there 180 degree phase shift if there is actually multiple of it and accordingly it will be phase shifted.

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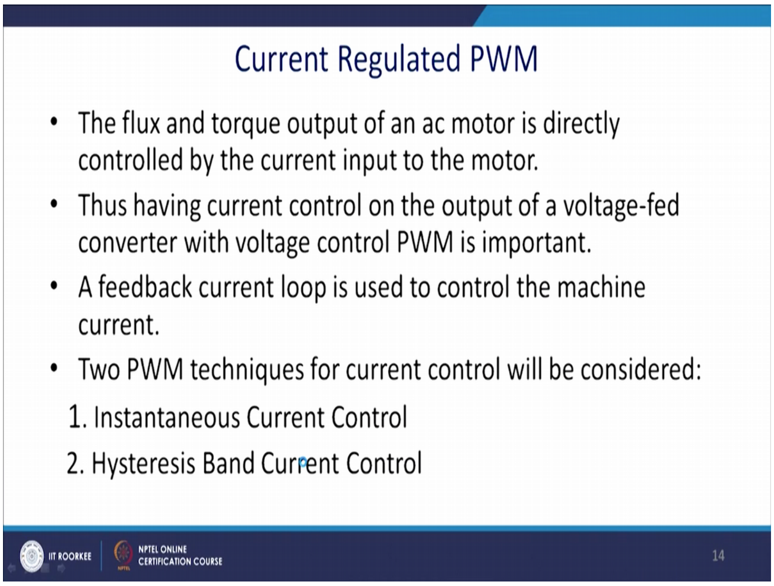

Now, current regulated PWM. This is very important for our thrives and the facts point of view, since the flux and the control torque output for the ac motor it directly controlled by the current. And same principle in used for the SATCOM for DQ based technique. So, current P current by PWM control has input to use for the facts devices.

Now, what you have generally a current control with the output voltage of through a voltage fed converter. So, it is voltage control. So, it is current control voltage source invertor essentially put into use, feedback current loop used to control the machines currents in case of the drives applications and for the facts devices for the actually for the stack of current.

And, you know we require we have two kind of PWM technique for the current control that is instantaneous current mode control and hysteresis band current control.

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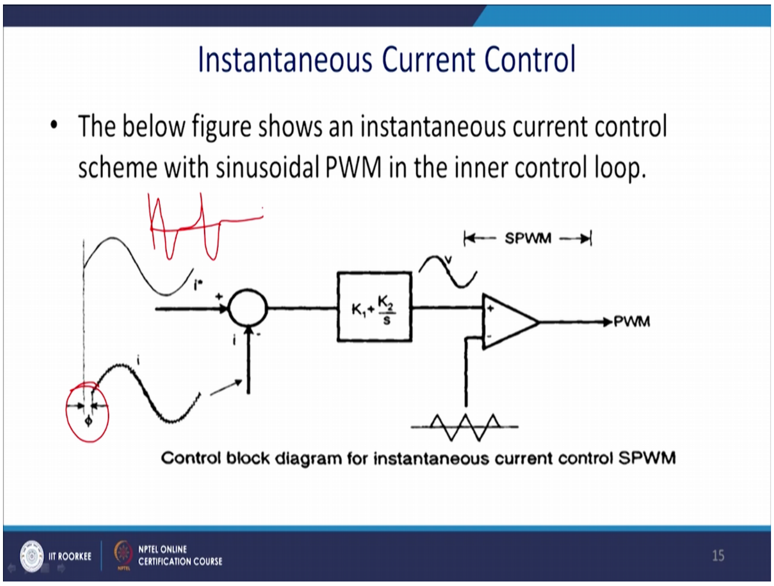

Now, this is instantaneous current control. You have this I reference which is AC, but why we discuss DC here you know actually most there is a SATCOM operation can be done in DQ frame, where this quantity actually will be treated as AC and thus you know it can be also the same principle what is has been used for the simple DC to DC converter, can simply be extrapolated for those applications when you are actually convert this abc frame to DQ frame.

But, anyway here let us consider that you have a ac reference and we are controlling the hysteresis loop here your consoling the instantaneous current. So, what happen you are basically may be actually injecting the current in the same case of SATCOM. So, you have the, I reference and ultimately this is the I actual it has been send back to you and there will be a little phase difference phi.

And that required to be eliminated, ultimately you compare it and you put it to the pi controller you generate actually a signal for the SPWM or different kind of signal for this actually for this active power filter you may have a this kind of peaky kind of single. This will be the reference and you have to track this reference essentially for the stunt active power filter, you have actually the harmonic contents of fifth several even 13. So, you have this kind of reference and it has to track that reference not necessary all the cases, this will be sinusoidal and that value would be set to generate PWM is case of the instantaneous current control.

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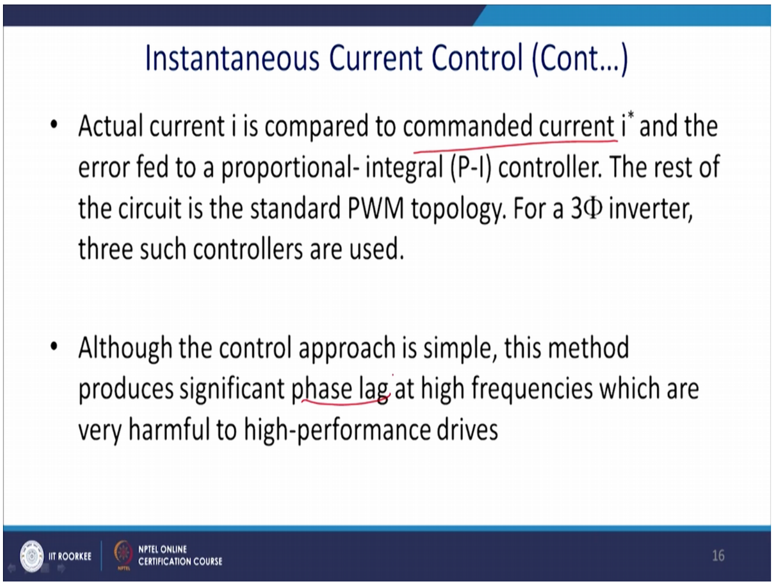

Now, what are the advantage of it here actual current i is compared with the command current i star and the error is fed to the pi controller. The rest of the circuit is a standard PWM topology of the 3 phase inverter and same control is used for the other 2 lag. And, for the 3 phase 3 wire systems generally will 1 lag actually to be control accordingly.

Although, the control approach is simple this method produces significant phase lag which I pointed out there is a delay in estimation. And of course, the delay can be compensated by a control circuits by a lead compensator, but designing an lead compensator also will be difficult where this delay is not constant. And high frequency, which are the very harmful for the high frequency drives as well as the SATCOM application.

So, instead of that we use hysteresis band current control that is more actually popular for it is simplicity, but problem is that you know there is disadvantage of it we will come little later.

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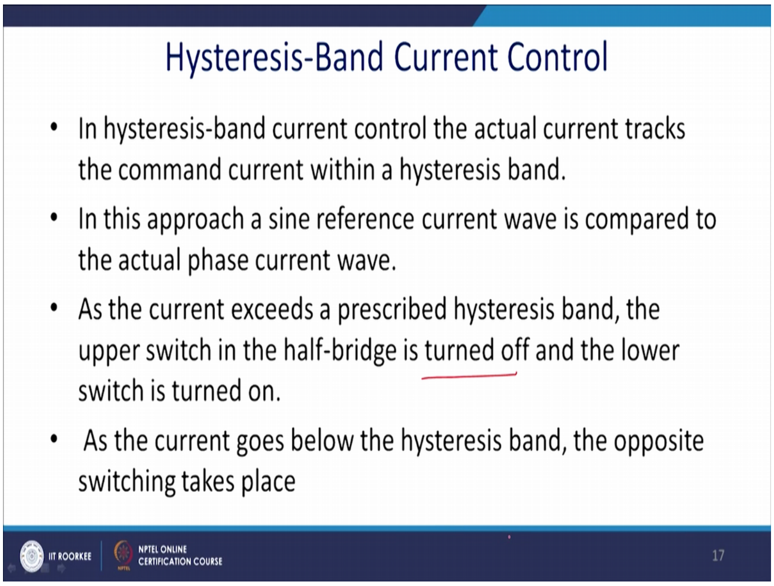

So, hysteresis band current control the actual current control current tracks and the command within the hysteresis band, which I have just shown few slides ago. In this approach, sign of other reference of the current is compared to the actual phase current; the current exceeds the prescribed hysteresis band the upper switch in the half bridge is turned off and the and the lower switch is turned on and when it is crosses the lower limit then the reverse applications happens.

The current goes below and the current goes below the hysteresis band and the opposite switches are been put into the application. This kind of band this is called actually constant band PWM.

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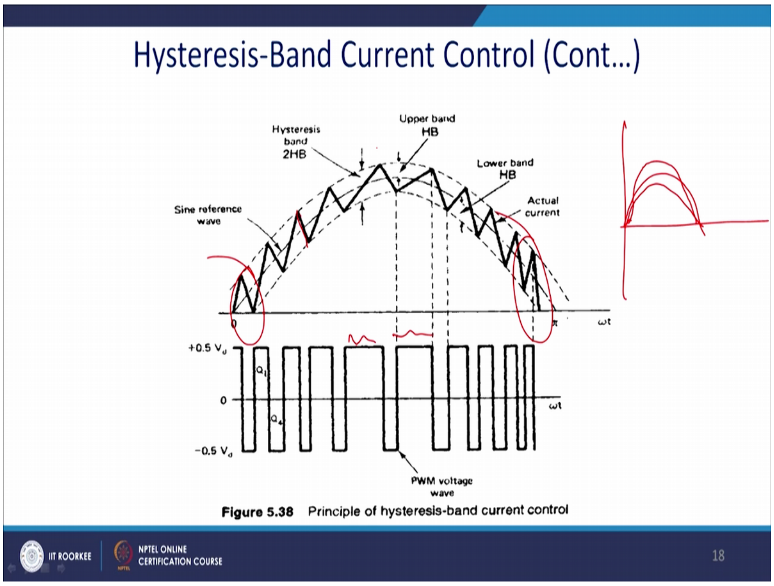

These are different kind of band it is an algebraic band PWM we may have also proportional band PWM. So, this is sine wave. So, this is the lower band and this is the upper band.

So, let us discuss about the constant band PWM, which it can be you can generate a band op amp pretty simply. So, essential let us consider a 2 level inverter. So, actually this is the switching off it. And, once it hits the upper lag. So, correspondingly the lower lag will be on and ultimately, you will get the lower voltage. And once it is stop and hits the lower band and upper lag will be on. It is quite similar to the PWM sine triangle PWM, which has been already it is been seen. You can see that this actually width are quite big in duration in middle to reciprocate the area of the sine curve and it is almost same of the sine triangle PWM.

But, problem lies the frequency of this actually this current is not constant it is variable. So, designing filter for it little painstaking.

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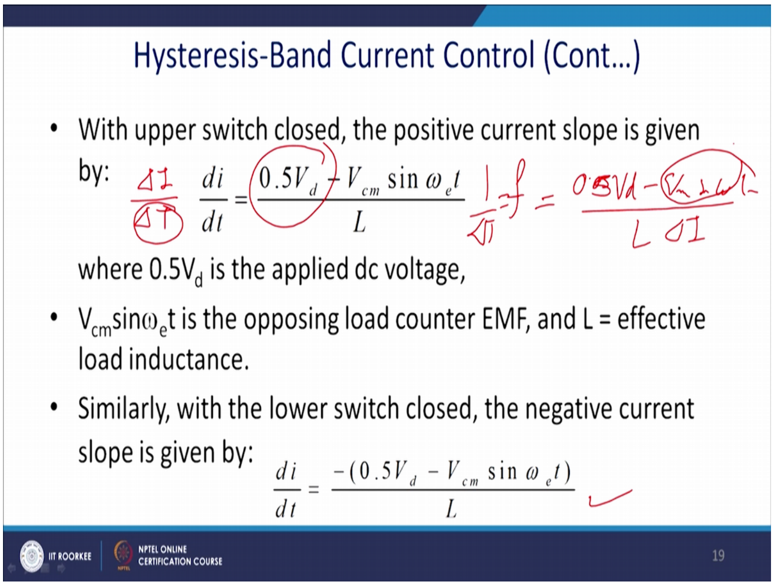

So, let us analyze it so L di dt equal to equal to V dc minus p sin omega t. So, essentially this is for actually the voltage of half bridge pdc minus the current mode voltage V sine omega t. Now, what we can find we can actually reduce this equations. And since, sin omega t is varying plus l di dt is varying. Since, you have you can assume that the del you can write the 0 it is equation as del I by del t and del t you can think of as actually 1 by del t you can think of about the frequency.

Since value of del I is constant we can say that frequency is varying. So, what happened here? V sin omega t opposing the load current and L effective of the inductance, similarly in the lower switch this is the equation it is basically minus point V d minus V m sin omega t by l. So, there few thing we required to keep in mind why this frequency varies.

So, we can write 1 by del t as f equal to this 0.05 0.5 V d minus V cm sin omega t by L into del I. So, what happen here you can see the frequency is maximum when v sin omega t is 0 and it is minimum at the peak. So, you will find that as you have you can see this wave form here frequency is more here frequency is more and here frequency is less. So, one of the disadvantage of it is not a constant frequency operation for designing the filter for it is been taking. So, let us see that what happen here?

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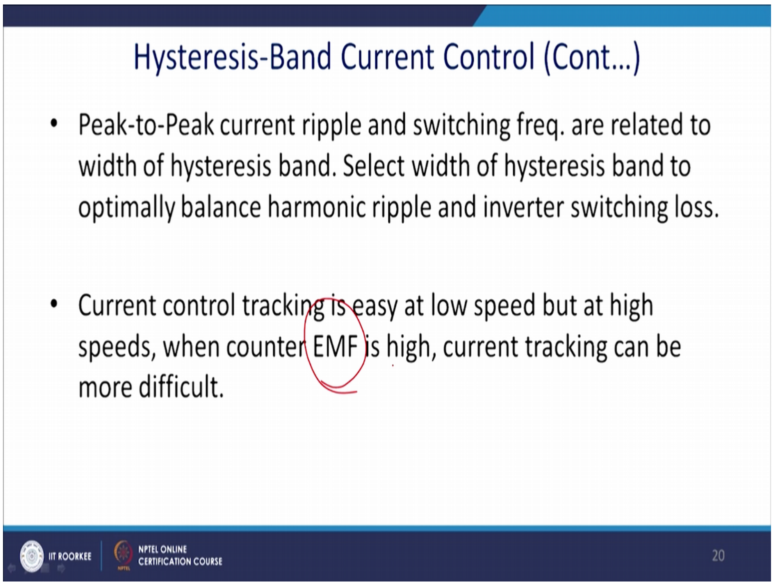

Peak to peak current ripple and the switching frequency are related to the width of the band. Of course, because it is a ramp size tramp will be taken on that much of time select width of the hysteresis band to optimally balance the harmonic ripple. And the convert a switching losses that is very important thing we have to keep in mind. And current control is easy is at low speed, but in high speed since actually since encounter any high value of EMF current tracking will be more difficult, but since our particular cases we have a fifty years supply it works excellently. Apart from the pain we required to put it for designing the filter.

So, now let us see that how you design it?

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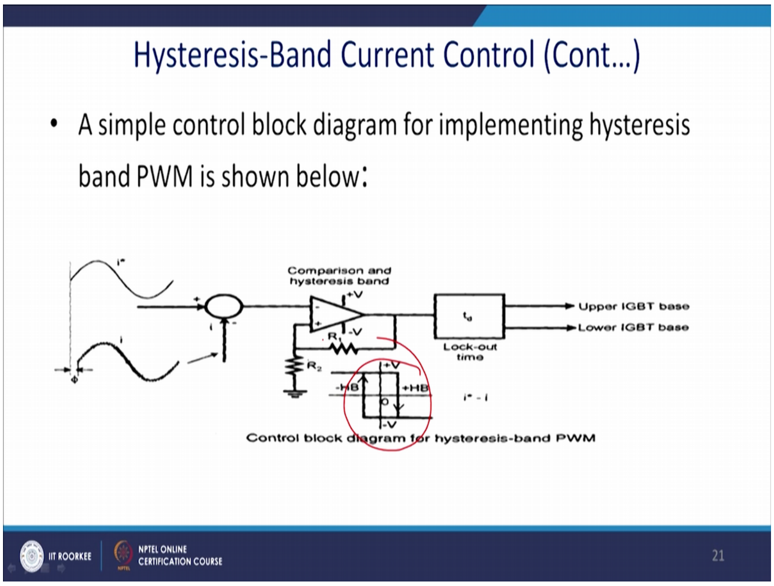

This is I told you that it can be generated by the simple an op amp. So, this is an op amp in a positive feedback as it works in a hysteresis manner. And this is the actually the hysteresis loop and ultimately from the lookout time t d upper in the lower switches will be on, this is a very simplest implementations of hysteresis control.

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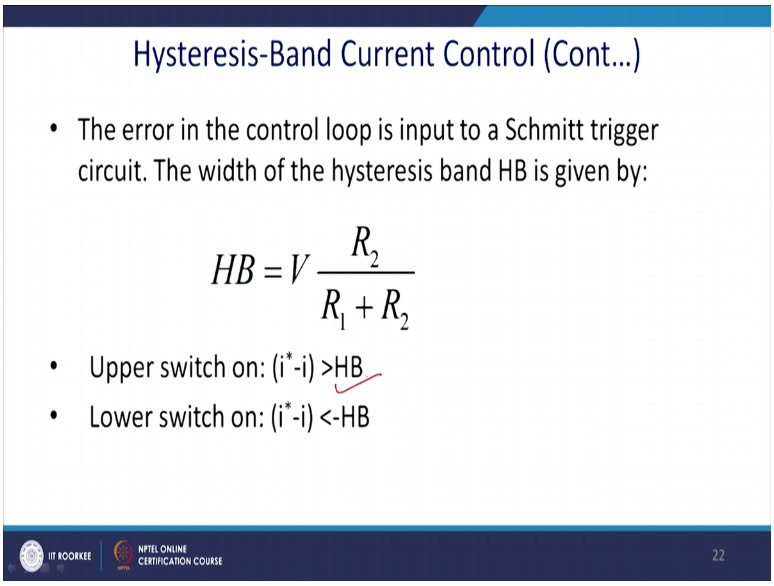

Now, how we can generate this actually hysteresis band you can actually you `can take the ratio. So, this ratio will be R 2 by R 1 plus R 2 it can be 1 percent it can be 5 percent depend on optimally, you can turn it on depending on the switches. And when upper switch is on when it low goes to the upper circuit and when minus HB, it goes to the lower switch should be on.

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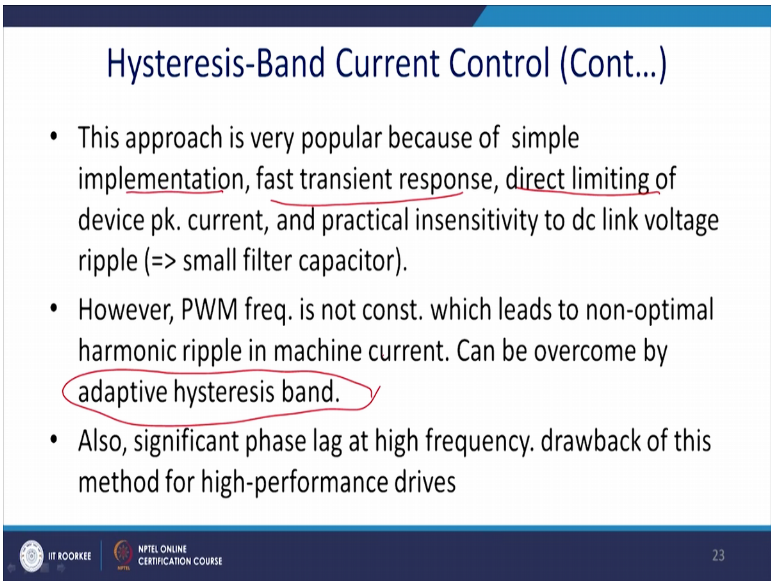

So, in this approach because this approach is very popular, because it is very simple to implementation fast transient response there is no phase delay. And direct limiting of the peak current and for this is an it is very frequently used and there is a smaller DC link voltage because of it is fast action.

However, that is the disadvantage of it like the PWM sine triangle PWM, it is not a constant frequency operation, which leads to the harmonic ripples of the machines as well as the selecting harmonic elimination all those things and can be overcome by adoptive hysteresis band, where actually value of del I will change according to the back EMF or the actually point of common coupling of PCC in case of the stack and also significant phase lag at high frequency, that is noted on a constraint for our facts devices, but for the high frequency application this is with a constraint ok.

Thank you.