Power Quality Improvement Technique
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Lecture – 23
PWM for Voltage Source Converter

Welcome to our Power Quality Improvement Technique. Today we will discuss about the PWM for the Voltage Source Converter, control technique required for the voltage source converter. Voltage source converter is an integral part of your active compensation, which we will see after few classes as a series compensation, shunt compensation.

So, for this reason we require to revisit the control technique or the pulse width modulation technique required for the voltage source inverter. So, most common voltage source converter is that that 3-phase 6-steps type that offers simple control with the lower harmonics.

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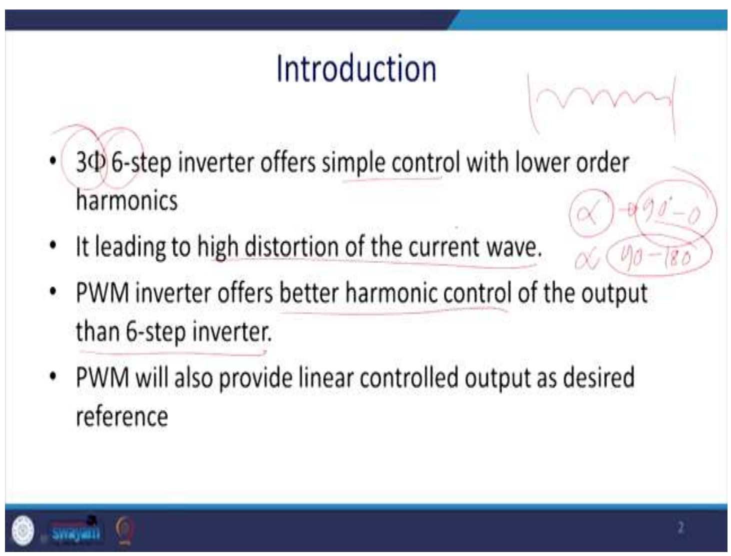

So, for this reason we do not require the return wire for three phase three wire system and for this reason we go for the three-phase. That is a worldwide accepted standard.

Once you feed it, you consider that uncontrolled rectifier. So, it is essentially the 6 steps, you will find that there are harmonics of the order of $6n \pm 1$ and the output voltage will have a ripple of the 6 steps in a cycle. There is one pair of diode conducts from the 120-

degree mode and, that is the common aspects of all those adjustable speed drive, because there is a front-end converter, may be a passive rectifier.

What does happen? It will be leading to high distortion on the current value and PWM inverter on the other hand offers better control of the output voltage than the 6-steps inverter. Because if you have studied that full controlled converter for triggering angle in continuous conduction mode, you know that, for triggering angle of constant load current where alpha is 90 degree, 0 to 90 degree, it is in the converter mode. Alpha 90 to 180 degree it is in the inverter mode. That is the mode of operation for the inverter and that is your 6-pulse inverter.

Instead of that we require to go for the PWM inverter. The logic behind is that, PWM inverter offers better harmonic control than the 6-steps inverter. Why? Because in a one of the necessary conditions of the 6-pulse inverter or the 6 steps inverter is that, your load current required to be continuous in the converter or the AC side.

So, for that reason definitely you require to have a very high value of the inductor. That is a prerequisite and thus it makes the system costlier. Also, there is sometime like may be a commutation failure. This is a challenge once you go for the thyristor drive. Depending on the switching you may go for the IGBT base devices for which switching frequency can be as high as a 10 kilo Hertz or the GTO based drives where the frequency will be around 1 kilo Hertz. But either of the cases PWM is preferred.

Then why it is so? We will see in the subsequent lectures. So, PWM will also provide linear control output as desired and let us see that how it has been done.

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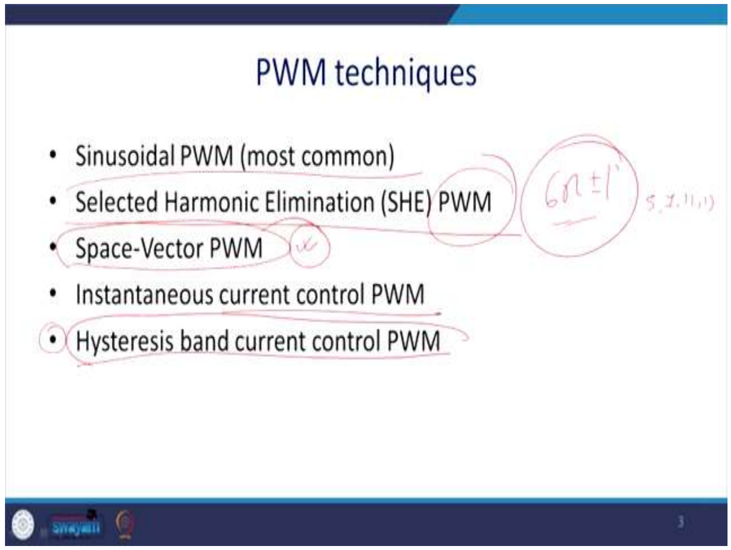

We can broadly classify the PWM technique as a sinusoidal PWM, that is a common PWM. And we can have a SHE we say in abbreviation, that is called the Selective Harmonic Elimination and this is quite useful in the power quality applications for the grid fed inverters.

Because, you know that if it is a 6-plus converter, (mainly if you use) $6n \pm 1$ are the dominating harmonic, and thus how you can mitigate those harmonics from this power quality? So, can go for that is 5th, 7, 11 and 13 and so on. You can go for SHE and, another important aspect of the PWM category is space vector PWM or space vector modulation technique. There we can use higher utilization of the DC bus voltages and thus you can get a better modulation index.

What is modulation index? I am coming after few second and thereafter it will be followed by instantaneous current control PWM. Where control will be on the current side. It is preferred mostly. It is called current controlled voltage source inverter in full form. Another thing you will see that, this is a hysteresis band current control PWM. It will be mostly used in your D-STATCOM or the shunt active power filter for it is simplicity. But there is a complexity of it in a different domain.

Because you will throw this complexity somewhere and you do not care and you feel that you are happy, but it is not so.

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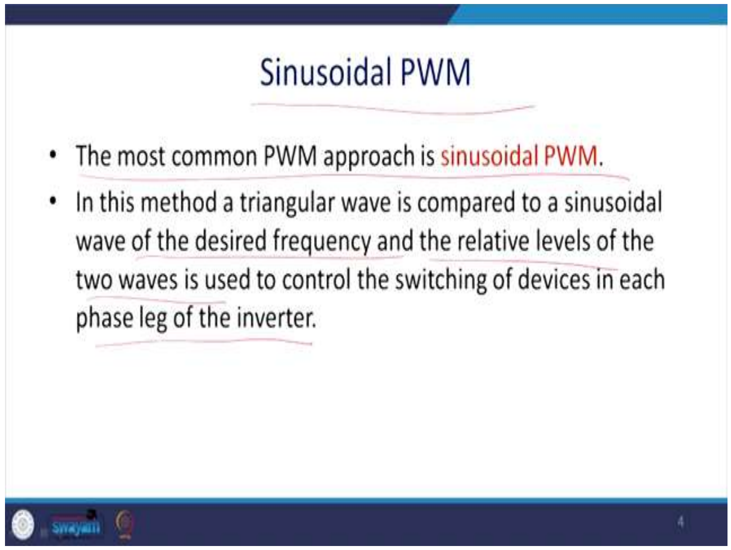

So, let us move to the first. There are other PWM which you have studied in your basic power electronics courses trapezoidal PWM, square wave PWM. For sake of time we are not going to it and we are not using it nowadays anyway. For this reason, we are straightaway going for the sinusoidal PWM technique.

So, that is what it is. The most common PWM approach is sinusoidal PWM. In this method a triangular wave is compared to a sinusoidal wave of the desired frequency and the relative levels of that two waves are used to control the switching devices in each phase of the inverter. Let us see that, how does it work.

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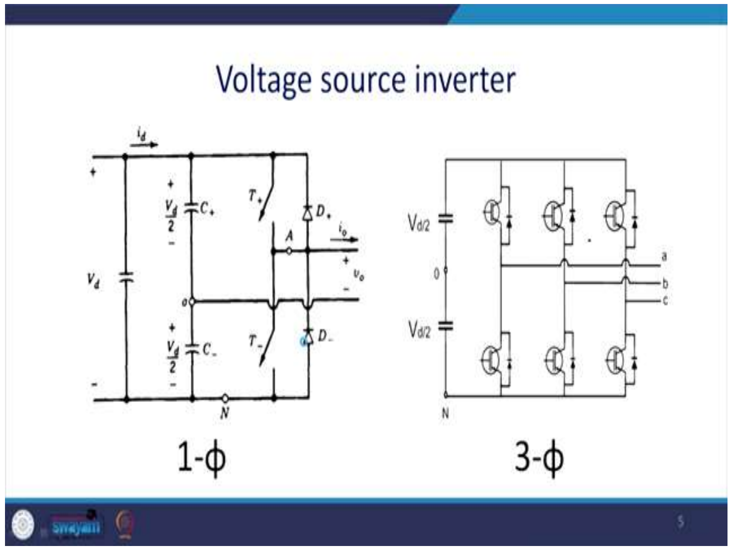

This is its single-phase version and here it is implemented. This configuration is called the half bridge configuration. Generally, if it is a voltage source inverter current is bi-directional depending on whether it is a leading or lagging. Only it will be unidirectional in unity power factor operation. For this reason, we require to provide the anti parallel diode with it.

Generally, we have to provide the center tap by splitting this midpoint by the two same value capacitor 'O' and that fictitious midpoint required to be available in to the system. Depending on the switching, you get a square wave and we require to get a PWM wave here. Same way this is the 3-phase version of it. You can see that these have been implemented by the bi-directional current, because it does not have a reverse current blocking capability because of the diode and it can also only have a forward current blocking capability, forward voltage and the current blocking capability.

So, it is a two bi-directional current and single direction current blocking capability is required here. So, this is the configurations of your 3-phase voltage source inverter.

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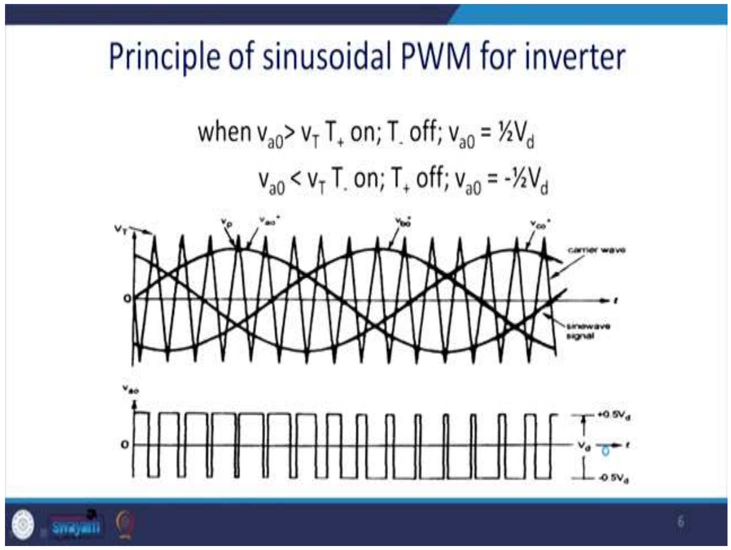

Now, for the sake of understanding frequency has been kept very low. Generally, it is quite big. Its carrier frequency generally around 20 times more than in case of the GTO. Because if it is a 50 Hertz. Your carrier frequency is in around of 1 kilohertz and in IGBT it generally more than 100 times, it may be 5 kilo Hertz.

So, the logic is this, V_{ao} is the modulating signal and V_T is called the carrier signal, then if V_{ao} is greater than V_T then T plus, that is if you go back this switch T plus will be on and otherwise T off will be off. Ultimately the load will get the voltage V_{ao} that is half of the V_d that is the case of the half bridge configuration. But if you have full bridge configuration, you get full V_T.

Similarly, if V_{ao} is less than V_T, then the lower switch will be on or T minus will be on and T plus will be off and you will get minus V_{ad}. Thus, you will get this kind of pulses. So, this is the pulses and since this is operating this way, you will get these pulses like that. This is for one of the phases and if you combine so you get a, b, c all the phases. So, these V_{ao} is the phase voltage.

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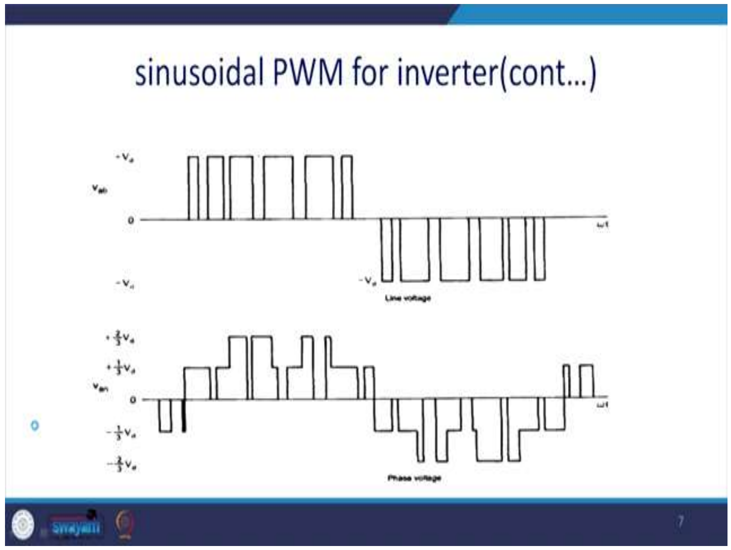

Similarly, if you combine ‘a’ and ‘b’, you get the line voltages here and line voltage will have this PWM pattern. Because you can see this pulse width is modulated. Ultimately it will be equivalent to this sin wave. Sorry this magnitude has to be less. So, this volt area of this sin wave and these buildings has to match. So, there will be an instant voltage difference between this sin wave and the exactly actual voltage has been injected.

That is the cause of the harmonic because there is an instantaneous error and that has been filled. That cavity is filled by the harmonics. Let us go back to this circuit. If you talk about the neutral voltage, then you will get this which is basically phase voltage. This is basically v_{an} and ultimately one observation you can see here. Here this is bipolar, because it is switching on plus V_{dc} and minus V_{dc} phase voltage. But the line voltages are unipolar.

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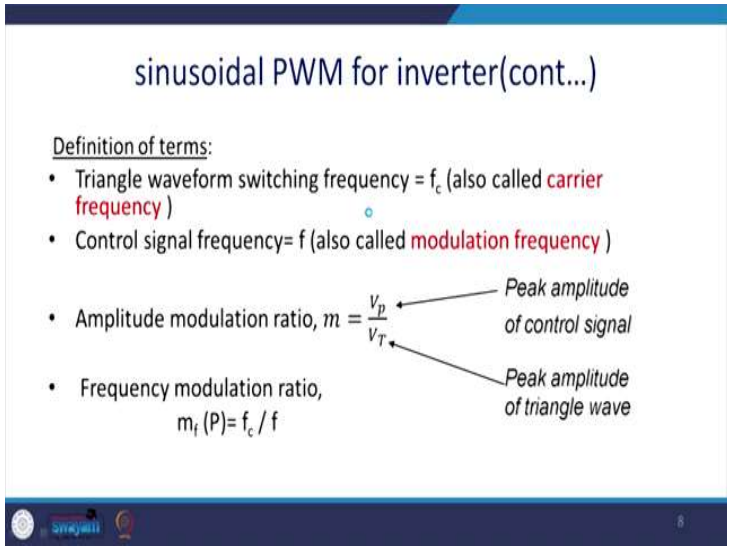

So, let us define few terms, for sake clarity. We will be using those term very frequently. The triangle waveform, triangle waveform switching frequency sometimes it is called, or it is called something called carrier frequency also. That term is derived from this communication. Also called as a carrier frequency, and some time called as control signals. It is also called modulating signals or modulating frequency.

So, the ratio of the amplitude of this $\frac{V_P}{V_T}$ is big of the amplitude of the control signal at the peak of the amplitude of the triangular wave. That ratio is called the modulation index and frequency modulation index ratio is $\frac{f_c}{f}$. Let us consider that, it has a switching frequency of 10 kilo Hertz and this has the frequency of 50 Hertz. So, it is 200 times than this m_f.

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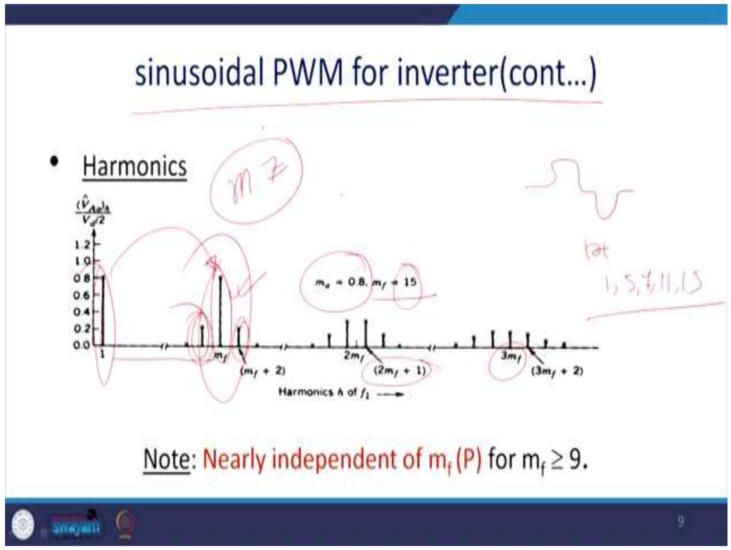

Now, what happened? This is the harmonic spectrum. Here if you do this FFT of this waveform (please go back this one), you will get this kind of waveform. It is for this ratio 0.8. That means, this modulating index is 0.8 and m_f is 15. That means, it is around 750 Hertz for 50 Hertz supply. For 6 years supply it is 900 Hertz.

So, what we will find there? there is a modulation index of '1' and thereafter there is a no frequency available and no frequency strength will be available. After that as you understand that this strength essentially is 750, if it is a 50 Hertz. So, there will be a two sideband. So, it is 800 and this one will be 700 and this band will be the 750.

Ultimately what happened? In case of the square waveform you get 1st harmonic, 5th harmonic, 7th harmonic, 11 harmonic, 13 harmonic and so on. But here straight away first you get the 50 Hertz in the context of India. Thereafter it will be shifted to, but with the same magnitude with a 750 Hertz that amount is given by this m_f and there will be a sideband that magnitude will be generally one third of 0.8. So, one third of the m_a. Here it is 0.8.

Similarly, at $2m_f$ you also get two harmonics. So here also at 1550 and 1450, you will get another two-spectrum same way and so on. Ultimately what happened? It shifts the spectrum at a higher frequency region.

Thus, what happened? Since your power system itself is a low pass filter, this high frequency component can be eliminated by very small size filter and thus your drives become compact.

But disadvantage, of course since there is a high frequency component, hence there are huge amount of the conducted and the radiated emissions. Also, your EMI, EMC will be a great demerit of this PWM. But as far as a THD is concerned you are getting a better THD. Voltage THD will be the same. It is not very good, because you know you have a whole length of sort of thing.

But since you are sending, let us go back to this PWM voltage waveform. Through an inductor, if you are feedings let us say you are driving an AC drive and ultimately it as a wire. Wire has got an inductor. So, for this reason current will be sinusoidal. Thus, what happened? You can see that for fundamental it will offer some amount of impedance. Once for this, next this one, this will employ the m into z. Thus, current will be reduced by m times and thus current THD will be lower in case of the PWM. That is a biggest advantage of this PWM.

But of course, you know you pass these bugs somewhere. If you are concerned about EMI, EMC, this method is not at all suitable.

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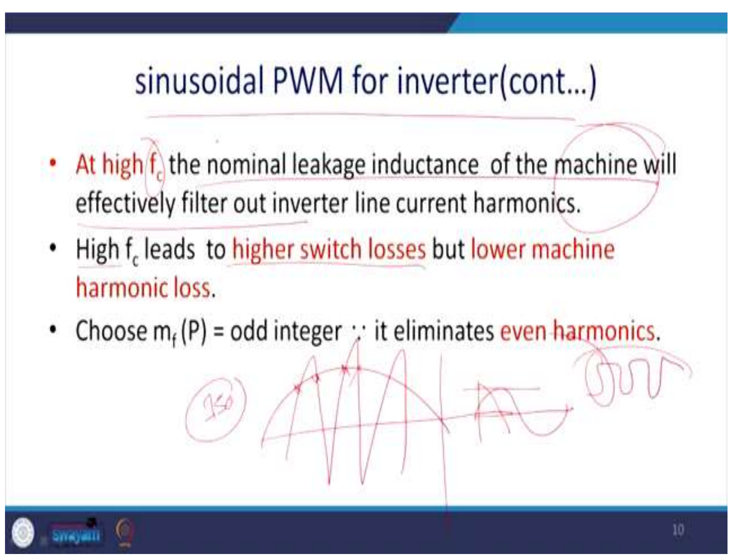

So, we can say something about it. That is the sinusoidal PWM inverter has some points to be discussed here. At high switching frequency or the carrier frequency, the nominal leakage inductance of the machine will effectively filter out the inverter line current harmonics. That is what I was saying.

So, your inductor is present into the line or you may require to put a small filter too. Otherwise what will happen? It will kill the insulation of the machine and machine life will come down. So, for this reason it is advisable to put a filter, before you are putting to the machine, so that you almost get a sinusoidal waveform. Because you know, sinusoidal waveform is something like best suitable from this AC machine because rate of change of voltage is sine theta. If you differentiate it is cos theta.

It is best, because once you are 90 degree, your cos value is 0. So, at a high voltage, rate of change of voltage is 0. But since you got a PWM pulses, your dv/dt is very high and due to that leakage current will flow and there is a capacitance in between the different point of the machines, because there is a different voltage at the different part of the machine.

You have to ground it because of this operator will operate and ultimately $C\frac{dv}{dt}$ is the current. High leakage current will flow and that will essentially damage the insulation on the machine. For this reason, it is advisable to put a filter. So, that your filter will eat up the hen lock. Filter will eat up this harmonic part and try to increase and try to feed the good quality supply to the machines. Otherwise machine life would be going to degraded.

Another disadvantage is that, high fc leads to higher switching losses. There are these power electronic devices as you know, there are two major losses. One is definitely the conduction losses and that another is a turn on and turn off losses unless you make the switching soft. But if you try to make it turn on and turn off with zero voltage or the zero-current like zero voltage or the zero-current switching, in that case also there are a lot of demerits. You have to put an extra resonant bank.

For this reason, let us assume initially that, we are having a hard switching. That means when you got a turn on and turn off losses. If you have a 750 Hertz then of course, you are cutting this waveform 750, you are cutting this waveform this many much of times. So, you are cutting here, you are cutting here, you are cutting here and cutting here and accordingly the pulses will be generated. So, there is a turn on and there is a turn off, there is a turn on and turn off. In that way there will be a 750 turn off. If it is 20 kilo Hertz, you will have a 20000 turn off and turn on. For this reason, you know how it has been calculated. So, there will be a huge turn on and turn off. How many cuts is will be there? It is not about the switching frequency. But how many cuts.

So, here you can see that, this carrier frequency is 3 times more. So, it is 3f and this is f. You have a 6. If it is 200, then it will be 400 turn on. 400 time is turned on and 400 time turn off. So, there will be a huge loss. For that reason, we will turn on and this turn on and turn off losses will increase or switching losses will increase but you will get an advantage which is the size of the filter will be low.

But device also has to support that switching frequency. IGBT you know that you had a current trail. Due to the huge current trial than the MOSFET you cannot put it on another cycle unless the current trail is finished. For this reason, most of the modern IGBT is limited to its switching frequency in and around 10 kilohertz.

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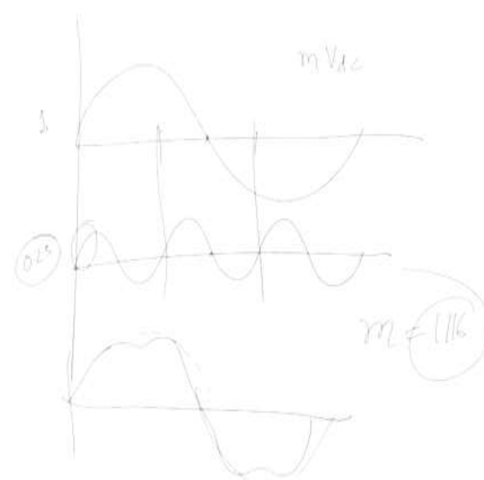

So, another one is that third harmonic injection modulation. This is quite interesting. Let us go to the white board. You have a sin wave and you have a third harmonic to be superimposed on it. Beauty of it is that third harmonic will finish here, here and here. So, you have third harmonic like this and they are co-phasor also. So, ultimately you have a zero crossing here and ultimately you have a zero crossing here.

Beauty of it is that, after 30 degree you got this contribution and if it is '1' let us say and it will be around 0.5 or something, we have to fix it up. There is a way to calculate it. With what should be the amount of we say contamination and if you contaminate then what will happen? The waveform will be a flat topped one and this waveform has a peak higher peak than this, and generally the maximum modulation index you get is 1.16.

In that way you can use your DC bus voltage better. Because you know ultimately what you get the amplitude is $m \times V_{dc}$ or $V_{dc}/2$ depending on whether you are using the half bridge or the full bridge configuration.

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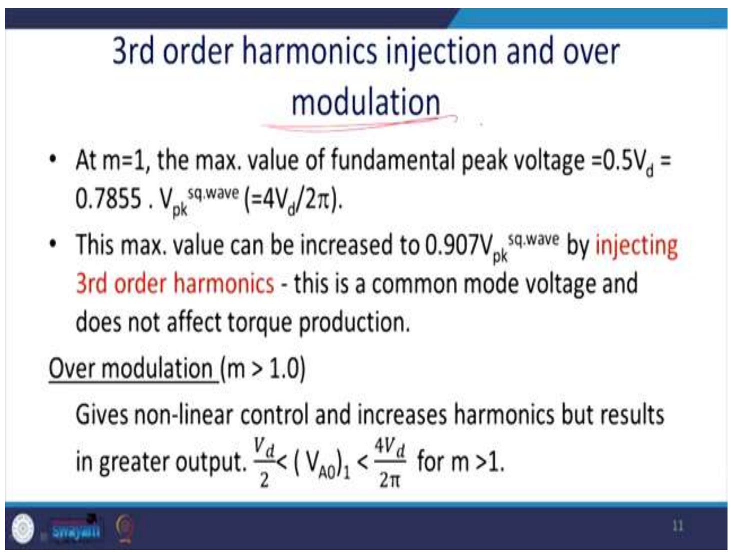

So, theoretically if it is m=1, the maximum value of the fundamental peak is at (for the half bridge) 0.5 V_d and for a square wave what happened? It is $4V_m/2\pi$ and it is $4V_m/\pi$ for the full bridge.

So, what happened then? The maximum value can be increased to 0.9. Basically, you can make let this 0.7 part and that is for the square wave injection by injecting the third harmonic. That is the enhancement of the DC bus you get. Normally if you have a one modulation index of 1, you get 0.785 and with the third harmonic that has a quantity. Whether there it is two issues. If you use third harmonic the THD generally degraded.

So, there is a condition of what should be the amount of the contamination for injection of the third harmonic. Generally, if it is one sixth, the THD is minimum. Generally, if it is 1.25, one fourth, then generally you have a maximum utilization of the DC bus voltage that is your 0.97 Vpeak by injecting third harmonic. This is a common mode voltage, as you have seen that. Third harmonic you know. You have studied in your basic transformer courses that they are lying only on the surface and for this reason circulating current will be there.

Since it is a common mode voltage, it does not flow with not connecting the midpoint of the capacitor in three phase three wire system. It does not affect the torque production. That is a beauty of it and if you go to this modulation index above '1' which is called the over modulated region, it gives non-linear control and increases the harmonics. But DC bus utilization voltage does not increase as much. So, it is kind of hysteresis curve. We will come to the next figure. It is limited to you and can give these equations.

It gives a non-linear control and increases harmonic, but results in greater output. So, it is V_{dc}, $V_d/2$. It should be less than the phase voltage and that is limited to $4V_d/2\pi$ or π depending on half bridge or full bridge. For full bridge I have told you it will be π. For the half bridge it will be 2 π for modulation index. If this is a case of the square wave inverter, where you get the voltage $4V_m/2\pi$.

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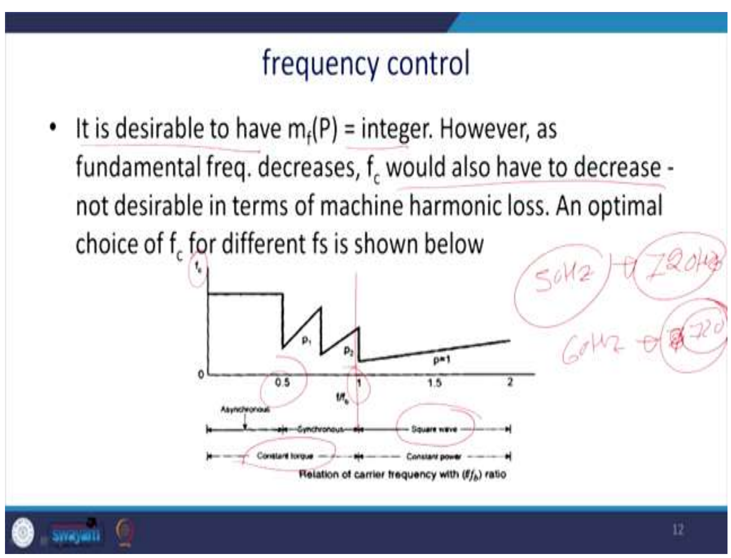

Now, this is the examples you know once you operate in a synchronous domain and another issue is that I told you. You have calculated the harmonics. It can be 15. It is, if you have a 50 Hertz supply. What happened if I set the switching frequency? Let us say you have taken the drive from the USA and there it was operating at a 60 Hertz supply and your switching frequency were 720. It was running extremely fine.

Now, all of a sudden you brought it to the 50 Hertz supply and you got 72 Hertz switching. Then what will be the problem? Will there be any problem? That is an issue. So, we have to look and revisit it and it is desirable to have an integral. However, as fundamental frequency decreases fc would also have to decrease which is not desirable in terms of the machine's harmonic loss.

You know if you have this kind of cases, it generates the inetr harmonic. So, you will have sub harmonics issues also. This sub-harmonic issue is a very big problem because elimination of those low frequency will be very difficult. For this reason, it will increase the losses.

For our discussion fc would also have to decrease not to the desirable level in terms of the machine's harmonic loss. An optimal choice of fc with different fs is given below. This is the value of the fc. Generally, we called till 0.5 as asynchronous region 50 Hertz. Thereafter, you got two peaks and 0.75 and P_2. Thereafter, you got this. This is called a asynchronous region and here you will get a constant torque and for the ratio f/f_b more than 1. Here it will be a constant frequency region and ultimately you will get a constant power.

So, this is the case. But you required to have a integral multiple of it and preferentially you should have an odd symmetry. That is what we generally take into the consideration and try to make the multiple integers of the odd symmetry. Then odd harmonic will be present.

Thank you for your attention. We shall continue to our discussions with the PWM technique for the voltage source converter.