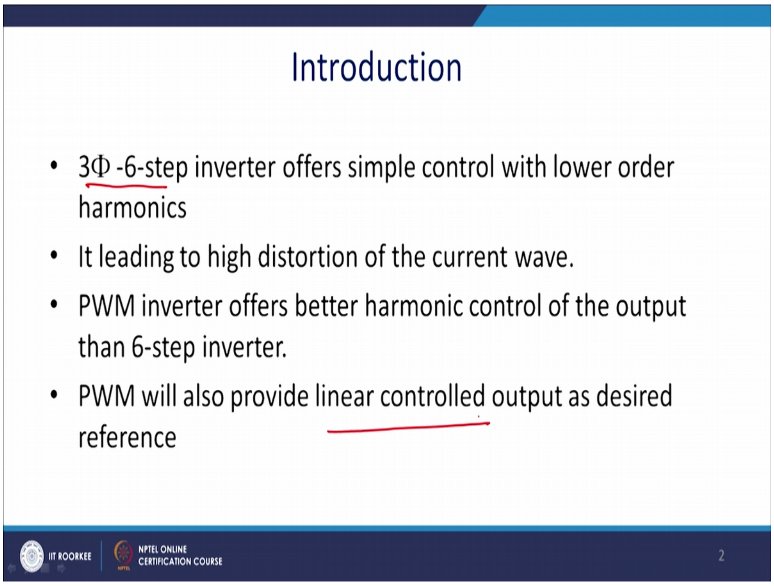
Flexible AC Transmission Systems (FACTS) Devices
Dr. Avik Bhattacharya
Department of Electrical Engineering
Indian Institute of Technology, Roorkee

Lecture - 04
PWM - I

Welcome to our 4th lectures of NPTEL on Flexible AC Transmission System FACTS Devices. Today we shall discuss about the PWM. PWM technique will be covered in detail and we shall see that what are the different kind of PWM technique. This is, so we have already seen on studied in power electronics that 180 degree mode of conduction and the 120 degree mode of conductions of this inverter.

And, generally these are the actually salient point of it. These are called actually 3 phase 6 steps inverter, and it is control is very simple and it can be put into this application with the SCS.

(Refer Slide Time: 01:08)

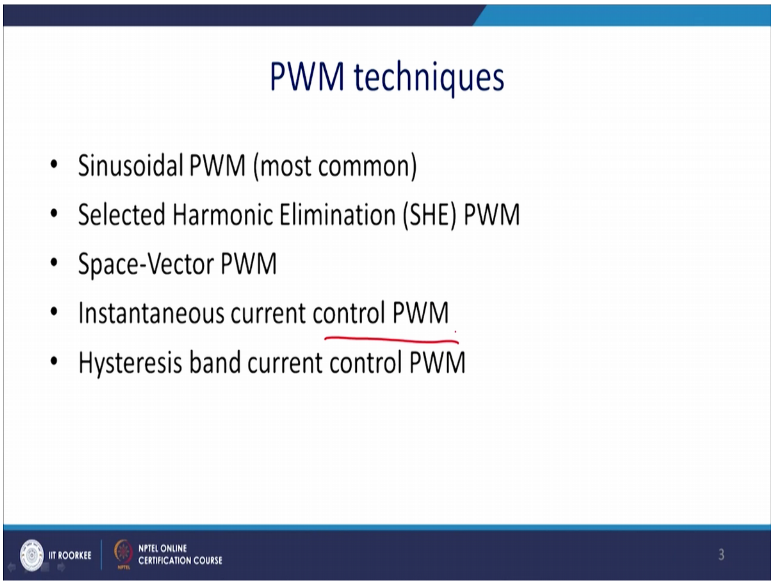


But, and it also contained lower order harmonics that is one of the disadvantage of this kind of converter. And that leads to the higher current distortion. PWM on the other hand PWM inverter on the other hand can actually offer better harmonic better TSD, because here what happen here? It actually voltage harmonic almost remain same, but current harmonic actually been reduced because most of the cases you know facts applications on the drive system.

Now, our system itself is a low pass filter and ultimately it will shift to the spectrum to the 20 times or 30 times depending on the ratio of the carrier available the controller that we will see later. And thus, TSD content with current TSD content will be very lower compared to this square wave inverter. And it can also scale up and scale down the voltage in a linearly chain that is one of the advantage of it.

PWM also provide that is linear control of the output as desired by the reference that is what actually was been mentioned.

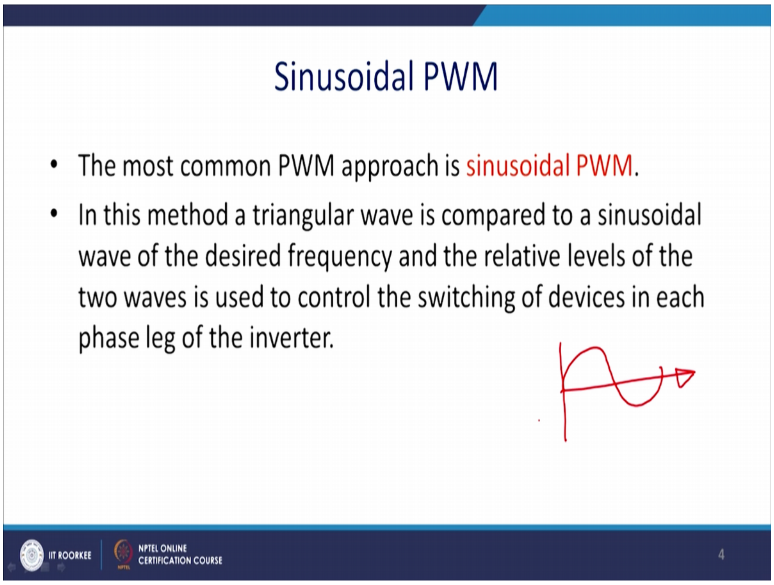
(Refer Slide Time: 02:22)



Now, we shall first discuss this is our presentation layout today. We shall discuss sinusoidal PWM that is most commonly used where another different kind of PWM also that is (Refer Time: 02:33) PWM another thereafter we shall see that actually selecting harmonic eliminations. And, they have to be we shall discuss space vector modulation and instantaneous current control by the PWM, it will have a application because in our facts devices mostly we use voltage-voltage source inverter in current control mode so, these edges or actually advantage.

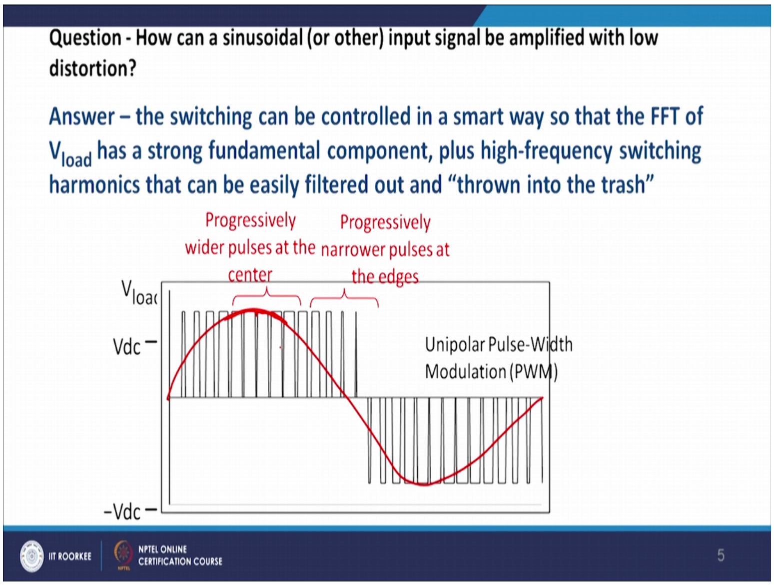
Thereafter, we shall discuss this advantage of the hysteresis current more control PWM. So, which is very simple to implement? Now, a most common as told in previous case, most common approach is a sinusoidal PWM.

(Refer Slide Time: 03:18)



Here, in what happens in this case sin wave that is mostly the control wave or the modulating wave, it will be actually compared with the triangle wave and we accordingly actually reference will be generated we can see the next slide.

(Refer Slide Time: 03:37)



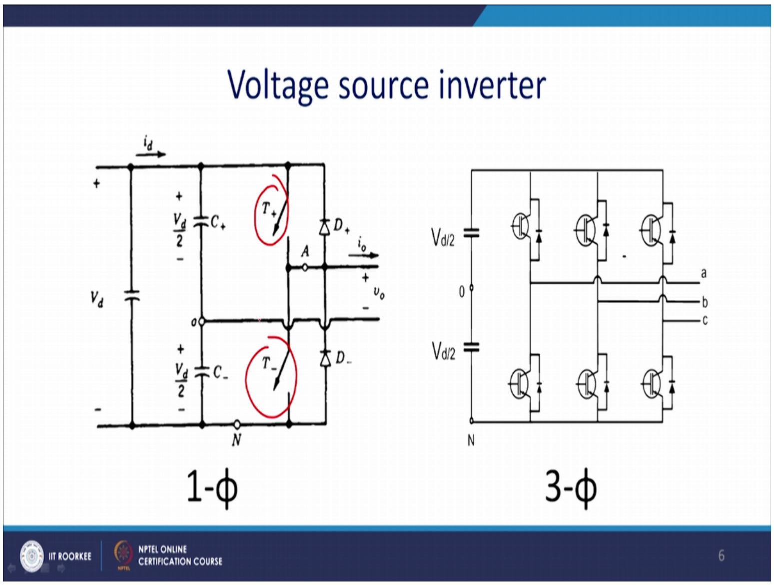
And so, the question is how a. And so, the question is how a how can a sinusoidal or other signal it can be trapezoidal or any other signals in case of the shunt acting power filter, the reference is actually little picky and different kind of contain actually combinations or harmonics.

But, each of the cases whatever may be the input signal can be a identified with the low destruction this is a challenge. And, answer is the switching can be controlled in a smart way. So, that effective of the V load has a strong fundamental component plus high frequency switching harmonics, that can be easily filtered out by the system or by a small low pass filter.

So, this is basically the PWM signals. And where actually it is bolt area will match actually it is not that we are applying a sine wave, but sinusoidal volt area and this actually PWM volt area will match each other. We, will come later this is called a where actually unipolar PWM and this is one of the advantage. You can see that since this area is a central portion is more and thus we can see that it will be more squarer at the center and it will be actually. So, it will have a less this will have a narrow fringes in the end at the beginning of the cycle.

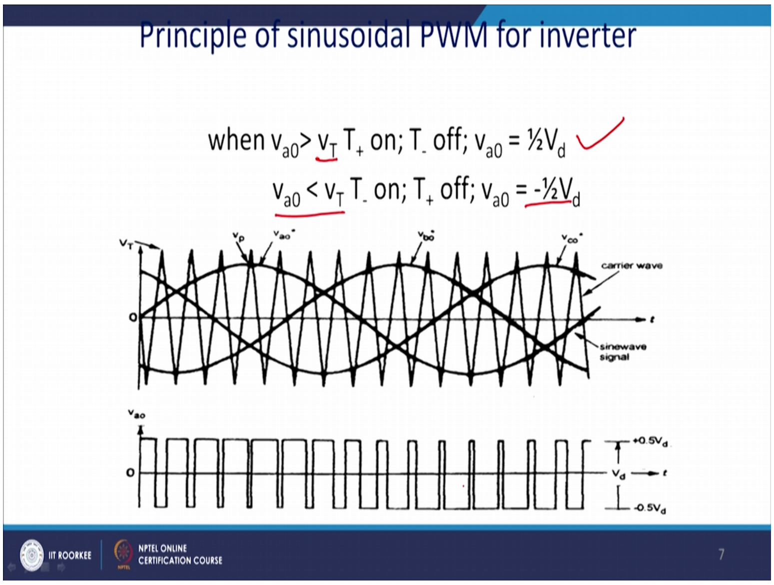
So, this is actually the single phase and the 3 phase voltage source inverter.

(Refer Slide Time: 05:07)



And, we take a simple breast wire simple breast topology of the 2 level inverter subsequently classes we should discuss about the PWM applicable for the 3 level inverter and it is applications.

(Refer Slide Time: 05:22)

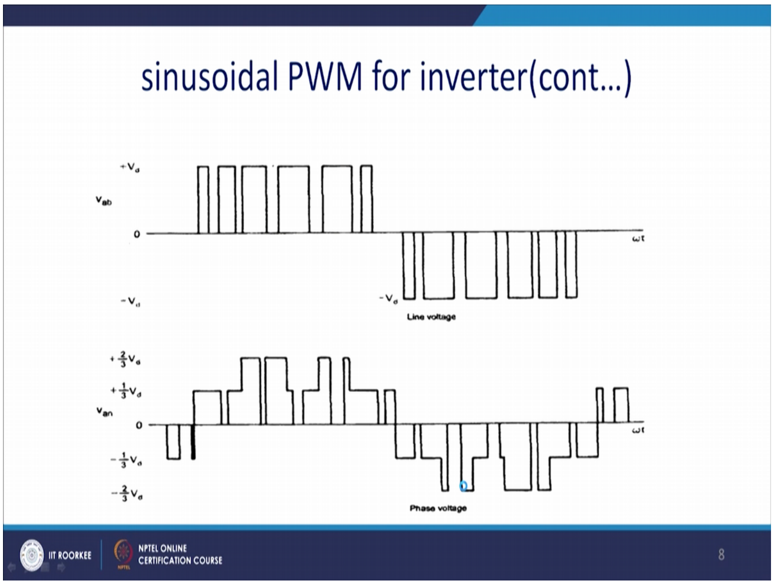


So, let us now see that what is now the, what is the functionality and principle of operation of the inverter? Please go back this circuit. And see that what are the switch has been mentioned, this is a half breast combinations and in a half breast combinations average voltage applied across is BDC by 2. And so this is the upper switch and this is the lower switch.

So, you see that an upper switch is marked as a T plus and the lower switch is marked as a T minus. Now, see that what is the logic when the control signal a V a O actually is greater than the triangle signal V T, then upper switch will be on and lower switch will be off that is you will get a voltage of half V d c.

Similarly, when actually reverse condition is satisfied that is triangular wave is greater than the modulating signal and then upper switch will be off and the lower switch will be on and you will get a signals of it. And thus, you will getting this kind of PWM wire form which amplitude actually varies plus minus V d c.

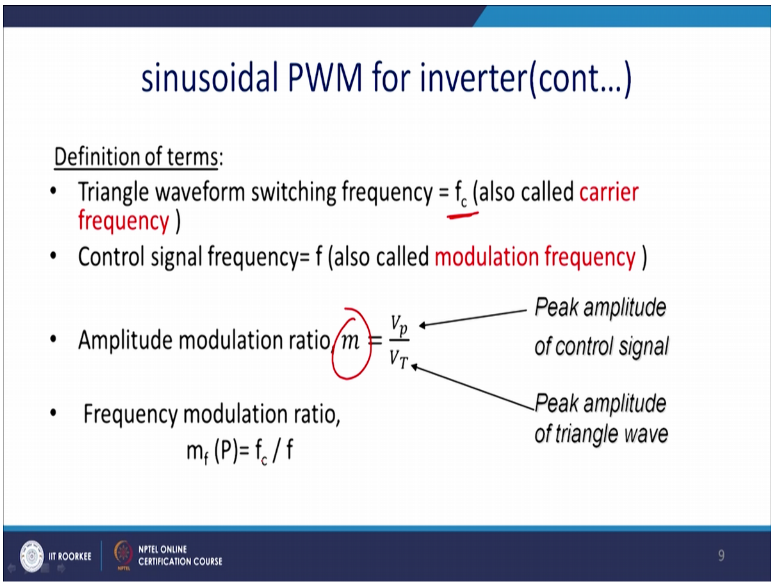
(Refer Slide Time: 06:36)



Now, one of the beauty of it that this is a line voltage, where you subtract the V a V and this is one of the phase voltage. So, you see that line voltage may have a huge amount of the harmonic content and also sometime it will have a actually bipolar in nature, but you will find that actually line voltage is unipolar and harmonic content is considerably low.

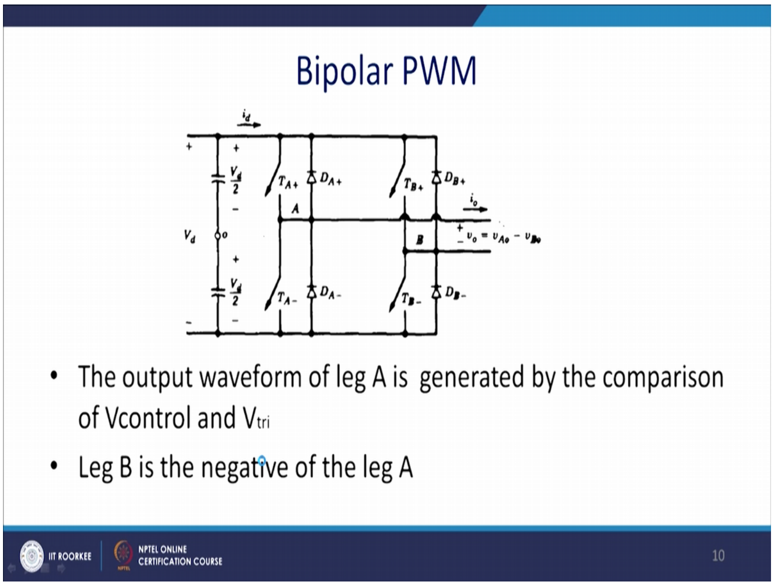
See now these are the few basics of the PWM.

(Refer Slide Time: 07:11)



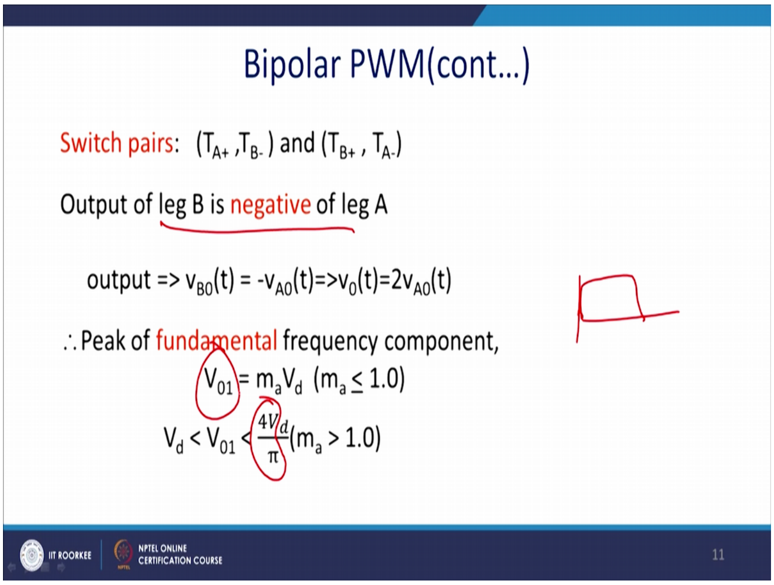
We, refer actually the triangular wire frequency a triangular wave frequency or the carrier frequency and it will be referred as a f c and same way the control frequency will be referred as f. So, the amplitude of the modulation is a ratio of actually peak amplitude of the control signal V p and a peak amplitude of the triangular signal V T, that is called a amplitude modulation. Same way there will be another term that will be actually frequency modulation that will be m f that will be given by, actually the ratio of the f c y f for f c is a carrier of the triangular wave say frequency and f is a control signal frequency.

(Refer Slide Time: 08:03)



Now, again let us go back to the same circuit and we shall discuss about a bipolar PWM and it is a simplest PWM of itself. And the output voltage of the leg a is generally a compulsion between precontrol and the V T or V tri and leg B is nega leg B is a negative of the leg a and this is actually the bridge configuration.

(Refer Slide Time: 08:32)

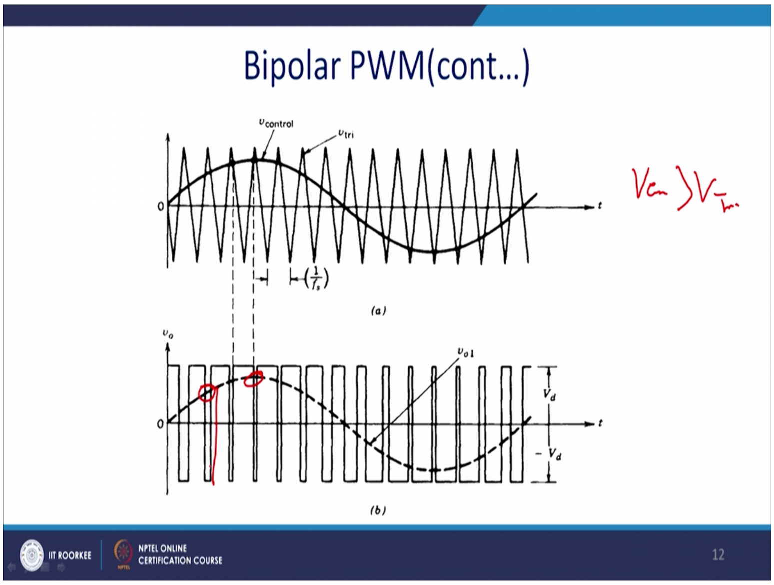


Now, what happen? When the pair of switch as actually tai minus T B and plus T B and minus T A. When the leg B is negative of leg A, then what happen you know you will get actually the output voltage V O B and that is given by 2 that is a actually the minus 2 V O. And thus you know actually the fundamental voltage which is available it is m times of the distilling voltage in case of the full bridge configuration by an half bridge configuration, it will be half of it and provided then modulation index is less than 1.

We shall go little; we go to the little discussions of it and you know when we have a fundamental wave form if we do the furrier series analysis. And, we can find it is fundamental voltage, that is it is 4 4 4 by pi into the distilling voltage. So, for this result this will be the fundamental voltage for this actually modulating index when more than 1 and for half bridge it will be actually 2 V m by, because if we actually the distilling voltage will be half this distilling voltage of the bridge converter.

Now, we will continue with the actually PWM one of the advantage is that it required only one control signal and it can be controlled as said earlier.

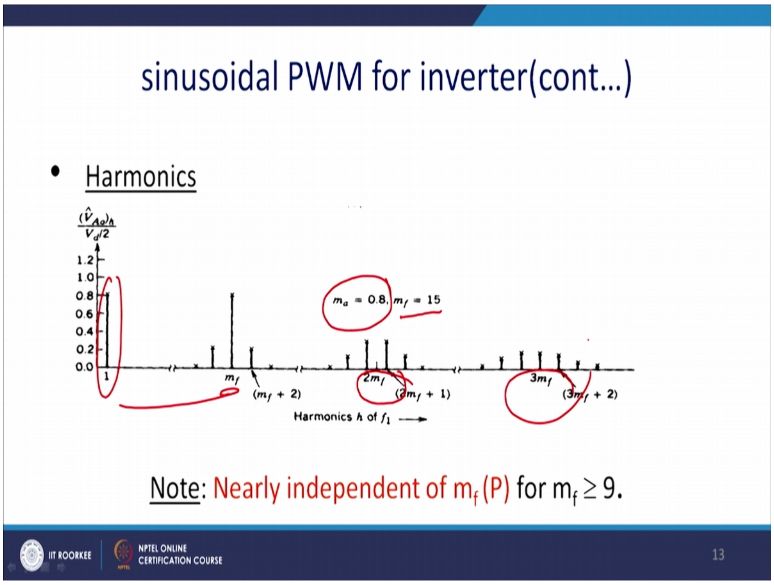
(Refer Slide Time: 10:10)



We can see that when sign or the V control is greater than T tri then the output of the controller will be higher, but problem is that it is the one of the decide biggest despite on which of this bipolar pre (Refer Time: 10:28) is that harmonic content. For this is and you take this region into the account, here you can see or this region into the account. You can see you are applying the voltage of minus V d c or V d c by 2 depending on the topology and where you got a huge instantaneous voltage error. And generally this instantaneous voltage error is filled back by the harmonics.

So, harmonic content will be mo moreover and it will find it out it is dominate a when we will discuss about this harmonic spectrum. We will find out that it is shifted by the ratio fm, but we will little later we will discuss about unipolar PWM then we will find it is applications and advantages.

(Refer Slide Time: 11:18)

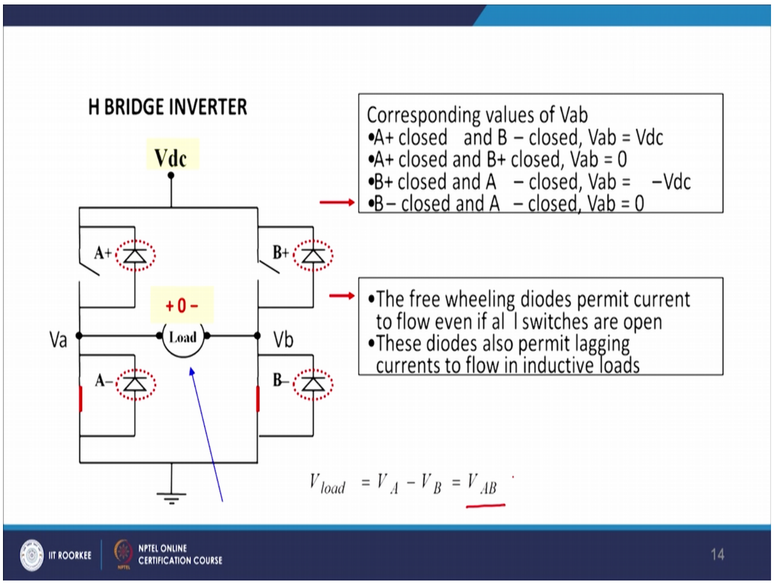


So, this is the harmonic spectrum this is a fundamental and then it will be shifted by the mf, where mf is a ratio of the triangular wave by the triangular wave or the carrier wave by the controller. So, this is from basically for modulation index in a linear region of 0.8 and value of the mf as 15. And, we can choose a we can choose mf in such as way that should be odd that should be odd number then we will find an odd harmonic only survives and in that way we can actually eliminate this actually even harmonic.

And, then again it will be available in 2 mf and subsequently 3 mf like that and since it is actually very high frequency lower order. So, it can be easily eliminated by a small low pass filter or a system, which is being an actually power system of the drives all come inherently is basically inductive and this will enumerate this high frequency very easily.

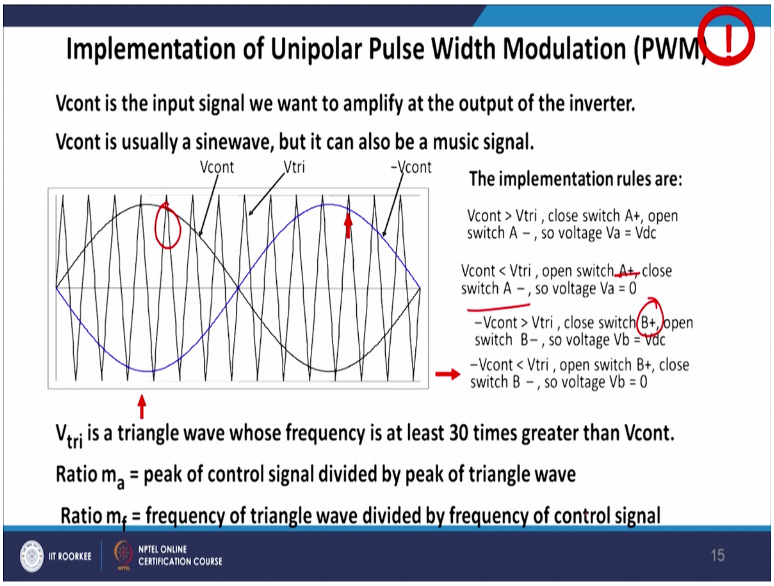
Now, let us go back again little bit and now we will discuss about actually the 2 level inverter and or the bipolar operation sorry unipolar operation.

(Refer Slide Time: 12:43)



In this case actually load voltage again will be V A be and we have already discussed how the what is the principle operation? And this is a principle operation when actually we see that when diode conducts? When switches conduct and other thing.

(Refer Slide Time: 13:01)



Now, let us come to this actually unipolar PWM operation. In this case actually you require a V sin omega T and the minus V sin omega T and you require actually this inverted signal also. So, that is basically you require little bit more complex circuit, but it is not very complex, it can generate the negative of the voltage by simply actually opamp in a inverting mode.

Now, we want to actually amplify the free count whatever actually control signal according to the amplitude and see the advantage of it over the previously discussed bipolar PWM. And, in this case we require to mention that actually this triangle wave it is frequency should be actually around 30 times more. Generally, there is I triple a standard I triple a standard say that you should have a 48 cuts in a cycle that mean the frequency should be around 24 times more.

So, as discussed previously ma is a peak triangle of signal ratio by the peak triangle of the wave ratio. So, here what we can find the implementation rules are same as same of it. So, where when actually we count is actually more than V tri upper switch actually a plus opens and the a minus actually also opens, that is you are getting a voltage for the full which configuration V dc. Same way when other condition is satisfied means in this region actually, you know V count is less than V tri. Then what happen, actually upper switch actually is O open that A 1 actually opens and the A minus which is closest. So, you get a voltage 0 1 minus V dc.

So, similarly when minus count is greater than tri then it closes the plus actually switches upper switches of the phase B and it opens actually the negative switch of the phase B, thus you are getting basically again plus V dc. Similarly, again you can get actually if it is minus V count is basically less than V tri then plus B closes and minus V closes. So, plus B opens and minus B closes and so, you get actually again the 0 voltage.

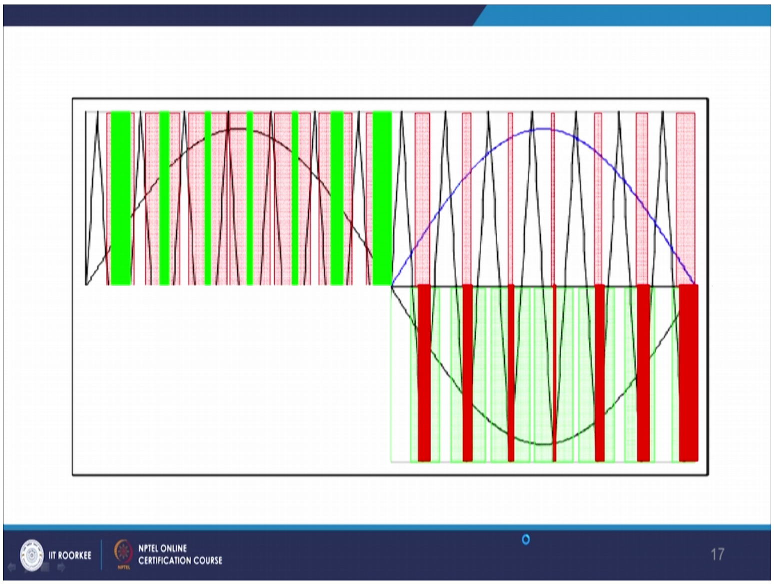
So, you can also here you can generate 0 voltage. So, for this what happen?

(Refer Slide Time: 16:02)

Let us see that this is a configuration of it actually the red or the purple line shows when capital A is closest. So, when this actually condition is satisfied what happen? Capital a is closest and minus A actually lower switch of the phase a opens and so, you are getting actually the voltage of v d c.

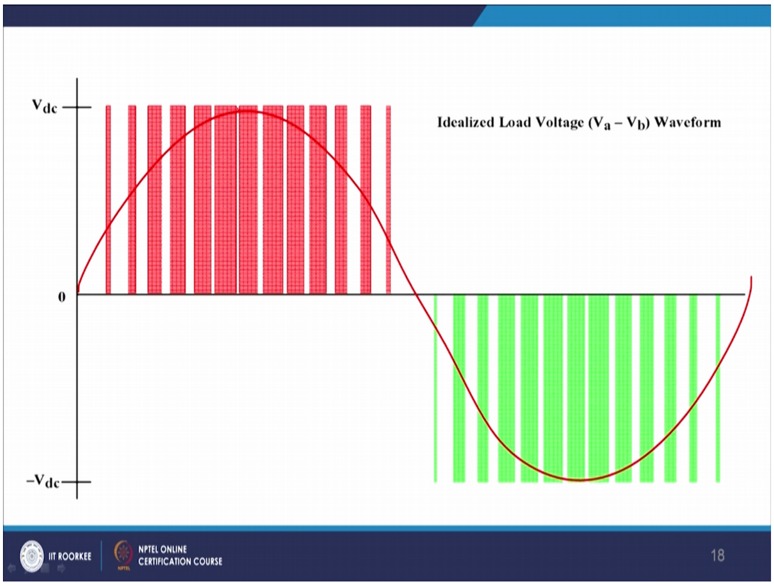
Otherwise, what will happen actually you will close minus A and plus will open and you will get a 0 voltage not minus V d c mind it. Similarly in low half basically plus B closes and sa plus B closed and minus B opened, you get actually V V equal to V d c. And else you get V b equal to 0. Since, you want to get a pole voltage of B A B. So, thus you know actually it will becomes unipolar.

(Refer Slide Time: 17:01)



So, ultimately this will be subtracted from it that this is basically A voltage and this is which is a B voltage and ultimately this will get subtracted. And so, you get actually the resultant wave form something like this.

(Refer Slide Time: 17:26)

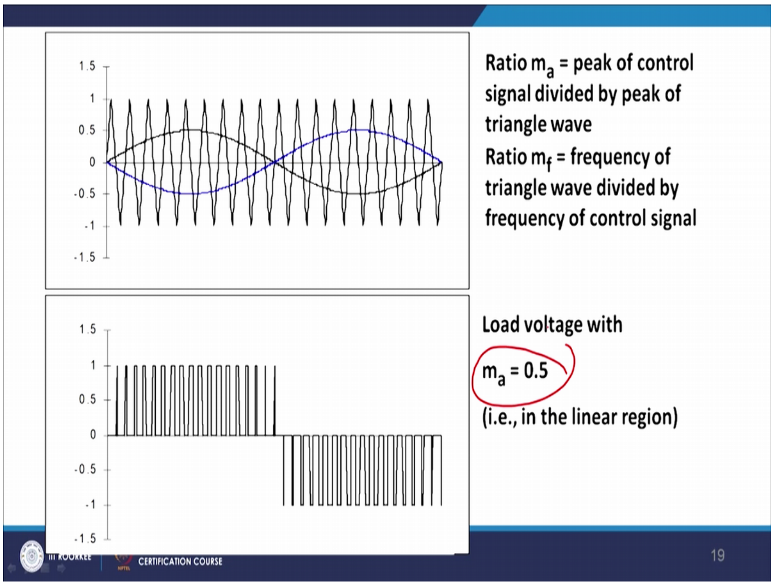


And, what is the advantage of it? Advantage of it that actually it is instantaneous voltage error is half. Since, let us consider that this is actually the sin wave where actually volt area curve is as matched. And so, for this you can find that voltage error here actually will be actually only half of the error voltage that compared to the bipolar.

Another advantage is that it eliminates which amount of harmonic, why because you know it forms a note in this actually the 0 plotting. So, in that way actually many undesirable harmonic is been actually truncated. And moreover instead of shifting this dominating frequency after fundamental to f it will actually transfer to 2 f.

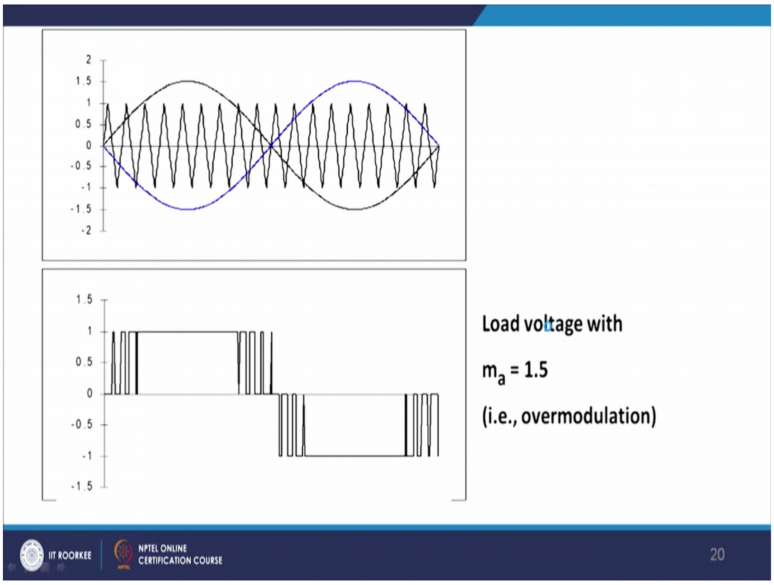
So, you require very smaller inductor or the low pass filter to eliminate this high frequency ripples.

(Refer Slide Time: 18:37)



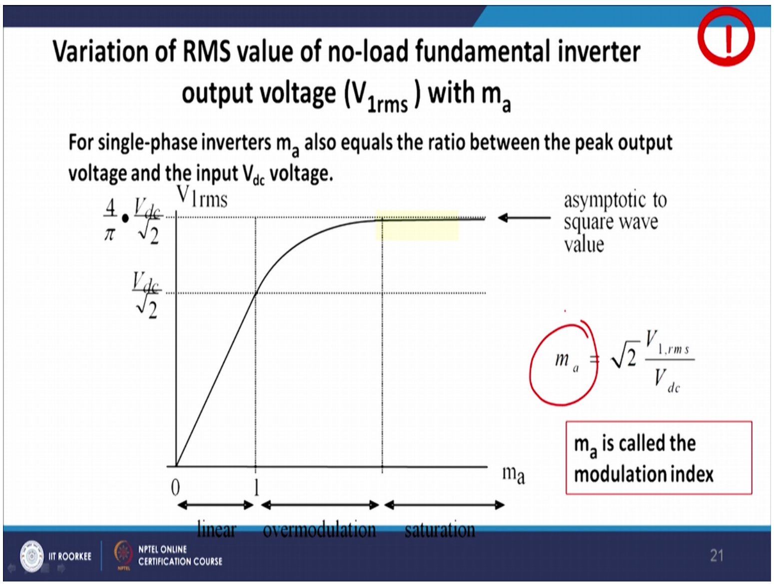
So, this is actually the b a PWM wave form and that will be generating and assuming that actually the value of ma as 0.5. That means it is in a linear region.

(Refer Slide Time: 18:52)



Thereafter, if what happens if we go to the m greater than one it is same as discussed into the bipolar PWM, here value of this will be actual he had to lead to the saturation, only we will have a it will have a crossing at the very beginning. Thereafter actually where does almost a square kind of wave form and it is called over modulation.

(Refer Slide Time: 19:22)

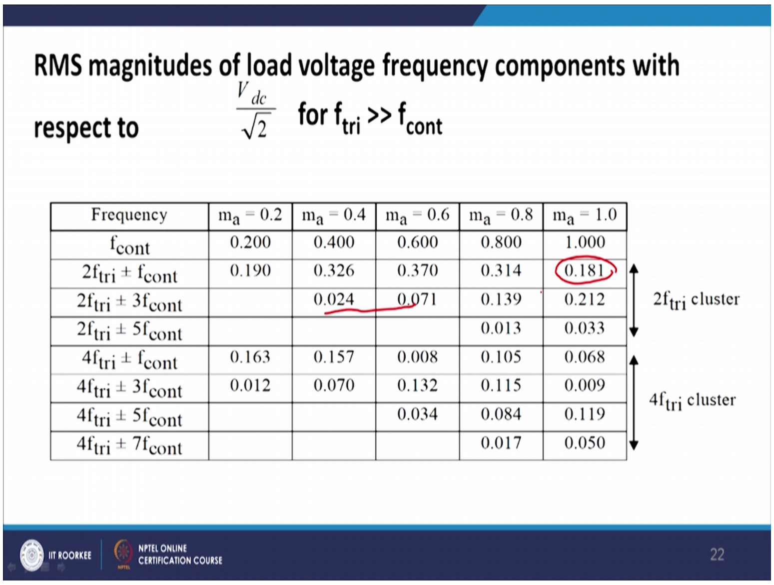


And, generally this m also sees some kind of some kind of hysteresis graph, which we have been all have studied actually in bh curve. So, what happen you know till 0 to 1, it is this linear region and in terms of the rms value you will get the value of m is something like this root 2 b r ms by V d c.

We know that for the square wave the fundamental value is 4 V by pi. So, this will be the saturation value, which you can have from this thing, but you may actually having a higher fundamental value. But you will be sacrificing actually higher contamination on the TSD. That is one of the disadvantage of this kind of when you go to the overall modulation.

Otherwise, in this region you can control the magnitude of this output voltage by simply controlling the modulating index.

(Refer Slide Time: 20:29)

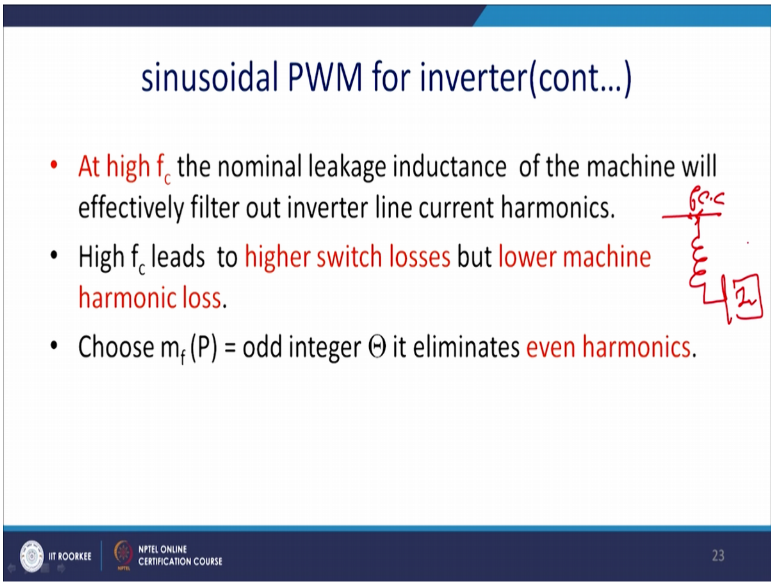


Frequency	$m_a = 0.2$	$m_a = 0.4$	$m_a = 0.6$	$m_a = 0.8$	$m_a = 1.0$
f_{cont}	0.200	0.400	0.600	0.800	1.000
$2f_{tri} \pm f_{cont}$	0.190	0.326	0.370	0.314	0.181
$2f_{tri} \pm 3f_{cont}$		0.024	0.071	0.139	0.212
$2f_{tri} \pm 5f_{cont}$				0.013	0.033
$4f_{tri} \pm f_{cont}$	0.163	0.157	0.008	0.105	0.068
$4f_{tri} \pm 3f_{cont}$	0.012	0.070	0.132	0.115	0.009
$4f_{tri} \pm 5f_{cont}$			0.034	0.084	0.119
$4f_{tri} \pm 7f_{cont}$				0.017	0.050

Now, this is actually this table shows how this relative strength of the different kind of harmonics, you can see that at fundamental. So, if you it will be increasing linearly, but higher harmonics will be actually changing first of all linearly, then after actually at the one it will reduce. Same pattern will be followed actually here you can see that it is actually increasing, thereafter it is strictly increasing. So, we have to keep in mind for it will designing filter, what will be the relative strength of the different kind of harmonic in different frequency accordingly actually we require to take a call to design the harmonic.

So, what are the take away or advantages of the PWM? PWM is very simple to implement.

(Refer Slide Time: 21:30)

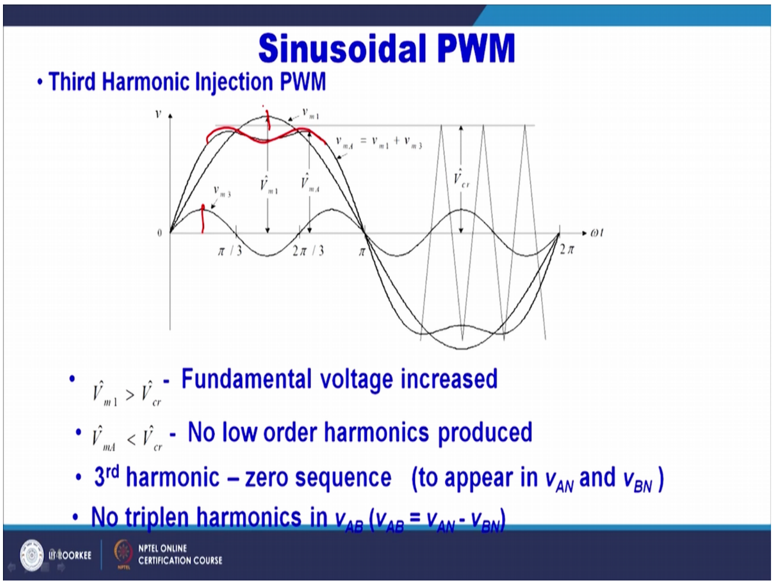


High frequency normal leakage inductance of the machine will effectively filtered out and thus inverted current or in case of the STATCOM was in case of the facts an application. Generally, we connect the pole of the inverter with we will connect pole of the inverter that is this point is called point of common coupling with an inductor with the inverter.

So, since there is a instantaneous difference between the actually the value of the phase voltage value or the line voltage value and the pole of the inverter. So, for this we put an inductor ultimately this inductor itself also will filter out the high frequency harmonics. And generally what happen actually there is a second point f c leads to higher switching losses. And also we require to choose switch of the higher frequency rating so, but it actually lowers the harmonic losses since amount of the TSD will be low. And we require to choose generally the ba actually ratio of the triangular wave by moderating wave some kind of odd number. So, that all even harmonic will be eliminated.

Now, there is another technique to increase the value of the PWM value of the modulation index above one this is one application, it is called basically third harmonic injection.

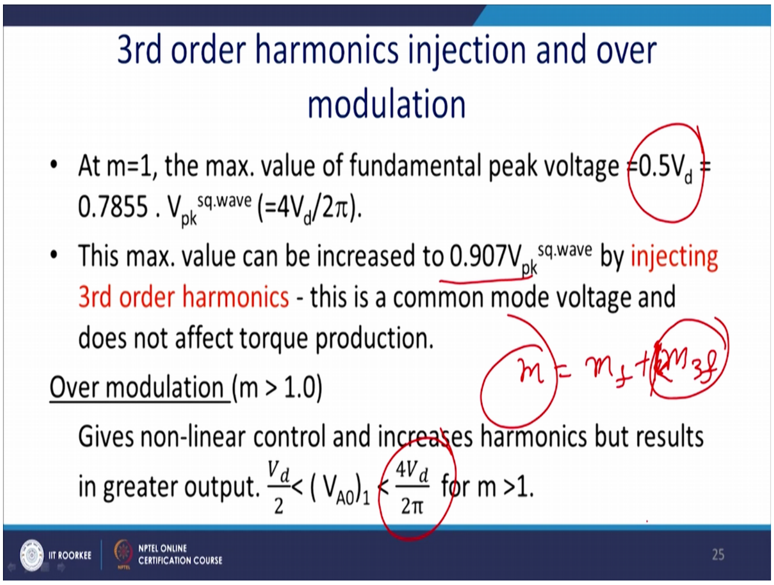
(Refer Slide Time: 23:07)



And you know actually third harmonic will be present only in phase voltages or this is in the line voltages we will not have any a any third harmonic. Moreover, you do not connect actually midpoint and the neutral point thus within that you know actually they only have a infinite impedance in for the third harmonics.

So, thus it will be trapped into the system and it will be go out into the line voltages. And what is the bad advantages of it? So, this is actually the modulation wav w wave form fundamental. With that you contaminate little amount of the third harmonics. And, thus what will happen actually the ultimately resultant peak will become like this, but effective this will be increased. And thus you will get little more modulation index and also it will be in a linear region that is these are the two basic advantage. And, this third harmonic will be restricted within the system it will not go out the line voltages.

(Refer Slide Time: 24:20)



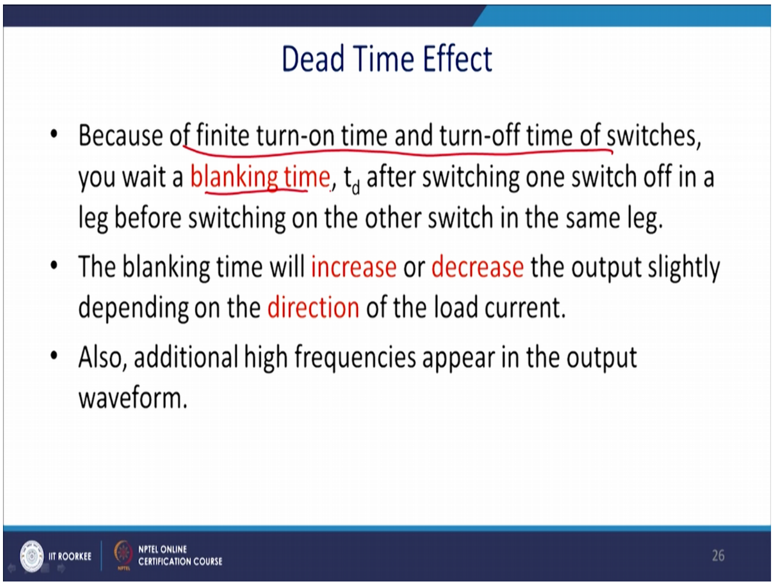
So, what are the advantages of it so at m equal to 1 modulating index equal to 1 so, ongoing part of the saturation. So, the value of the fundamental voltage it is actually 0.5 V d c and that is basically you know 4 by d by 2 pi for the half bridge configuration.

In this configuration we can show that this value can be increased to the 15 times more. So, maximum value can be increased to actually instead of the 0.785 to 0.907 by injecting the proper amount of the third harmonic. Now, there is a different amount of the can be injected for the different condition. So, one aspect that we require to reduce the TST another aspect is; what is the maximum available value of the modulation index in a linear region.

So, accordingly actually I left the student to calculate you know let us say that actually it is the m fundamental plus actually k into 3 f. So, value we can depending on the value of the k we have a different kind of actually strategy. So, what you can do you know actually you can think of so, you can take students are requested to take 2 values, 1 is 1 by 6 and 1 by 4. And let us check it out and we what are the two conditions were actually the TST is minimum and another case you will find that actually you will have a maximum utilization of the DC plus voltage. That can be achieved by actually simple calculation, while we are discussing this is assignment it will be co this part and this assignment will be covered. So, we left it for this assignment to be solved for this we are not discussing in details here ok.

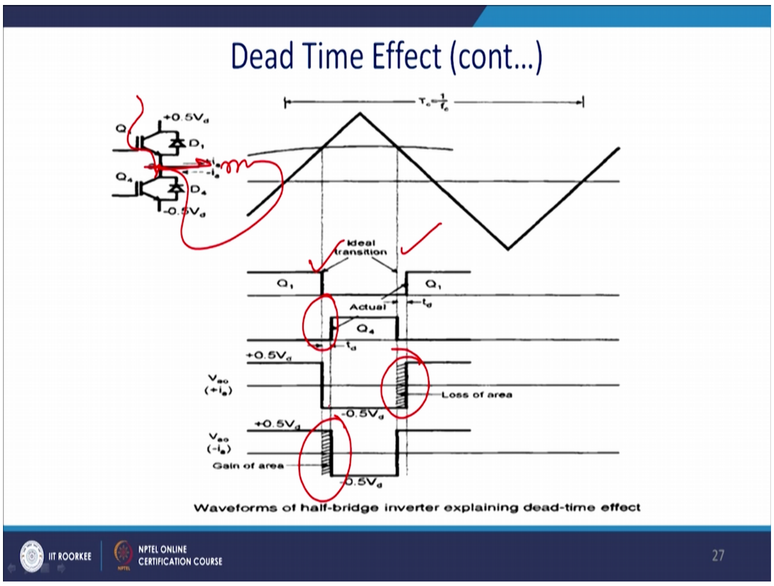
Now, what about a over modulation? Over modulation is almost same. So, we do not get any benefit of the over modulation and we are restricting to actually the saturation value of saturation value as a change it is 4 V d by 2 pi or the half bridge configuration.

(Refer Slide Time: 26:42)



Now, we shall discuss about effect of the dead time all the inverter we shall go back to the circuit first, thereafter we will discuss, all the inverter require to give a dead time.

(Refer Slide Time: 26:53)



So, what happen otherwise there may be a dead shot, because you know that most of this actually inverter made of (Refer Time: 27:05) have the current trial thus and it will take some time to turn off of this is an at any point of time both these switches are conducting, then there is a chance of the short circuit over the decibel voltage and decibel voltage may collapse.

And, for this reason we require to give little blanking. So, we say that because of the finite turn on time and turn out time of the switches, we wait and a blanking time td and this blanking time actually little bit increases and decreases the actually value of the load current. And also in addition some kind of high frequency may appear into the system. We can see that what is a we actually blanking is a necessary (Refer Time: 27:57), we require to provide blanking for the safety and the security, but due to that few phenomena will arise ultimately your control circuit require to actually rectify those problems.

See that this is a nope this is actually san triangle PWM and ultimately this is a ideal transition this point and this point, but what happen you know you actually give a delay. Here ultimately it will start in a conducting mode little time difference of td, but it depends you know if you find that you know load current is positive. Then you will find that actually when these transitions occur, then it will be losing; why because you know we require to see that what are the mode of the conduction is going on. In positive half cycle when current was flowing like this and it is going like this you know. Then ultimately when it will off there is a load. And thus D 4 start conducting within the blanking time. So, for the positive way assuming that this is a radiation of the current.

So, similarly when actually D 4 is conducting when Q 4 is conducting so, Q 1 will come into the picture and there will be a loss into the system. Similarly, when voltage V d is positive and current is negative sometime it happens most of the cases in statcom application.

Then what happen? Actually since current is negative. So, Q 4 was t 4 was conducting, then automatically actually D 1 will conduct. So, thus you will find that there is a loss component in it and actually system will be lossy. We will take care of that turn off and turn on accordingly. And we can make the system loss less by controlling the switching frequency.

This is the actually the lectures of the dead time. Thank you for your attention, we shall continue all discussions in next half an hour with respected modulations and other and the hysteresis control thereafter current PWM control.

Thank you.