Power Quality Improvement Technique
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Lecture – 26
PWM for Voltage Source Converter - IV

Welcome to our NPTEL courses on the Power Quality Improvement Technique. Today, we shall discuss this last part of this PWM converter and will be discussing one important topic. That is, SHE. So, one of the problems of the sine triangle and the SPWM is that higher switching frequency and thus it has a huge switching loss. So, for every switching period it will turn on and turn off. Of course, it is switching on and off in 2000 time or 20000 time depending on the switching frequency.

Another issue is that, with a higher power rating we require to reduce the switching frequency. For the example GTO. GTO is operated below the 1000 kilohertz and this method is preferred mostly in GTO or thyristors having the commutations involved.

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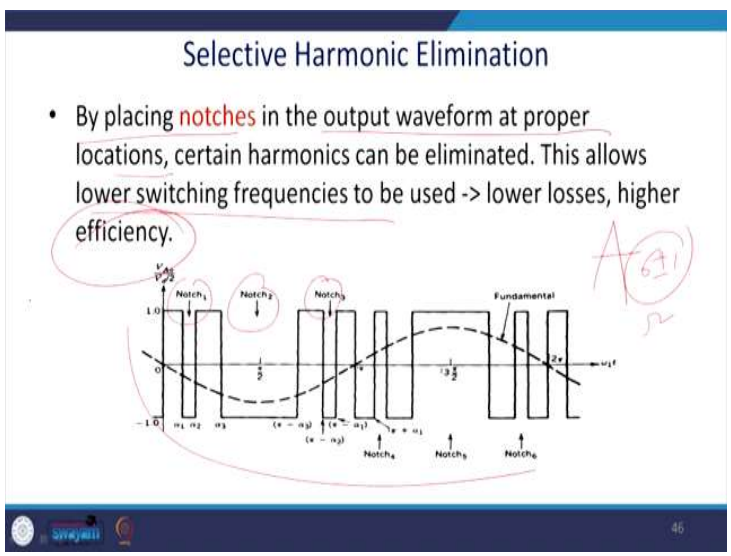

So, in this wave what happened? We know we have discussed in the square wave inverter and its THD and other problem. So, we know that if it is 3 phase 3 wire system and it content harmonics and how to reduce this harmonic that is a one of the method. We have discussed in detail that what are the effect of the harmonics. So, we are not going to that in detail here. We are discussing that it can be eliminated from beginning stage. That is all it is.

By placing notches in the output waveform these are the notch 1, notch 2, notch 3 and ultimately these are the fundamental. It is just like you play a guitar and you touch by hand or the metallic bar and there you create a node. Same way that when you create a node, a particular harmonic will be eliminated from the system and thus you generate a particular tune. Same way you can particularly eliminate your unwanted harmonic here.

In the output waveform at the proper location certain harmonic can be eliminated. Generally, what happens? If you see 5th harmonic is a form with respect to 6th harmonics. 6th harmonic is a co-phasor. Since third harmonic is a co-phasor, 6th harmonic and multiple are the co-phasor. With respect to 6th harmonic your 5th harmonic is a negative sequence harmonic and a 7th harmonic is a positive sequence harmonic.

So, if you have a 5th harmonic you are going to generate a torque ripple for the negative sequence. That is quite hazardous and for the motor drive and also if it propagates. I will show you the how does it propagates and all. So, this will be causing damage to the motor and thus, it is better once you are applying for the adjustable speed drive and other method. You eliminate this at the very beginning. This allows the lower switching frequencies to be used and also lower losses because there is less switching losses and that gives you the higher efficiency.

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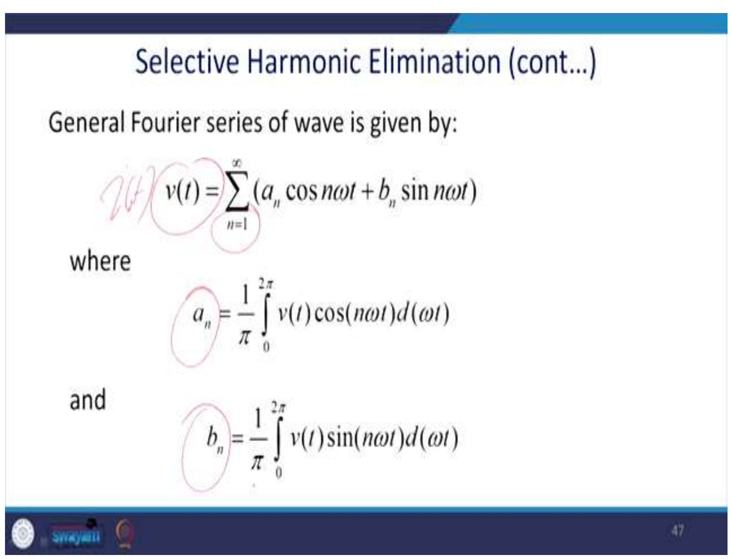

So, we have our general expressions of the Fourier series. We are revisiting here. So, it can be voltage or current. So, that will be given by $\sum_{n=1}^{\infty}(a_n \cos n\omega t + b_n \sin n\omega t)$. So, where $a_n = \frac{1}{\pi}\int_0^{2\pi} v(t) \cos n\omega t d(\omega t)$. Similarly, b_n is the sine component and where it will be $b_n = \frac{1}{\pi}\int_0^{2\pi} v(t) \sin n\omega t d(\omega t)$

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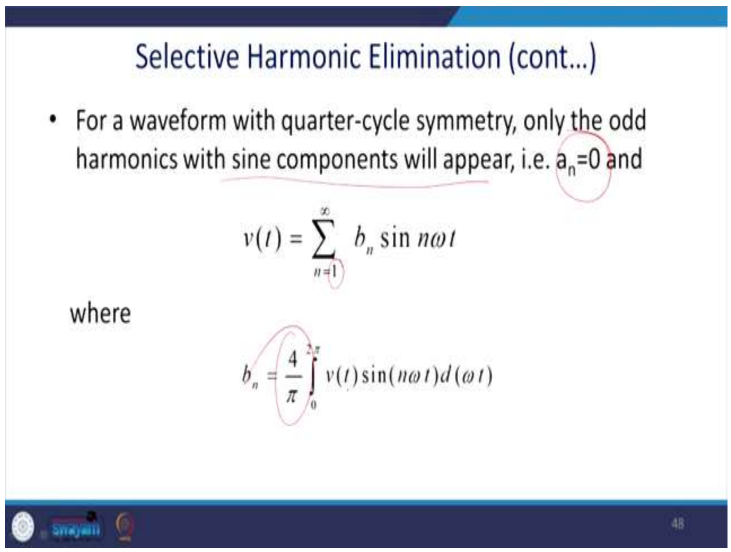

Generally we have a waveform with a quarter symmetry and we does not have a DC value only the odd harmonics with the sine component will appear and that be $a_n = 0$, thus $v(t) = \sum_{n=1}^{\infty} b_n \sin n\omega t$, where b_n equal to π. That is a square average value of it that is $b_n = \frac{4}{\pi}\int_0^{2\pi} v(t) \sin(n\omega t) d(\omega t)$.

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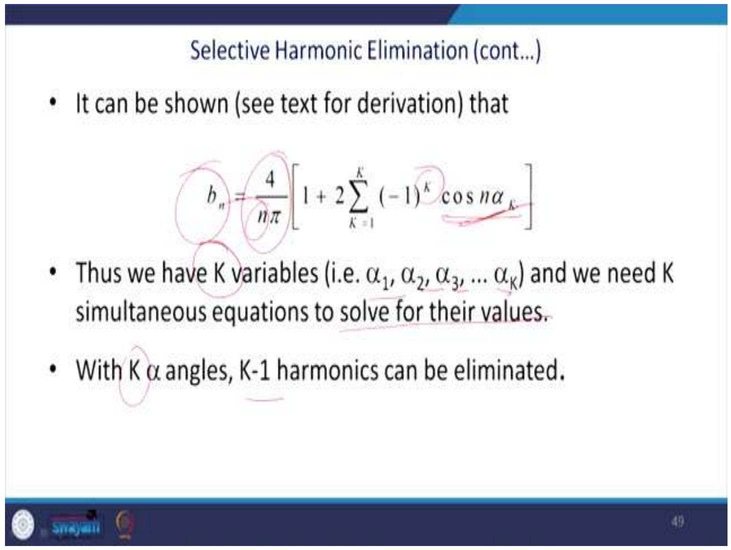

So, we can rewrite this equation. It can be shown that b_n will be $4/n\pi$, where n is the order of the harmonic. If it is 'n' equal to 3, then it will be 3. So, plus K equal to 1 to K to the power minus Kcos $n\omega t$. So, you can see that 5th and 7th will have a minus value here and thus we can choose K variable that mean alpha 1, alpha 2, alpha 3, alpha K and we need K set by solving the simultaneous equations because cos is involved. You cannot have a algebraic equation.

The computer can solve this online, and thus we get the values with K alpha angle K minus 1 harmonic can be removed from this system. You can see that. In that way a particular harmonic can be eliminated. Ultimately you have to make this term which cannot be '0'. Thus, you know what happened? You require to make this term '0' by particular value of alpha.

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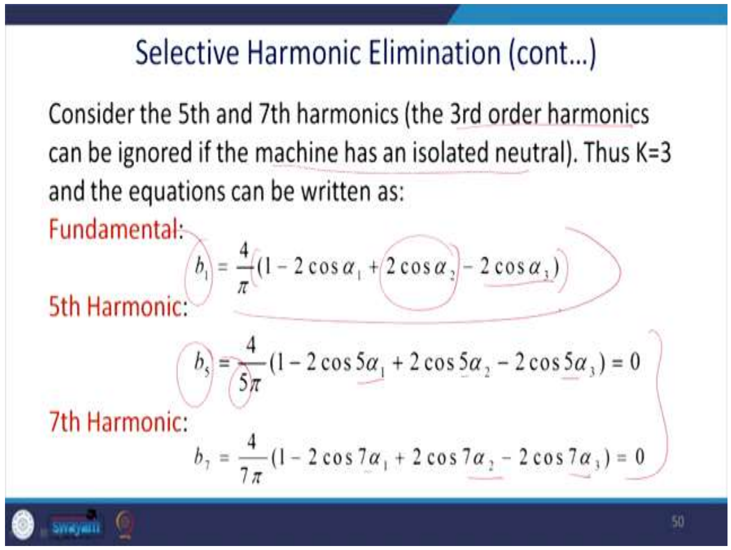

Thus, you solve it. We just put this value consider that 5th and 7th harmonic. We have considered a 3 phase 3 wire system and thus third harmonic can be eliminated or ignored. If the machine has an isolated a neutral thus K equal to 3 and the equation can be rewritten. If it is a fundamental then you write it the fundamental. Just expanded the previous equations like this.

Similarly, this has to be maximum rather. So, this should not be '0' and that will be max and b_5 will be 'n' equal to 5. This will be 5, this will be 5, this will be 5. Similarly, the 7, this will be 7, this will be 7, this will be 7, this will be 7 and these are the 3 simultaneous equations required to be solved.

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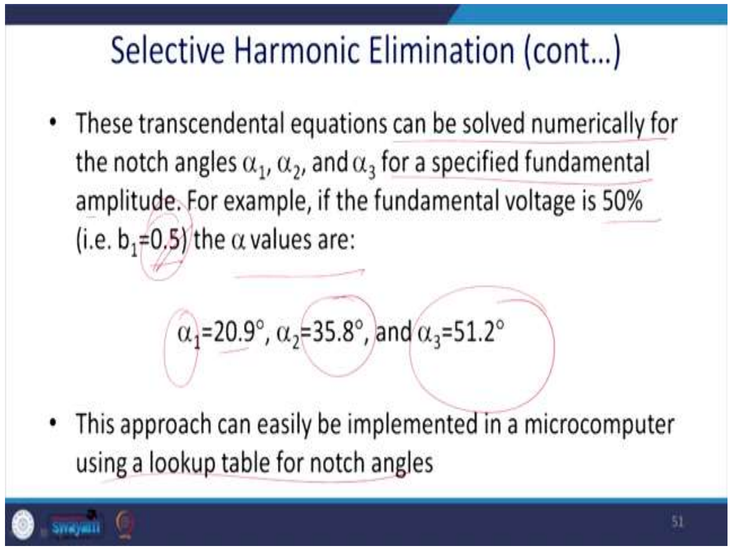

So, while solving what happens? This is a transcendental equation and can be solved by the numerical values having a notch angle, but you know once if load is fixed you know this angle. If load changes then you require to again readjust the angle, but you can see that this has a static value. So, once you know the '0' crossing you can change this value.

Generally, what happened? There is a load pattern. If it changes then power factor changes. So, you have to recalculate the voltage. So, for specified fundamentals amplitude for example. If fundamental we have voltage is 50 percent that mean b_1 equal to 0.5 and thus your alpha values are equal to $(alpha)_1$ equal to 20.9, $(alpha)_2$ equal to 35.8 and $(alpha)_3$ equal to 51.2.

This approach usually implemented by the microcomputers, DSP or with the lookup table with the angle of the notches because once it is done it is fixed. But generally power factor changes and all those things. You require to recalculate those angles because these values will change it is not fixed. We generally want to maximize this value and see that this is a representation of the triggering angle alpha and the fundamental value of alpha.

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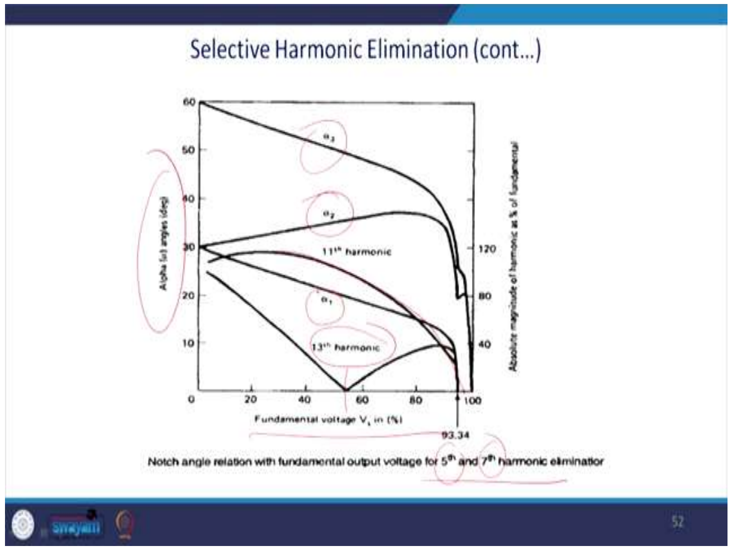

So, generally what happens? You can see that. So, for (alpha)$_1$ you gradually increase the (alpha)$_1$ and try to reduce it. You can see that. This is the 13th harmonic. 13th harmonic will be initially high gradually it will come down here and thereafter will increase. Similarly, this is for the (alpha)$_3$ and this is for the (alpha)$_2$ and this is the 11th harmonic. 11th harmonic you will have this kind of pattern.

Thus, this is the way. The notch angle relation with the fundamental voltage of 5th and 7th, you know it has been already eliminated. So, you are left with 11 and 13. If you change this firing angle alpha. This will be the next harmonic which will arise 11 and 13 and that has been represented in here. Of course, you can eliminate 11 and 13.

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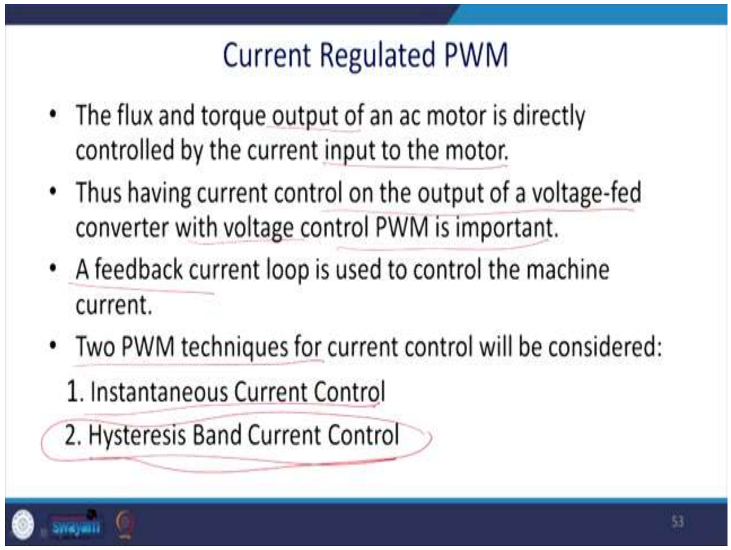

So, why we require to eliminate? Generally, you know it will propagate. We shall see that. if it is an adjustable speed time the flux and the torque output of a motor is directly controlled by the current input of the motor. Thus, having the current control on the output voltage of a voltage fed converter with voltage control PWM is quite important. So, this is something we require to know.

A feedback current loop is used to control the machines current. We required to have a control PWM and generally, what we do? Same thing can be extended to the shunt active power filter, and the PWM technique for the current control is been considered and it can be instantaneous current control or the hysteresis band. This hysteresis band is very much used in case of the shunt active power filter.

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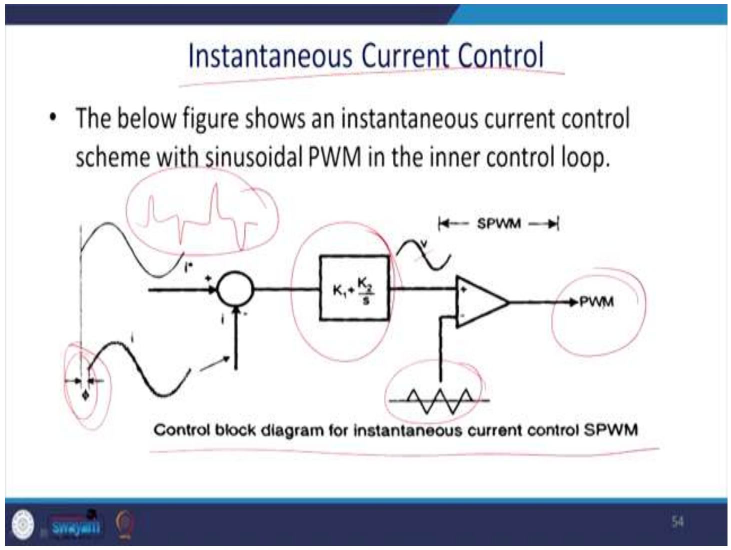

So, what happens? This is an instantaneous current control. In this case you have a reference sine wave and generally you will start with a delay. Because you cannot start. So, you have to match it. This current will be compared here and ultimately since you have started with the delay, you got a effective history and thus you got a steady state error and you required to eliminate the steady state error and for this reason we required to design this PI controller.

This PI controller will be giving you this kind of reference and ultimately you will put it to a simple op-amp for its sine triangle comparisons and that will give you the pulses for the PWM. It can be bipolar or unipolar which has been discussed earlier and this is the control block diagram or the instantaneous sine triangle PWM with a closed loop control.

This can also be used for shunt active power filter. You know that shunt active power filter reference is something like this. This is a harmonic part of it. Then we require to track it and this is a way it can generate pulses for the shunt active power factor.

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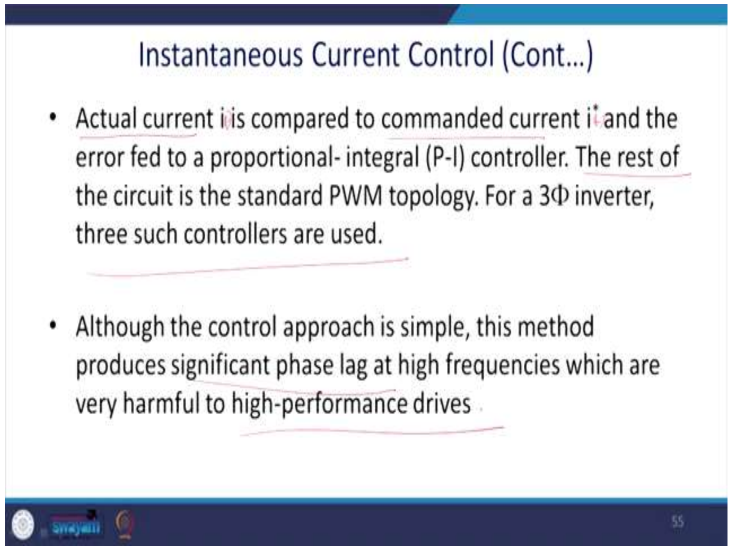

So, what we can say here? This actual current ‘i' or i(t) because this is in time domain, is commanded that and the commanded current $i^*(t)$ and the error is fed to the P-I controller. The rest of the circuit is the standard PWM topology. Although this control approach is simple. This method produces a significant phase lag because we can start correction that can take place little bit lagging.

Ultimately, P-I is challenged to get rid of this phase lag business. So, we require to design the pre-lag properly and high frequency which are very harmful to high performance of the drive. It generates the ripples and thus ripple in the torque will be presented.

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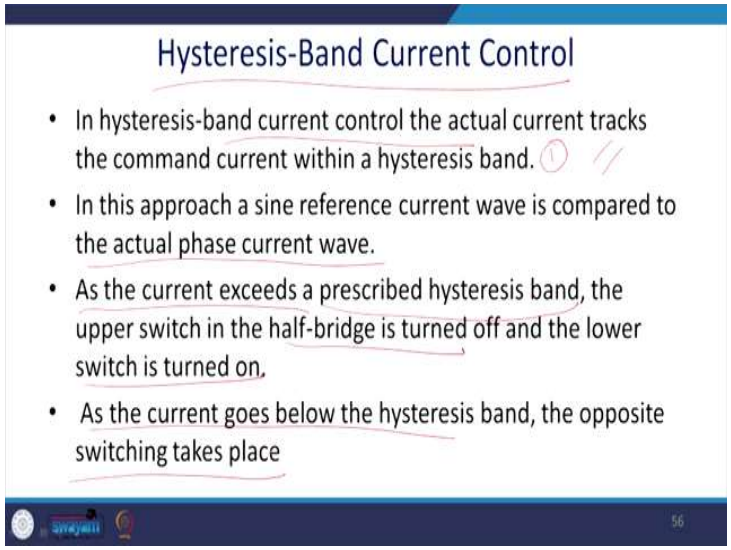

Now let us come to the hysteresis band. It is quite important. Hysteresis band is very frequently students used for the simulations of the D-STATCOM or the shunt active power filter. It has a many version. Let us try to capitulate some aspects of the hysteresis band of controller in this class. In hysteresis band this is all the current control techniques. The actual current tracks the commanded current within a hysteresis band. This hysteresis band can be proportional band or it can be an algebraic band or you can have a constant band.

In this approach, a sine reference current is commanded to the actual phase current waveform. We shall see it. What is it meant by that? As the current exceeds prescribed hysteresis band, the upper switch of the bridge is turned off and the lower switch is turned on, within a band it continued to allow to turn on the lower switch. Again, when it hits the lower band then again upper switch will be turned on. As the current goes below the hysteresis band the opposite switching takes place.

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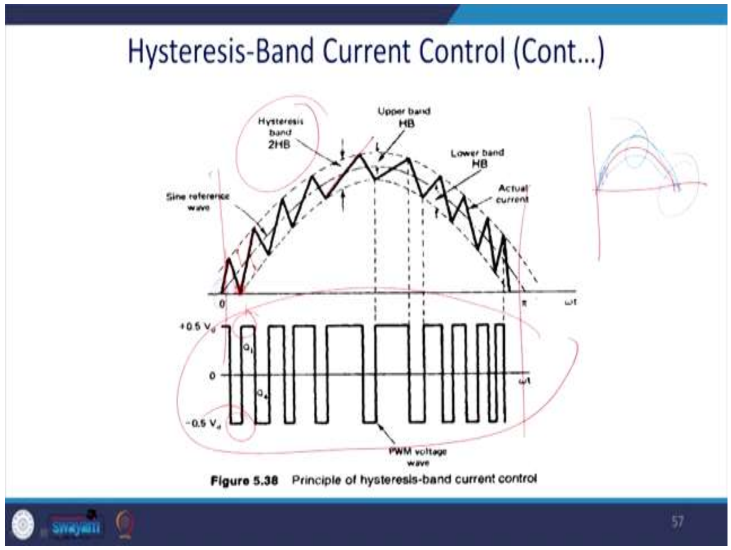

So, this is the case. You start from here. You allow the error to be increased and thus you have this band is called 2HB band and this is the middle is the actual value. With actual value you add up some voltage and thus you generate this and this band. This band is said to be the constant band. So, its bandwidth remains constant throughout.

So, what happens here? At this point you go off and since upper switch is on, current will increase in a positive half cycle and thus it will hit ultimately the upper switch will be closed. Generally, it gets a path through the diode to flow and it will come down and then again, when it will hit this lower band again. This, that will be stopped or switch will be stopped because you require to give a switch to give the path. Your switch is on, then lower switch will be on, for this reason for this time you are getting the value of minus V_{dc} or 0.5 V_{dc} for the half bridge.

Again you will go off for the switching on the upper switch and go down like this. So, you can generate the precision by controlling the band. But one of the disadvantages of this is that it is nothing but a PWM. You can see that. You have a maximum bandwidth at the center and you have a notches very small bandwidth at the close to this device, of this ‘0’ crossing.

So, in that way we can say that it mimics the PWM, but there is some difference.

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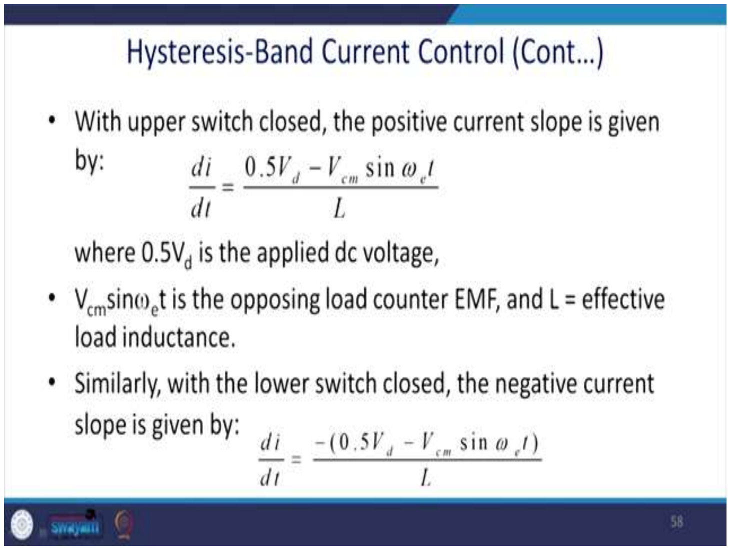

Generally, what happens? You know, we consider a shunt active power filter. This discussion is based on the shunt active power filter. I just taken example of the shunt active power filter where you have this point which is called PCC.

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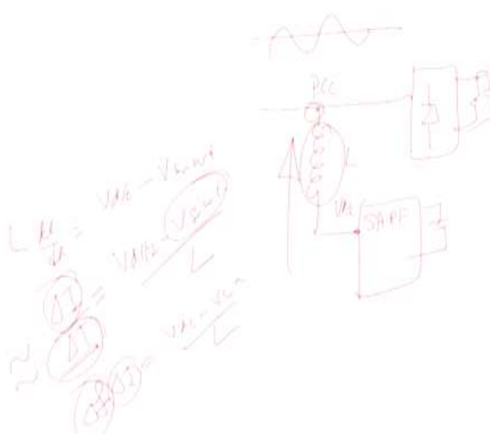

This is a one line diagram of the shunt active power filter and this one is your diode base rectifier and maybe a load and here you have a shunt active power filter and you have this load. So, what happens? You know. Once this switch on this pole of the voltage sees $V_{dc}/2$ or V_{dc} depending on the kind of topology it is using and this point is varying sinusoidally.

So, this point will be $V_m - t$ and you require to inject current and since there is an instantaneous different between this point and the pole of the inverter and the PCC we required to use the inductor and thus it is been shown here.

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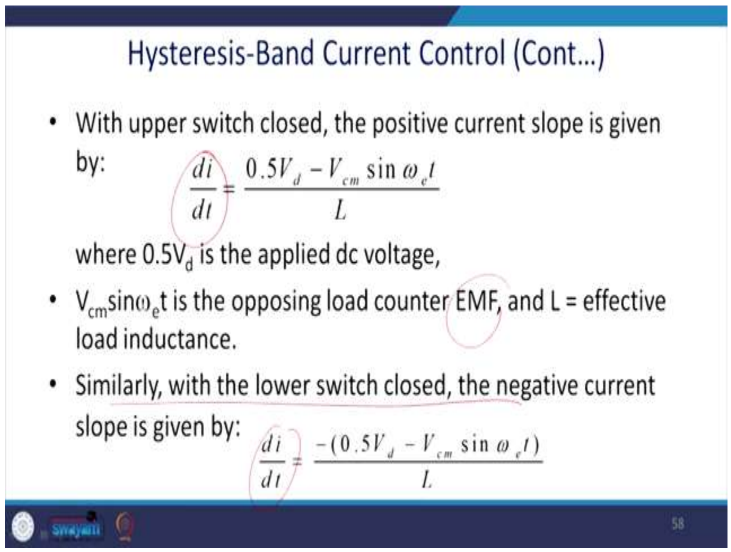

So, it is $\frac{di}{di} = \frac{-(0.5V_{dc} - V_{cm}\sin\omega_e t)}{L}$, where this 0.5 V_d is the applied voltage and $V\sin\omega t$ is an counter EMF for the motor or maybe it is connected to the PCC, and L is connected effective inductor. Similarly, the lower switch closed. The negative current slope given by this term will be negative $\frac{-(0.5V_{dc} - V_{cm}\,\mathrm{si}\quad {}_{e}t)}{L}$.

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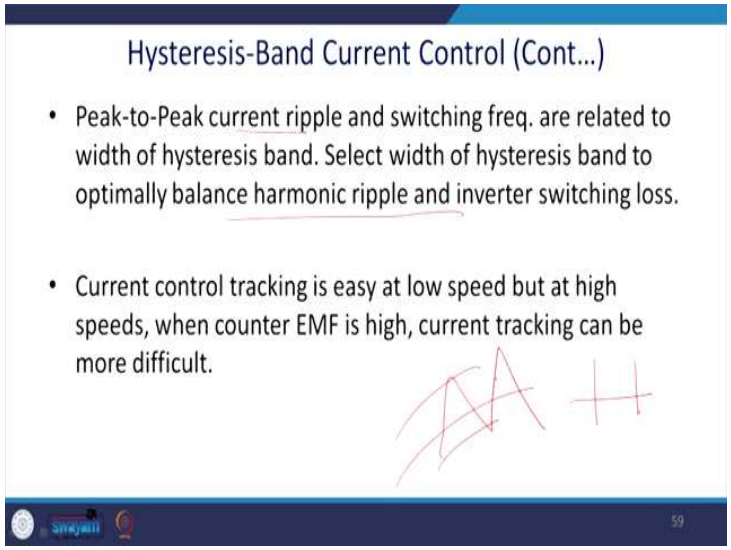

So, what happens here? Peak to peak current ripple and the switching frequency are related to the hysteresis band. If you have a larger band you have a lower switching. So, select the width of the hysteresis band optimally to balance the harmonic ripple and the switching loss. So, if you have more band, harmonic ripple will be more, but switching losses will be less because you are switching less. So, you have to optimize it.

Another problem is that in case of this sine triangle PWM, your frequency is constant. You know that where your bandwidth of the frequency will exist for the bipolar and the unipolar. But here you have a spectrum and that will have a wide range of variation with the change of the band but one of the major advantages of this method is that current tracking is easy at low speed. But at high speed when counter EMF is high current tracking can be more difficult. Let us just understand what it says.

So, let us switch over. Ultimately, $L\frac{di}{di} = (0.5V_{dc} - V_m \sin \omega t)$. So, what happens? Value of the inductor is constant. You can write di/dt. So, this is approximated to $\frac{(0.5V_{dc} - V \sin \quad)}{L}$. Now, what happens here? You can see that this is a band that is constant. So, it is at its peak. So, what happens? This value required to be quite high and the frequency required to be high because you can just change it to the frequency. Just the inverse of it you know. Thus, the change of frequency into $\Delta I = \frac{(V_{dc} - V \sin \omega t)}{L}$, this one is constant thus there will be a changing frequency. There is a constant change in frequency in the operation of this PWM inverter.

That is what it is. When PWM is high then switching frequency will be high and the current tracking is more difficult because it does not get much time to operate because once you are switching on you have to track it. Here you know since there is a peak value current will gradually will operate. This slope is quite blunt here and slope at the ‘0’ crossing is quite sharp here.

Generally, what happens? If you are working on the shunt active power filter you will find notches here. Generally, the student does the proportional band hysteresis controller. That is this PWM. This one is your proportional band. Here it will be ‘0’ like this and ‘0’ like this. So, if it is a proportional band, here you have a space and since you have a notch kind of thing, its frequency required to be higher and thus control fails and generally there will be a overshoot or spikes in case of the ‘0’ crossing that will.

That is very frequently observed. The students who are working on the shunt active power filter simulation, they go for this proportional band hysteresis controller. It is always advisable to go for constant band PWM hysteresis band.

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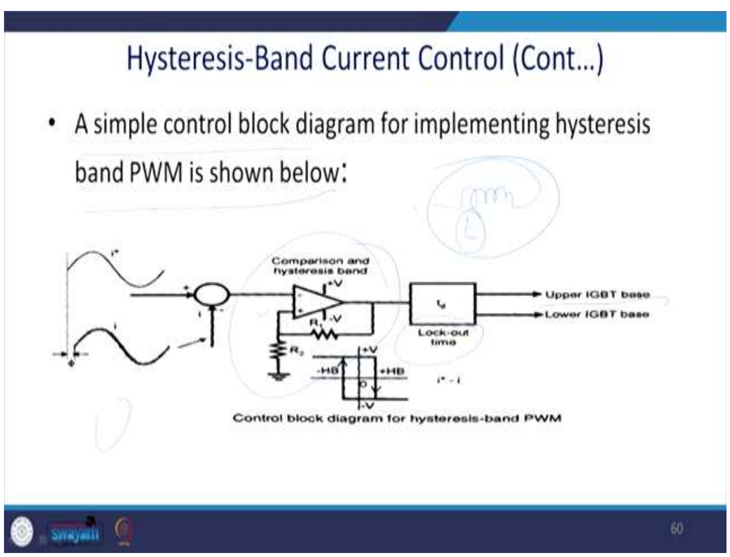

How you implement it? We have implemented everything by op-amp. Thus, it is also possible to implement it by the op-amp. So, it is a simple control block. On op-amp with a positive feedback, you know. You have studied maybe in your second year of the B.tech that op-amp with the positive feedback acts as a hysteresis controller. Same thing, you will have a positive feedback and R and R_2 will be the ratios of the band which you want to set. It may be 1 K, it can be 10 K. So, it may be that is 10 percent band. Similarly, you can have a 5 percent, 1 percent then whatever the band you want. But generally, this is a proportional band, mind it.

We required to have some kind of modifications which I leave to the students. I will be asking this question in your assignments because you required to revise the op-amp. So, there you will get an algebraic band, not a constant band and thus the simple controller will work. You have a lock-in lockout time within that no changes will be allowed to generate. If it is high then higher IGBT will be switched on. If it is low then lower IGBT will be switched on. So, it is a perfect match or the 3 phase 4 wire system where individual phase can run like this and for this reason this mode of operation is highly preferred in case of the shunt active power filter.

So, it is a simple and it is highly useful. But one of the challenges is that how to design the inductor of the shunt active power filter? So, there you know you will be finding this inductor design is quite challenging because of the hysteresis band. There i no constant frequency and you have been challenged for it. Otherwise this work is quite simple and fast.

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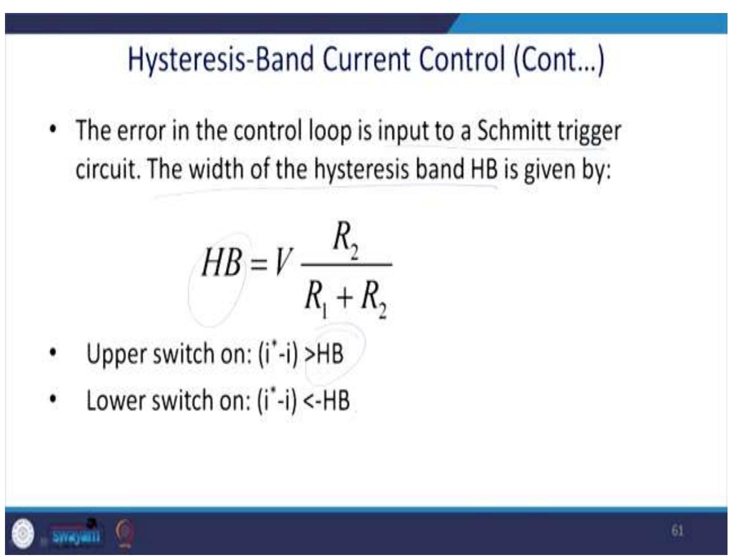

As I told you that the error control loop is a essentially a Schmitt trigger circuit with the hysteresis band HB equal to $V\ R_2/(R_1 + R_2)$. When 'I' reference is more than this 'i' then upper switch will be on and just reverse will happen. Once this one is less then lower switch will be on and that will say higher band and this is high and this will be low. So, these transitions will take place.

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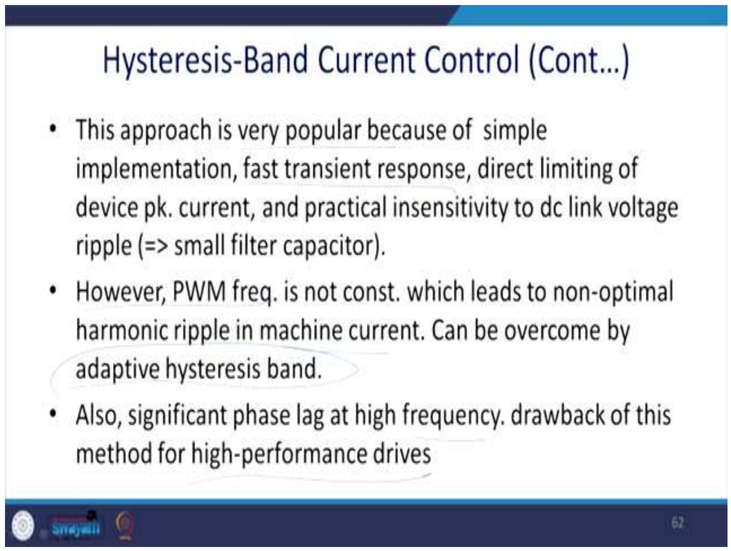

So, this hysteresis band is very popular because of the simple way of implementing it and fast transient response directly emitting the device peak current and practical insensitivity of the dc link voltage ripple. These are the few advantages of this hysteresis controller. However, that is a major challenge. PWM frequency is not constant which leads to the non-optimal harmonic ripple in the machine current as well as shunt active power filter and can be overcome by the adaptive hysteresis band. That band itself changes. Once there is a big error, band will be higher. So that you can ramp on and if the wire is minimized, so you can have a shorter ramp.

Also significant phase lag at the frequency because you start with the lag and there is no lag compensator because history will be prevailed and thus you will have a steady state error and draw backs of these methods are of the high frequency devices and it will lead to the time delay system also.

Thank you for your attention. We have completed the applications of the PWM in voltage source inverter in detail. That is very frequently used for different power electronic devices for compensating or mitigating the harmonics as well as total power quality control and these lectures will be useful for them or UPQC, STATCOM, DVR, any devices. So, all employs this kind of PWM technique.

Thank you so much.