Advance Power Electronics and Control
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Lecture – 18
PWM Rectifiers IV and Power Factor Improvement Techniques II

Welcome to our lectures on the advance power electronics and control. Today we will continue with the PWM Rectifier the power factor improvement techniques. We are discussing basically the control current waveform for the CPM mode same we shall continue in our coming class.

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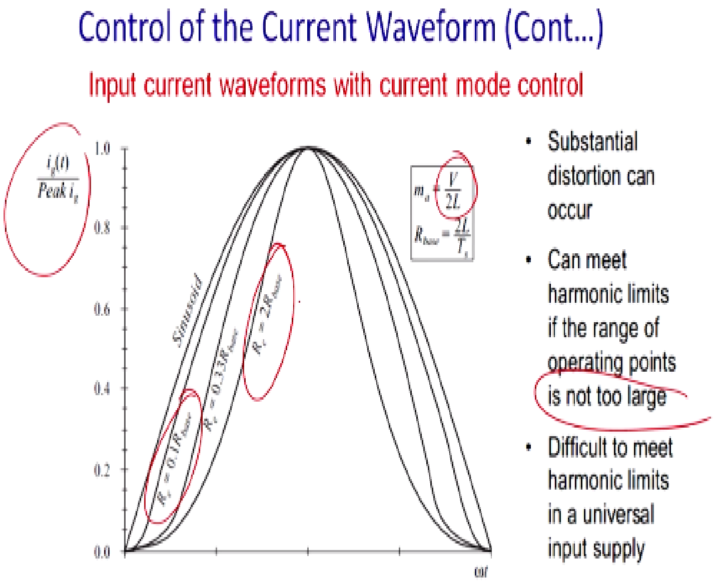

Essentially you know these are the frequency response you know. So what happen you know this is the basically the sinusoidal waveform and this value is basically a modulated index is something of the slope and R base is 2L/Ts and the peak value is basically easy it is a normalized value. So what happens you can see that when actually I base value R becomes 2 I base than actually distortion comes.

And distortion will be lower actually we have Re=0.1 R base and this is the actual sinusoidal. So more and more actually the current waveform will be picky if this Re is more than R base. So we can meet harmonic limits if the range of the operating points is not too large. So if it is actually huge variation of the load current that is form Re=10 R base to 1 R base that is what we have seen in this waveform.

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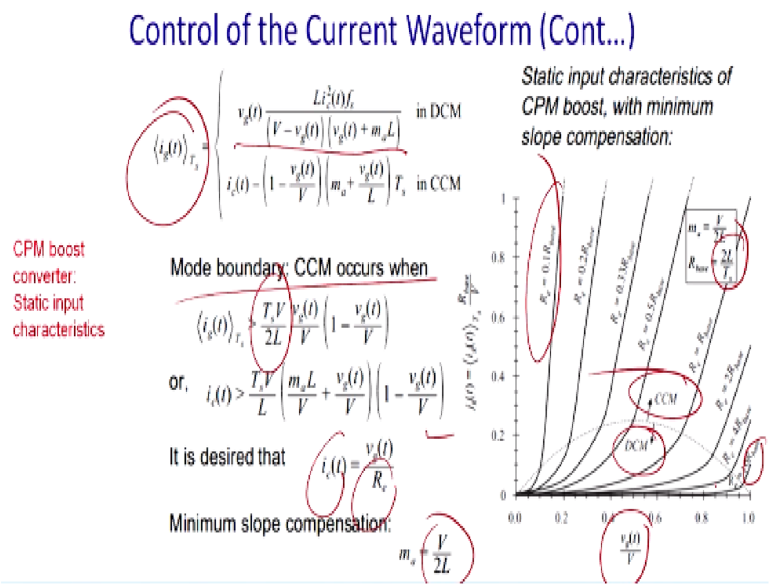

Then what will happen in this range so we may not actually have a control over the THD of the desired THD. So we have a control over the THD in a short range of time so accordingly it will be designed. And thus what happens when it has a distortion we cannot control the harmonic contain of the system. So difficult to meet the harmonic limits in a universal input supply.

This is one of the biggest disadvantages of this boost type power factor corrections, but you can actually for the fixed load it is very well designed, but if there you have a very huge variation of the load. So it may have a problem of the distortions. Now to overcome this we can think of some hysteresis controller, but what happens you know till now you had a constant switching frequency and all those things.

So your switch you can choose a particular switch choosing on the particular frequency. Moreover, your design of the boost inductor become easy you know that actually this is your switching frequency. Once you go for this hysteresis control your switching frequency is not fixed, but you can have some added advantage but it is limited by some percentage of it so you can approximate it.

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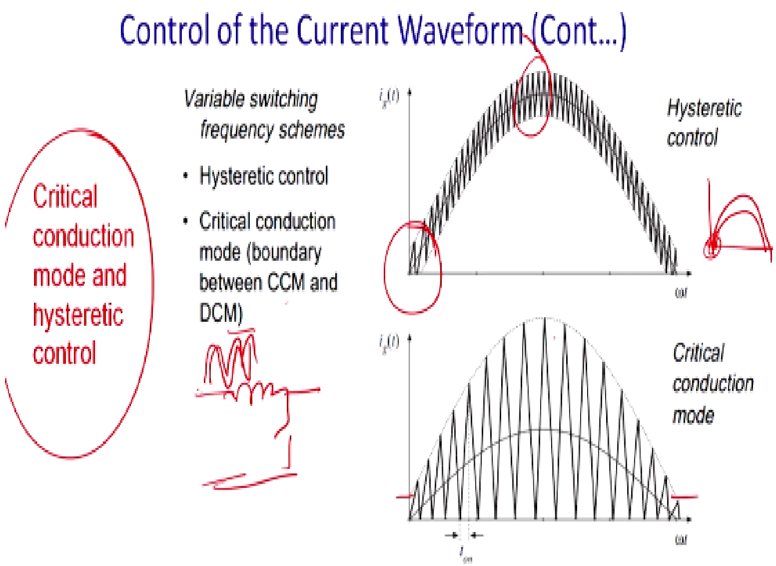

And thus what happens you got a hysteresis control this is a hysteresis control. What happen you have this vg which is basically nothing you have vg after rectification you got a ripple kind of voltage thereafter you have a boost topology. There you generate a envelope a hysteresis envelope which can be generated by a single open positive or negative band and you can keep the current within a positive or negative band. So you can have a different kind of band this is called actually constant band.

You can have some band is something like this it is called proportional band 1% band because here it will be 0 and here it will be more and ultimately then you can see that actually here current required to be frequency is very and frequency is quite low. And also here you can see that here frequency if you keep it like this you can see that frequency here is low and here it is high.

So you do not have cost and frequency operation and you can have this kind of operation that is called proportional operation this is another mode of control or there is one Fairchild chip that operates in this mode and UC 3854 operates in this mode. The critical condition mode of boundary between the CCM is actually what happen you know you will allow the current to grow according to your voltage limit.

So you will have a voltage envelope so and you will give some DC biasing so that you can get a minimum current. So accordingly as this envelope changes you know currently you allow to go and strike this envelope and thereafter current will be switching and a petal type of waveform you may get and you may have a interleaved boost converter there is interleaved between another A they can super impose it and almost you get a sinusoidal waveform.

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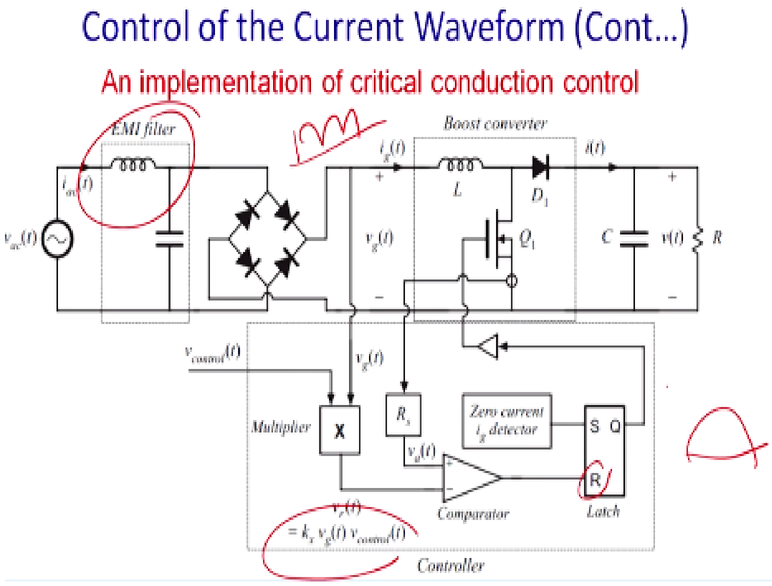

So this is the way of implementations of hysteresis control. Since you have high frequency switching and you have a EMI EMC filter generally it suppresses the conducted noise and you have vg that is of this pattern. Thereafter you sense it thereafter you multiplied you have a kg and you have a same thing. What happened you know you got a ig zero crossings detector. So it will actually fit it here and ultimately current you will be allowed to ramp on till actually it touches this envelope.

So it has envelope so once it touches that envelope that will be reset again current will come back then again actually once current touches zero then again it will be reset and current will be allow to ramp on till it is actually touches the envelop in this pattern or this pattern. This is the way of operation of the critical conduction mode control.

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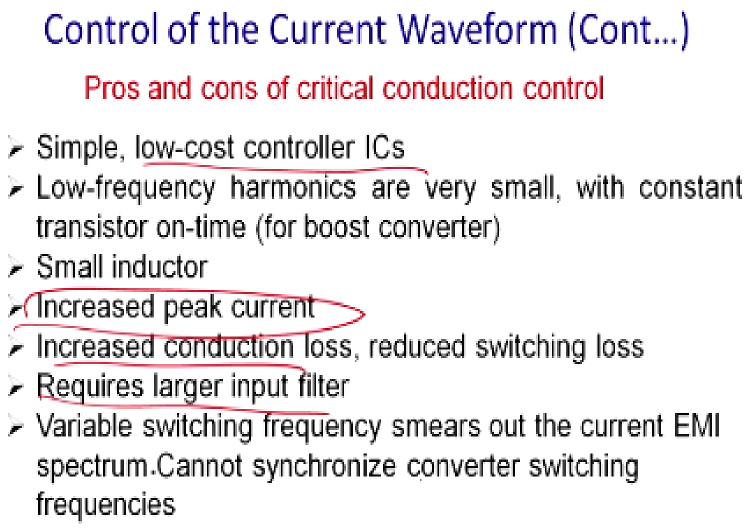

So what is the advantage of it. This is the pros and cons of this actually first take the advantage rather simple and then low cost ICs. So it does required to sense the vgt that is rectified ripple voltage and accordingly when it touches this actually upper envelope switch will be off. Low frequency harmonics are small with constant transistor on-time for the boost convector and size of the inductor will be less.

Because it can operate in a discontinuous conduction mode because there you can find that in a continuous mode control is quite difficult, but disadvantage is this basically it increases the peak current and current become peaky and thus when current become peaky the biggest disadvantage of it is that you have a problem of EMI EMC. Then thus increase conduction loss and reduce switching loss require larger input filter, filter it out, variable switching frequency.

And smear out the current EMI spectrum cannot be synchronized with the converter switching frequency and this bleach band actually leads to the radiated noise. So these are the disadvantage of actually control current mode waveform.

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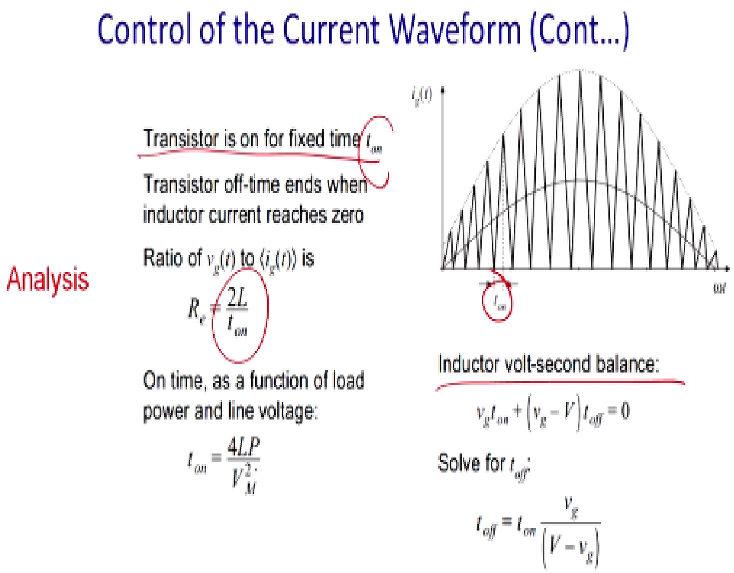

Now we shall ensure that transistor is on for the fixed time t on. So this is you have a on time control. Transistor off-time when inductor current reaches zero. Please refer to this actually the model how you reset it and how it has been triggered here. So the ratio of Vg to I gt is actually Re 2L/ t on and on time is a function of the load power and the average voltage. So it will be t on will be actually 4 LP/ V square M and the inductor volt-second balance you can do and from there actually you can calculate that actually if it is around 50% 30 off= t on that= vg=- of this value.

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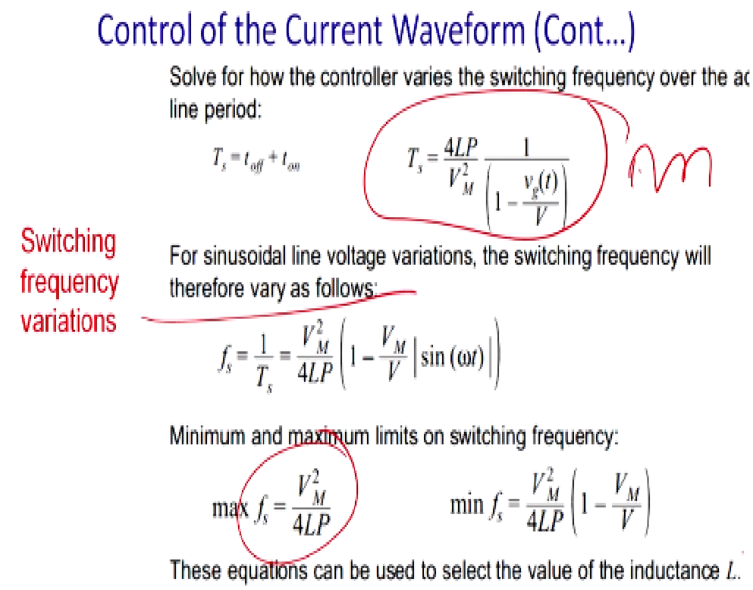

Now solve for how the controller varies the switching frequency over the ac line period. So Ts= t off+ t on. So Ts you know that this depends on the parameters which has been described here that is basically average power, power and the average voltage and the value of the inductor. So you put it like that ultimately Ts will be VM squares actually it will be variable since basically vg varies vg is a ripple DC voltage.

So for this reason this term will vary ultimately Ts will vary. So when you will have a maximum switching frequency when this value actually close to 1 basically it happens once it is at the peak. So the peak you will have a large choosing frequency or a higher switching frequency and at the zero crossing we will have a lower switching frequency. So similarly for a sinusoidal voltage variation the switching frequency will be varied as follows reciprocal of it that is V M square/4 LP 1-VM/V sin omega t.

And from there you know you can calculate what should be the maximum value of fs that V M square/4LP and the minimum value of fs VM square/4 LP 1-VM/V and this equation can be used to select the value of the inductance, but depends whether you have a large variation or not. So it is very difficult to design inductor because inductor has to set for its switching frequency.

And if it is a wide range of variation if it is actually within a mean value varies 10% it is fine, but of course you know if frequency varies 1 kilohertz to 2 kilohertz or actually 10 kilohertz to 20 kilohertz it is very difficult to design those kinds of inductor and then you will find that roller will be defined because value of the inductance will change according to the switching frequency please mind that.

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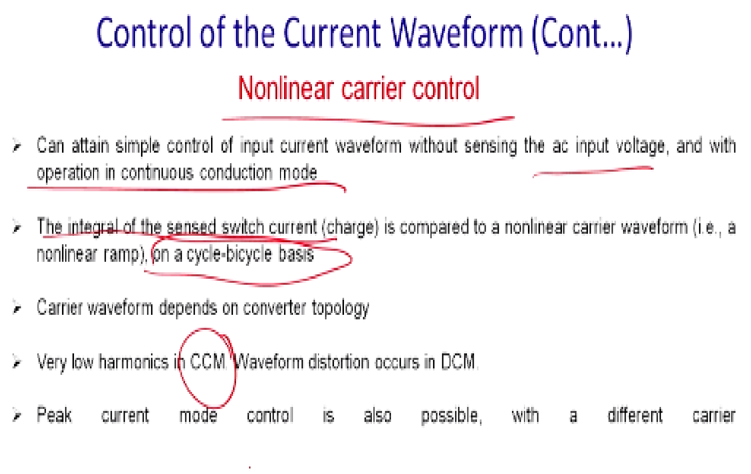

So to control the current waveform we have a following discussions. So it is essentially a non linear control because switching frequency is variable and instead of the average current mode control you have a variable control and can obtain simple control input waveform without sensing AC input voltage this is also possible and with the operation of the in continuous conduction mode.

So you do not require any input in your ac system. Mind you this same kind of system will work for the single phase system, but we require to change for the 3 phase system because 3 phase does not have a replica to find it out. So we required to do some kind of modifications to use it for a 3 phase system. The integral of the sensed switch current charge is compared to a nonlinear waveform and a linear ramp and by a cycle bicycle basis.

Carrier waveform depends on the converter topology. So if you have a boost topology it will be something else and it is a buck topology it is something else. Very low harmonics in continuous conduction mode, but waveform gets distorted in case of the DCM so it is very sensitive to the load. If load changes and your transistor occur DCM to CCM then you will that THD is not acceptable to you. Peak current mode control is also possible with different carrier.

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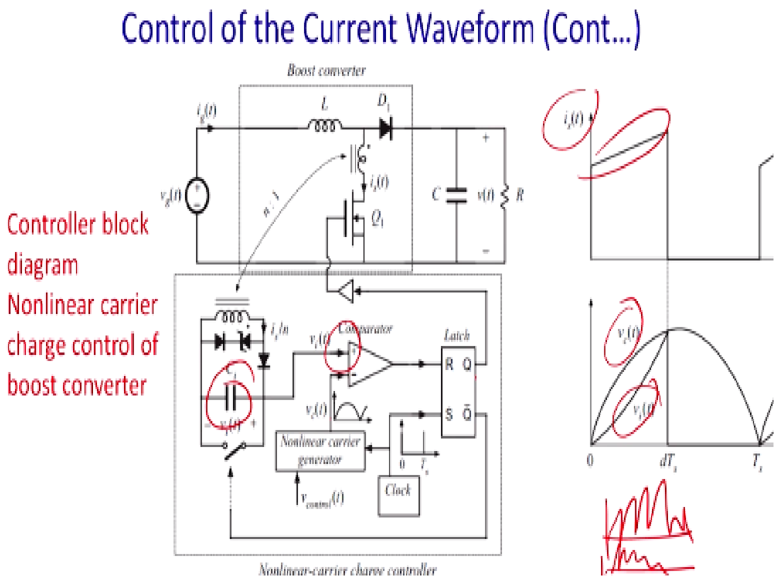

So for phase shift different carrier is also possible so that you have a petals kind of waveform another petal may be phase shifted by 30 degree you may super impose it and thus what happen or you get a better THD. So this is a control of the current waveform. Now you got a Ct so ultimately you sense this current and now it has been actually rectified and stored into the capacitor.

And of course you can discharge this capacitor by a switch. So then this value is spread to the comparator and what happen you got this rippled DC and you can see the petals of it so it required to be compared. So this is the value of is t and this is the value of the vc and ultimately this will be value of V and this is a way of actually current will increase and this will be the Ts.

So ultimately again it will be reset for the clock pulse once this linear carrier is over and again capacitor will be discharged after when it will be required to reset the flip-flop to capture the second cycle.

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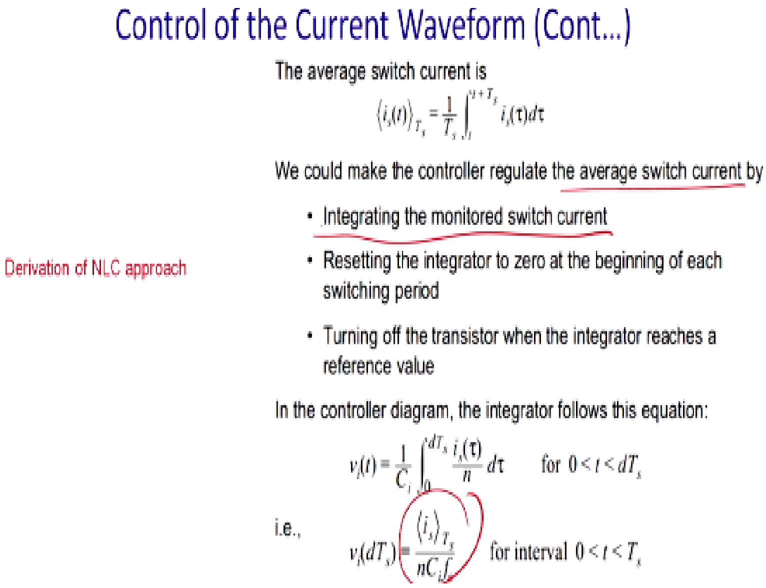

So average switching current is basically this we can make the controller to regulate average switch current by integrating it. So essentially integration can be done by the op-amp with the capacitor feedback. Integrating monitored the switch current resetting the integrator to zero at beginning of the each time period. See that this is basically the integration part of it so it will store the integration of the current.

And you will reset it at this beginning of the each cycle. Turning off the transistor when integrator reaches the reference value In the control actually diagram in the integration as follows so v1 should be=1/C 0 to dT you have to integrate over it. So you can get that basically vi is basically i s by n is a number of turns ratio of the transformer or the Ct *Ci*the switching frequency fs.

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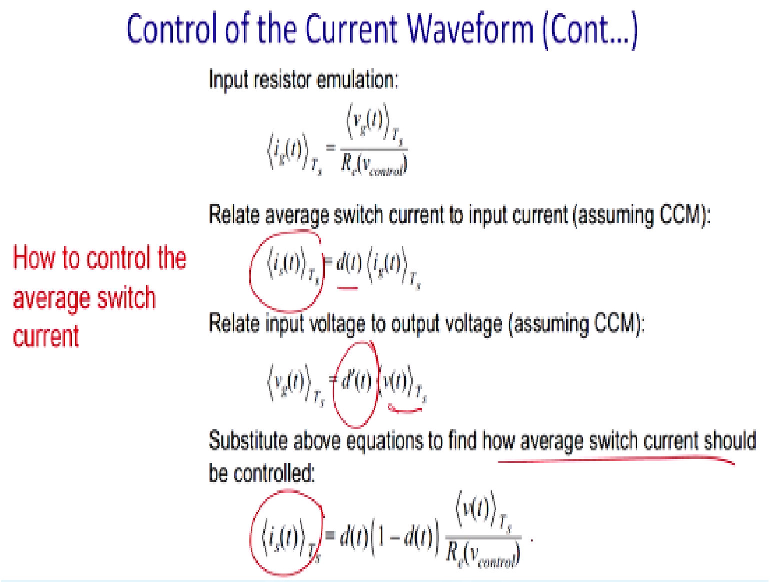

So what should be actually the emulated resistor. Emulated resistor as you know that it is Re that is ig Ts= vg/Re so it will be vg/ist= dt there is the duty cycle*ig Ts. Relate the input voltage to the output voltage and we assume that it is a continuous conduction mode then vg Ts= d dot *vt. We have please recall in our previous class we have done the actually small signal model so from there we can relate it.

So substitute the above equation how average switch mode should be controlled is i s=dt 1-dt vt/Re v control. So this way you can control this actually charging of the capacitor and thus the current of the switch.

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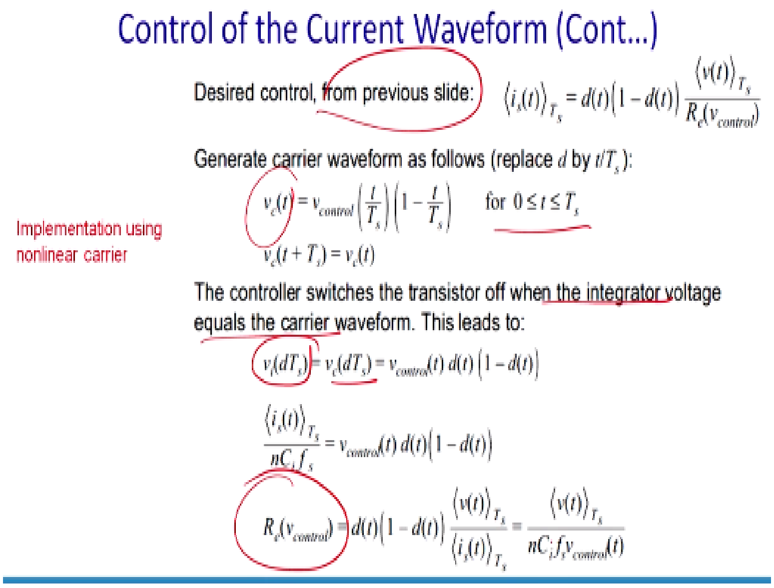

So to desired control from this previous slide we can re write it as i s=dt 1-dt* this one from there the control voltage vc become actually v control t/Ts 1- T/Ts for this and vc t+Ts= vc t.

The controller switches the transistor of when integral voltage basically= carrier waveform and leads to this actually this vi dTs should be=vt dT and thus that should be=v control dt*1-dt and we can do a little approximations and after doing this approximation that this emulator resistor with a control becomes dt 1-dt vt/is t/Ts.

So ultimately it leads to vt n Ci fs v control. So this will be the emulated resistance in case of the current control mode.

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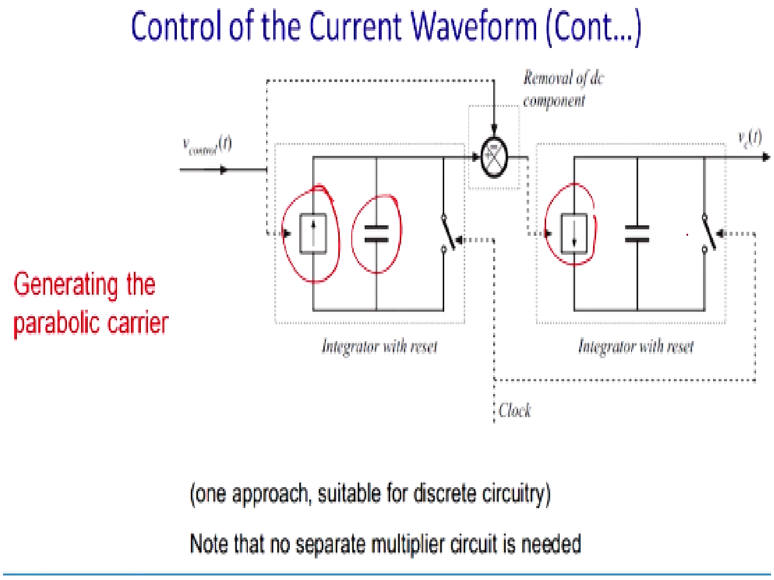

So essentially the block diagram become this. You got a v control and you got actually the current switch and you got a capacitor. Capacitor is required to be reset in every clock pulse. Staring of the clock pulse ultimately it will compare with the vt. Once actually this results becomes this becomes a current control and integrated go into reset by this switch. So please note that this is a way actually we operate this actually continuous controller mode of operation for this converter. So this is the explanation of this converter.

Now we have discussed for the boost PWM technique and its different way of control. Now but it is restricted to the single phase supply and thus is restricted to the low power applications, but in case of the higher power applications and the 3 phase system this kind of system required to be modified because after rectification you know if it is a diode-bridge rectifier you have a 6 pulse waveform.

So that the 3 phase waveform pattern is missing and you have a constant DC value and for this reason all the methods is required to be change. Let us see let us have some analysis now on power factor improvement techniques. So essentially you know that in power electronics we have a displacement power factor and the actual power factor.

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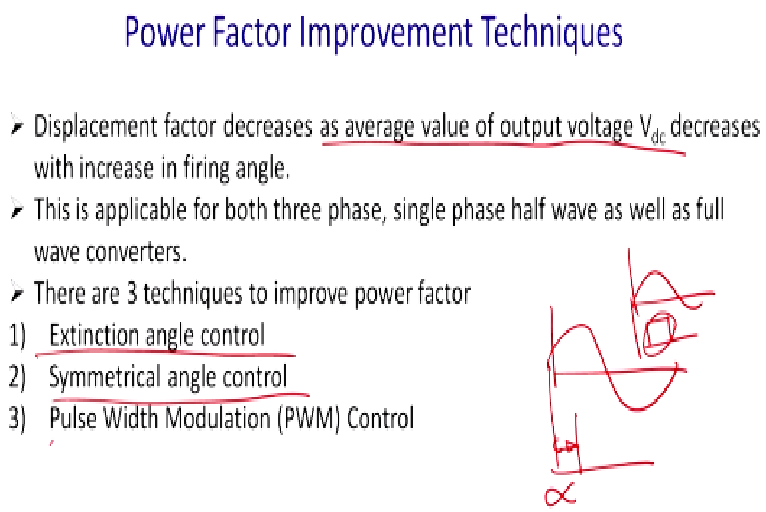

Displacement power factor decreases as average value of the output voltage Vdc decreases with increase in the firing angle. Since this is your sinusoidal waveform you are triggering at an angle alpha if you are increasing the alpha your displacement power factor is going to be increased and thus you get poor power factor. This is applicable both 3 phase as the single phase waveform as well as full waveform full bridge, half bridge so all kind of things.

There are 3 techniques to improve power factor. We have seen while discussing with the different pulse converter that is 6 pulse converter, 12 pulse converter, 24 pulse converter, 48 pulse converter. So we can see one thing that is a extinction angle control. Generally, thyristor can only give you turn on control turn off control is not possible. So we require a full control switches like GTO or IGBT have a full control switches and to have a extinction control.

So that you can actually you have a sinusoidal waveform, you can chop here and chop here. So current waveform may be this, but it may have a THD, but it can have a unity power factor. Similarly, you can have another method that is symmetrical angle control. Third method that is quite important method is pulse width modulated PWM control. We shall see all one by one.

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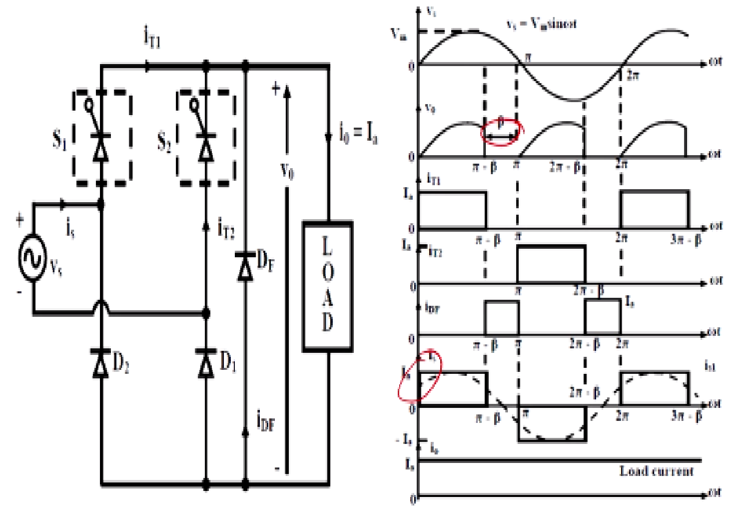
Extinction Angle Control



Now see that extinction angle control so what happen in this case. If it is required to be line commuted it you require GTO otherwise you can have a actually a current that can be leading so you can do that. So what happens your sinusoidal voltage and you have actually chopped it before 180 degree and thus what happens you know this actually this is the current through the thyristor and input of this current is given by this.

And you can find that the fundamental of this actual input current is basically the leading because we have chopped at an angle beta. So this kind of thing is called the extinction angle control.

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Extinction Angle Control cont.

- Here this control technique is applied on single phase full wave half controlled force commutated converter.
- Thyristors T_1, T_2 are replaced by self commutated switches (power transistor or equivalent).
- In this control technique S_1 is turned ON at $\omega t=0$ and turned OFF by forced commutation at $\omega t=(\pi-\beta)$
- S_2 is turned ON at $\omega t=\pi$ and turned OFF at $\omega t=(2\pi-\beta)$
- Output voltage is controlled by varying extinction angle β.
- In the waveform, fundamental component of input current leads input voltage. So displacement factor is increased.
- This technique is useful to simulate capacitive load without line voltage drop.

So this control technique is applied on single phase full wave half controlled forced commuted converter. Either you have to have a forced commuted converter or you should have a GTO. Thyristor T1 and T2 are replaced by the self commuted switches power transistors or it is equivalent IGBT, IECT, GTO. This controlled switch S1 is turned ON at omega t=0 and turned off by the forced commutations when omega t= pi-beta.

So the turn on at omega y=pi and turn off at 2pi- beta. Output voltage is controlled by varying the extinction angle. So you have a integration change and the waveform of the fundamental component of the input current leads the input voltage and thus so what happened displacement power factor is increased and this technique is useful to simulate the capacitive loading without line voltage drop. So this is quite actually good applications for it

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Extinction Angle Control cont.

The average output voltage is

$$V_{dc} = \frac{2}{2\pi}\int_0^{\pi-\beta} \sqrt{2}V\sin\omega t\, d(\omega t) = \frac{\sqrt{2}}{\pi}\cdot V(1+\cos\beta)$$

The value of V_{dc} is varied from $(2\sqrt{2}/\pi)V$ to 0, as β varies from 0 to π.

The rms value of output voltage is

$$V_o = \left[\frac{2}{2\pi}\int_0^{\pi-\beta} 2V^2\sin^2\omega t\, d(\omega t)\right]^{1/2} = V\left[\frac{1}{\pi}\left((\pi-\beta)+\frac{1}{2}\sin 2\beta\right)\right]^{1/2}$$

Here also, V_o varies from V to 0.

Now let us see that what happens to this average value and we have actually started at angle alpha now we have a extinction angle control you will actually chopped at an angle beta. So for this reason the average voltage Vdc will be actually you can write it 1/pi 0 to pi-beta under root Vm sin omega t root 2/pi So you can get if you do that integrations effective value will become actually V+ V cos beta.

So value of Vdc is varied from 2 root/pi to 0 as actually this beta varies from 0 to pi and similarly you can have the rms value that is v0 you can same way integrate over it 2/2 pi 0 to pi-beta V square sin square omega t dt= V/1/pi pi-beta+half sin 2 beta to the power half. So again you have a double frequency repel and all those things so this will be the value and V0 also varies from you can see that you can choose pi= beta and we can have also if it is pi then also this value becomes 0. So similarly this value can also vary from V to 0.

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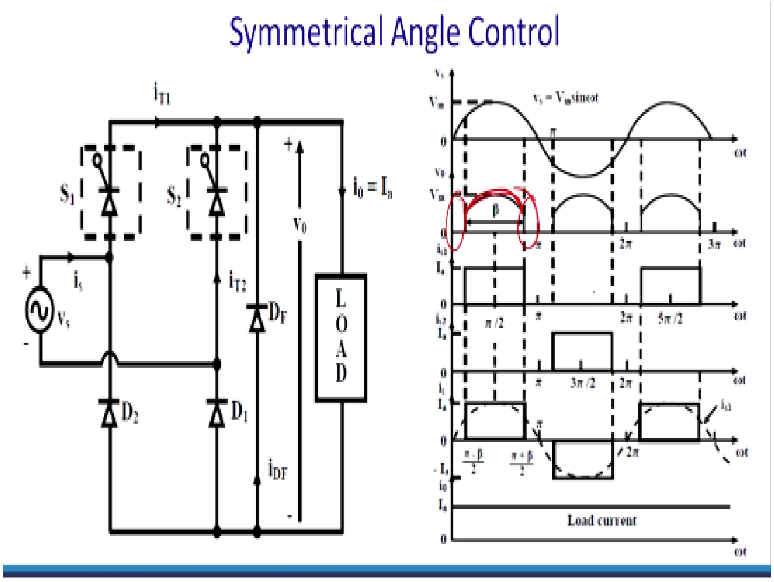

Now another is a symmetrical angle control so you will chop from both the sides so you chop this side as well as this side. So what happen here you have a upper 2 thyristor and thyristor can be actually commuted it or you can have a forced commutation or you employ GTO. So you trigger an angle alpha and thereafter you actually tear it off at an angle actually beta. So you get actually this part of the performance and so on it will continue and we assume that load current to be continuous.

So thus you have i s something like this and source current I will be actually steps and the fundamental of it will be the sinusoidal one and you can see that it is at unity power factor. And by changing this actually conduction angle and extinction angle you can also change the power factor of it.

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Symmetrical Angle Control cont.

- This control technique is applied to single phase half controlled force commutated bridge converter as prev. technique.
- Thyristors T_1, T_2 are replaced by self commutated switches S_1,S_2.
- S_1 is turned ON at $\omega t = (\pi - \beta)/2$ and turned OFF at $\omega t = (\pi + \beta)/2$.
- S_2 is turned ON at $\omega t = (3\pi - \beta)/2$ and turned OFF at $\omega t = (3\pi + \beta)/2$.
- Output voltage is varied by varying conduction angle β.
- Gate signals are generated by comparing half sine waves with a DC signal and half sine waves can be generated by using full wave diode rectifier.
- Gate signals can also be generated by comparing triangular wave with DC signal.
- Fundamental component of input current is in phase with input voltage. Thus displacement factor is unity. So power factor is increased..

So this control technique is applied to the single phase half control force commuted which converter as shown in the previous pattern. Thyristor T1, T2 is replaced by the self commuted devices S1, S2. S1 is turned ON at pi-beta/2 and turned OFF at pi+ beta/2. So beta should be the angle of conduction. Now S2 is turned ON at 3 pi-beta/2 2+3pi+beta/2. Output voltage is varied by varying the conduction angle beta.

Gate signals are generated by comparing half sine waves of the DC signal and sine wave can generated by using a full wave rectifier either of it. The gate signal can be generated by comparing the triangular wave with a DC voltage and fundamental component of the input component is in phase or you can change if you wish you can then we have to have a different little change of this value.

Input voltage and thus displacement power factor is unity. So power factor is here also it is improved. So you can do the control like this so this is the actually the triangle wave and this is the DC the controller voltage. Ultimately you will have here you will turn it on and here you will turn it off. So this angle is beta and you can change this level accordingly you can get a lower conduction angle.

And you can bring it down you get higher conduction angle. So average output voltage is same way you can integrate. So you will find that 2 root 2 pi Vm sine beta/2. Similarly, you can calculate the rms value for pi-beta/2 to +beta/2 V square/2 sine square omega t. Ultimately you get V/1/pi beta+ sin beta. So this will be the average value and this will be the rms value for continuous conduction mode.

So for actually symmetrical control we shall continue to the another method in our next class. Thank you for your attention.