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Lecture - 37

In my last class I discussed the operation of 3 phase inverter feeding either delta connected load or a star connected load. We have kept the conduction period for each device equal to pi radians. What did we find? We found that the line current in both the cases; whether the load is delta connected or star connected, has 6 steps in a cycle, whereas, line to line voltage waveform has a constant magnitude for 120 degrees and for remaining 60 degrees, it is 0.

The magnitude of line to line voltage is equal to the input, DC link voltage. When every cycle or every half a cycle, the 0 voltage period is of 60 degree duration, remember. Whereas, if the load is star connected, we found that the phase voltage waveform, line to neutral has 6 steps in that cycle but each of magnitude 1 third and 2 third V_{dc}. There are 6 steps of magnitude, 1 third V_{dc} and 2 third V_{dc}. Therefore, a 3 phase inverter, wherein the device conduction period is 180 degrees is known as a 6 step inverter.

What are the harmonic spectrum of the line to line voltage and line to phase voltage? We know that is an odd function. But then in line to line voltage waveform, we found that there are no triple N harmonics. So, the frequency spectrum is it has a fundamental component and 6 N plus or minus 1 harmonics.

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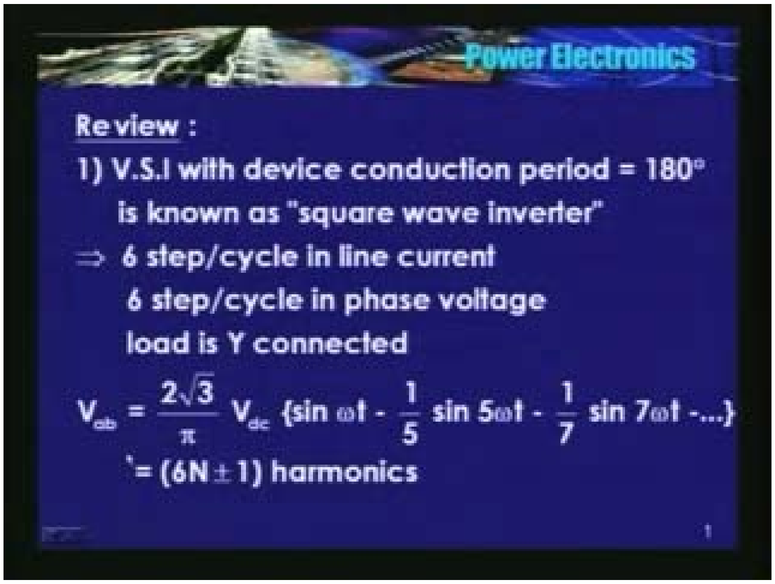

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Review :

1) V.S.I with device conduction period = 180°
is known as "square wave inverter"
⇒ 6 step/cycle in line current
6 step/cycle in phase voltage
load is Y connected

$$V_{ab} = \frac{2\sqrt{3}}{\pi} V_{dc} \{\sin \omega t - \frac{1}{5} \sin 5\omega t - \frac{1}{7} \sin 7\omega t - \ldots\}$$

= (6N ± 1) harmonics

See this, it is given by this equation; 2 by root 3 by pi V_{dc} and it has all 6 N plus or minus 1 harmonics.

What about the line 2 phase or phase voltage waveform, the harmonic series of the phase voltage waveform? Again, it has only a 6 N plus or minus 1 harmonics; the fundamental, fifth and the seventh.

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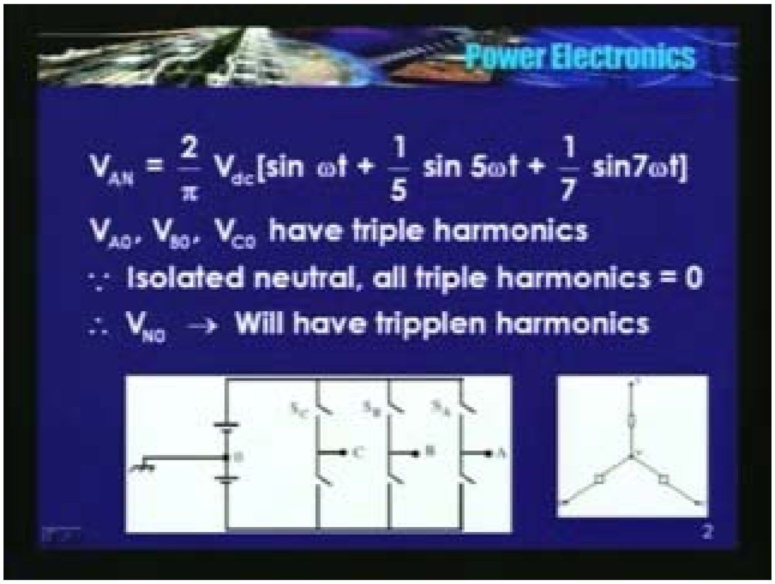

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$$V_{AN} = \frac{2}{\pi} V_{dc}[\sin \omega t + \frac{1}{5} \sin 5\omega t + \frac{1}{7} \sin 7\omega t]$$

V_{A0}, V_{B0}, V_{C0} have triple harmonics

∵ Isolated neutral, all triple harmonics = 0

∴ V_{N0} → Will have tripplen harmonics

See, the magnitude is as is here, 2 by pi into V_{dc}, line to line is 2 into root 3 by pi into V_{dc}. So, both line to line voltage waveform as well as line to phase voltage waveform, there are no triple N harmonics. But then pole voltage waveform that is V_{A0}, V_{B0} and V_{C0}, they have triple N harmonics. Where did they vanish? Where did they go?

In a star connected system, the triple N harmonics will appear in line, in the neutral and the center point of the DC link waveform. In other words, V_{NO} V_{NO} will have triple N harmonics, remember, V_{NO} will have triple N harmonics. Both line current waveform as well as line 2 phase voltage waveform, they have 6 N plus or minus 1 harmonic. Inverter, the output voltage varies linearly with the frequency. In other words, V by F is held constant.

So therefore, frequency at fundamental itself is changing. So, if the frequency at a fundamental is changing, the frequency of the predominant harmonic also will change. So, how to filter this predominant harmonics whose frequency is continuously changing because fundamental itself is changing, In other words, it is rather impossible to filter the harmonics that are present in the output voltage waveform when the fundamental frequency itself is changing. That is one problem. We will address the solution to this problem sometime later.

Now, coming to how do I change the magnitude of the output voltage waveform? Frequency can be controlled by varying the time for which the device is on. In other words, the time for half a cycle if you vary, you vary the frequency of the output voltage waveform. But, when the device is on, what will be the input voltage will appear at the output? How to vary the magnitude of the output voltage?

One way is to change the input DC voltage itself. As the frequency changes, you vary the input voltage to the inverter.

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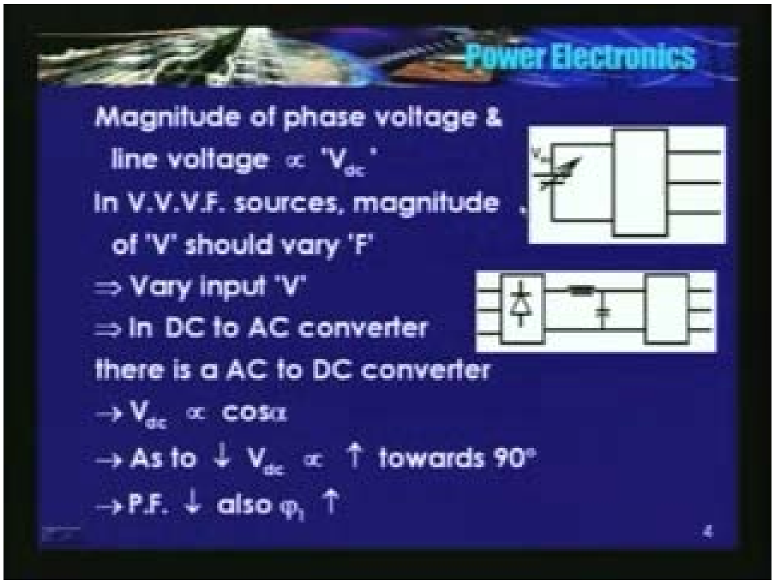

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Magnitude of phase voltage & line voltage $\propto$ 'V_{dc}'

In V.V.V.F. sources, magnitude of 'V' should vary 'F'

$\Rightarrow$ Vary input 'V'

$\Rightarrow$ In DC to AC converter there is a AC to DC converter

$\rightarrow V_{dc} \propto \cos\alpha$

$\rightarrow$ As to $\downarrow V_{dc} \propto \uparrow$ towards 90°

$\rightarrow$ P.F. $\downarrow$ also $\varphi_1 \uparrow$

How do we get this DC voltage first of all? We we obtain this DC voltage by rectifying the input AC. So, in order to vary the input voltage to the inverter, I need to have a controlled bridge at the input. See, we have studied 3 phase controlled bridge or a single phase controlled bridge, wherein output voltage is proportional to cos alpha. So, as alpha increases towards 90 degrees, output voltage also decreases. So, by introducing phase angle delay or increasing the alpha towards 90 degrees, you can reduce the input voltage to the inverter.

But then, what is the disadvantage of line commutated converters? We know that the displacement factor is a function of trigger angle alpha. As alpha increases, the displacement factor decreases, remember. In a in a single phase fully controlled bridge, displacement factor is or displacement angle is same as the trigger angle alpha.

What is the second disadvantage? Second disadvantage is again, there is only 1 pulse for a half a cycle at the input side or or at the source side. So, in a 3 phase AC to DC converter; there again 6 N plus or minus 1 harmonics, in a single phase case there are all odd harmonics. But then only difference is the input frequency is the supply frequency the 50 hertz.

So, if I am using a 3 phase AC to DC converter to provide a DC voltage to the inverter, the source side may have 6 N 1 plus or minus 1 harmonics. Since, the frequency in the fundamental itself is held constant or this frequency is nothing but the source frequency and it does not vary over a wide range; so, in principle it is possible to design a filter at the source side.

I will repeat; it is possible to design a filter to filter out source side harmonics because the frequency of the fundamental itself is constant. Whereas, at the output side output side of the inverter, the frequency is continuously changing, therefore the frequency in the predominant harmonics is also changing. So, it is rather very difficult to design a filter for the output side.

So, what next? What did we do in DC to AC converter? We had kept the device conduction period constant or in other words, each device is conducting for 180 radians 180 degrees sorry, each device is conducting for 180 degrees. Now, output voltage has to be changed. So therefore, we try to change the input voltage. Instead, why cannot we keep input voltage constant and vary the the period for which the device is on? Or or you control the period for which the device is conducting in that 180 degrees.

So, what you do now is you have an uncontrolled rectification at the input side. So therefore, the input DC link voltage remains constant. You have to vary the output voltage. Now, instead of keeping device conduction angle constant at 180 degrees; now, you control that period, something known as the pulse width modulation.

I did cover this topic in AC to DC conversion. In pulse width modulation, I said there are large numbers of pulses in a cycle. So therefore, the frequency of the predominant harmonic also increases. So, if the frequency of the predominant harmonic increases, now the filter that is required to filter this harmonics reduces, the size reduces. Almost same philosophy, even in DC to AC converters but then I will just briefly revise them here.

We know that the switching frequency of the devices is a function of load. As the power level increases, you need to reduce the switching frequency. But then, as the switching frequency comes down, the distortion in the current waveform increases. In other words, as the switching frequency comes down, the harmonic content that is present in the current increases.

So, what the PWM method should do? The PWM method should aim at reducing this distortion. How does it do? See, I am just saying now, one statement that should be proved in a drives course; that statement is that in a machine is a total leakage reactance that limits the current due to harmonic voltages.

In other words, if I draw the equivalent circuit of an induction machine for a higher frequency harmonic component, you will find that there only there is leakage reactance. So, I will repeat; it is the total leakage reactance of the machine that limits the current due to harmonic voltage. We have been told that leakage reactance is very small. That is true at the fundamental frequency, leakage reactance, yes; it is true at fundamental frequency. But then has the frequency increases, the impedance or the value of X that is 2 pi F into L increases.

So, if you if a wave if your PWM waveform has a, it has a fundamental component and the next predominant harmonic is at a very high frequency, the reactance offered by the leakage inductance is very high for the higher frequency component.

See, I will repeat; a PWM waveform has a fundamental and it has a harmonic component also. If the frequency of this harmonic component is very high, the value of X that is 2 pi F into L where L is the leakage reactance is also very high. So then the current that is flowing due to the harmonic voltage is the magnitude of the harmonic voltage divided by the impedance offered by the leakage reactance at that particular frequency, the frequency of the harmonic component. So, as the frequency of harmonic component increases, they get filtered out, they get filtered out by the leakage reactance.

Now, what is the effect of harmonic current on the motor? This harmonic current, they produce torque pulsation in addition to additional I square R losses. I will repeat; this this high frequency harmonic components, they produce torque pulsation, they produce their own torque and and additional I square R losses.

As the frequency of the predominant harmonic increases, the torque pulsation due to this component, the frequency also increases. Motor has its own inertia and it does not respond to this high frequency torque. I will repeat; every high frequency component that is there in the line in the input current produces its own torque. But then machine has its own inertia, it does not respond to this high frequency torque. Therefore, machine runs smoothly at a speed corresponds to the fundamental frequency.

Now, this is true only if the frequency of the predominant harmonic is high. This is not true if the frequency of the predominant harmonic is low. In other words, if I use 6 step operations and the frequency of the fundamental itself is low, say 10 hertz or so; then the frequency of the predominant harmonic is 50 hertz. Then there will be problem torque pulsation and noise and other effects.

So, this is about the pulse width modulated converters or inverters. Now, how do I choose the number of pulses per cycle? I have told that instead of having 1 pulse per cycle, if you have large number of pulses per cycle, frequency of predominant harmonic increases. How to choose the number of pulses per cycle?

Now see, rule number 1: the sub harmonics can be eliminated, I will repeat, the sub harmonics can be eliminated if the pulse number is an integer.

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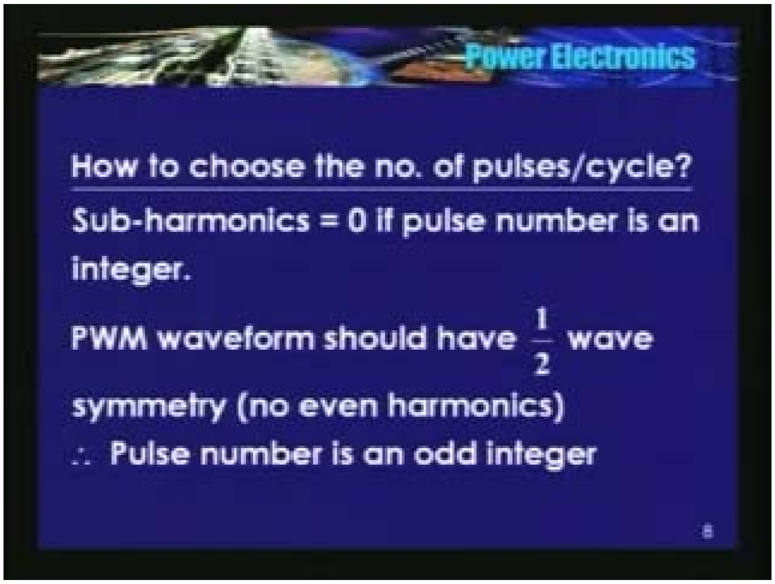
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How to choose the no. of pulses/cycle?

Sub-harmonics = 0 if pulse number is an integer.

PWM waveform should have $\frac{1}{2}$ wave symmetry (no even harmonics)

$\therefore$ Pulse number is an odd integer

In other words, the PWM waveform should be synchronized with its own fundamental. Now, this can happen only when the pulse number is an integer. Now, what is the second feature? The second feature should be the PWM waveform should have half wave symmetry. When the PWM waveform has half wave symmetry, there are no even harmonics. In other words, pulse number is an odd integer. What is the third feature? The third feature is that there should be a 3 phase symmetry there should be a 3 phase symmetry. Only then, every component or every frequency component is balanced.

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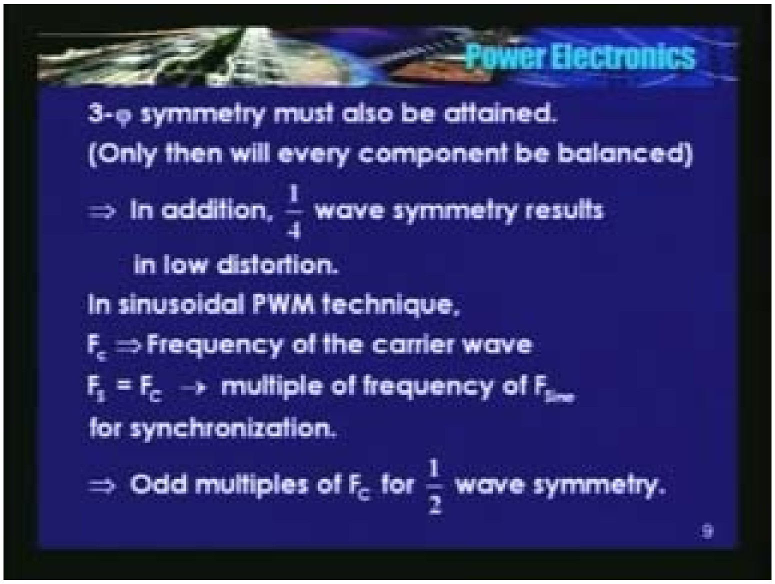
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3-φ symmetry must also be attained.

(Only then will every component be balanced)

$\Rightarrow$ In addition, $\frac{1}{4}$ wave symmetry results in low distortion.

In sinusoidal PWM technique,

$F_c \Rightarrow$ Frequency of the carrier wave

$F_s = F_c \rightarrow$ multiple of frequency of F_{Sine} for synchronization.

$\Rightarrow$ Odd multiples of F_c for $\frac{1}{2}$ wave symmetry.

So, these are the main features; 1 is for sub harmonics should be 0 - that I can make only when the pulse number is an integer, it should have a half wave symmetry - that is possible when the number of pulses is an odd integer and you need to have 3 phase symmetry. In addition in addition if there is quarter wave symmetry, it results in low distortion. I will repeat, in addition to all this if there is a quarter wave symmetry, it results in low distortion in the current waveform.

So, if I am using sinusoidal PWM technique which we also discussed in AC to DC conversion, F_C is the frequency of the carrier wave, in sinusoidal PWM technique, there is a modulating wave and a carrier wave. The feature of modulating wave, I will tell you sometime later. If F_C is the frequency of the carrier wave, the switching frequency of each device is equal to the frequency of the carrier itself. So, the frequency of the carrier must be multiple of frequency of sine wave for synchronization.

See here, F_S is the switching frequency, F_C is the frequency of the carrier wave. So, this should be multiple of the frequency of the the modulating wave or the sine wave, modulating sine wave for synchronization. So, only then I will get number of pulses is an integer. Now, it should be odd multiple of F_C for half wave symmetry it should be odd multiple of F_C for half wave symmetry. Then, what about 3 phase symmetry?

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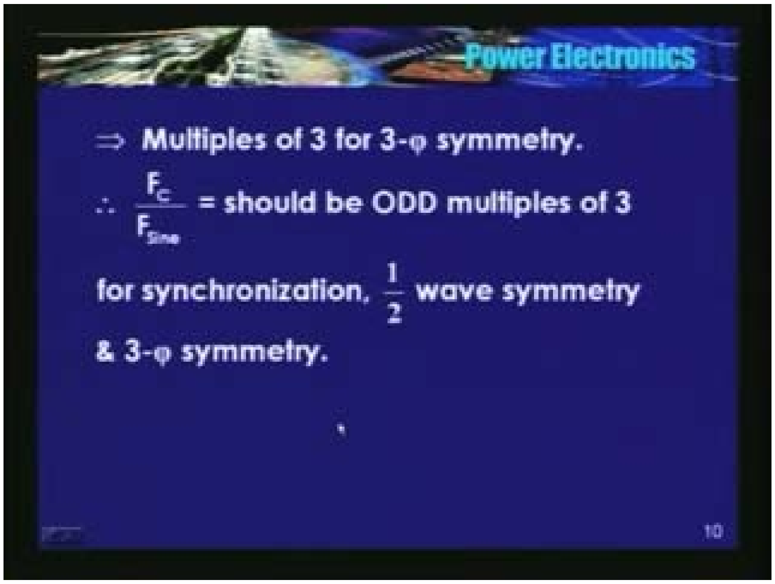

⇒ Multiples of 3 for 3-φ symmetry.

∴ $\frac{F_c}{F_{Sine}}$ = should be ODD multiples of 3

for synchronization, $\frac{1}{2}$ wave symmetry

& 3-φ symmetry.

Now, 3 phase symmetry, it should be multiple of 3 for 3 phase symmetry. I will repeat; for 3 phase symmetry, it should be a multiple of 3. So therefore, the ratio of F_C by F_{sine}, see here, the ratio of F_C by F_{sine} should be odd odd multiple of 3, remember. For perfect synchronization, half wave symmetry and 3 phase symmetry.

So, in order to have a synchronous PWM, ratio of F_C by F_{sine} should be odd multiples of 3. Only then you can have perfect synchronization; half wave symmetry and 3 phase symmetry. Now, let us see the sinusoidal PWM technique.

Inverter is a 3 phase inverter. So, the phase displacement between the fundamental components of each phase should be 120 degrees. So, sinusoidal PWM technique, there is a modulating wave which is sinusoidal and there is a high frequency carrier wave. So, for 3 phase inverter control, I need to take 3 sinusoids which are displaced in by 120 degrees. They have same frequency and same magnitude; you need to compare them. So, here are the circuits at the block diagram level.

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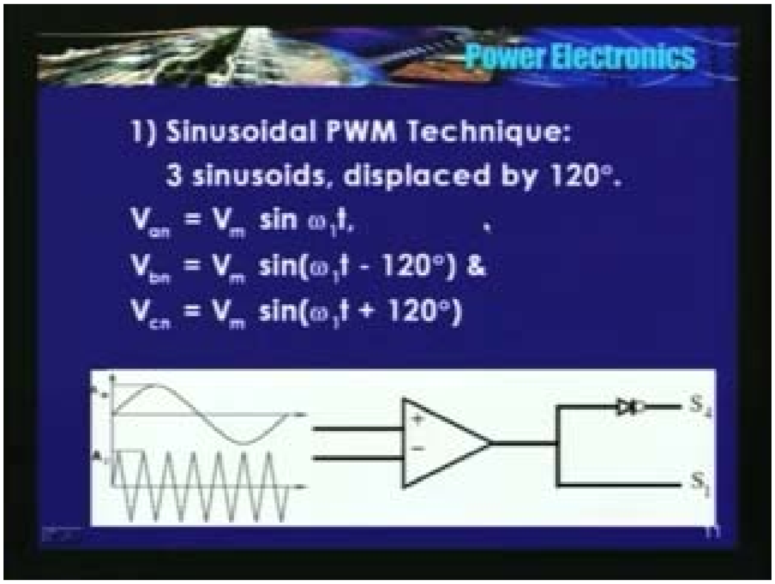
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1) Sinusoidal PWM Technique:

3 sinusoids, displaced by 120°.

$V_{an} = V_m \sin \omega_1 t,$

$V_{bn} = V_m \sin(\omega_1 t - 120°)$ &

$V_{cn} = V_m \sin(\omega_1 t + 120°)$

See, these are the 3 modulating waves modulating waves, wherein $A_m$is the amplitude of the modulating wave, A_C is the amplitude of the carrier wave. They are compared they are compared and they are fed to 1 leg of the inverter 1 leg of the inverter. It is a VSI so S_1 and S_4 are complementary are complementary. So, this is an inverter, inverter.

Now, the ratio, whatever, in the sense, the ratio of the frequency of the carrier and the modulating waveform, I have already discussed, what should be the value? Now, generally, magnitude of the carrier wave is held constant the magnitude of the modulating wave is variable.

In other words, we defined a modulate ah we have defined a factor that is known as the modulation index M which is equal to A_m divided by A_C. A_M is the amplitude of the sine wave divided by the amplitude or a peak of the triangular wave and I have told you, in AC to DC converter is that output voltage is proportional to the modulating index, the modulation index.

So, so here is the waveform for one particular frequency. Pole voltages, they vary from V_{dc} by 2 to minus V_{dc} by 2. For 180 degree conduction, I have only 1 pulse. Now, there is large number of pulses. So, this line to line voltage, I have shown only till pi.

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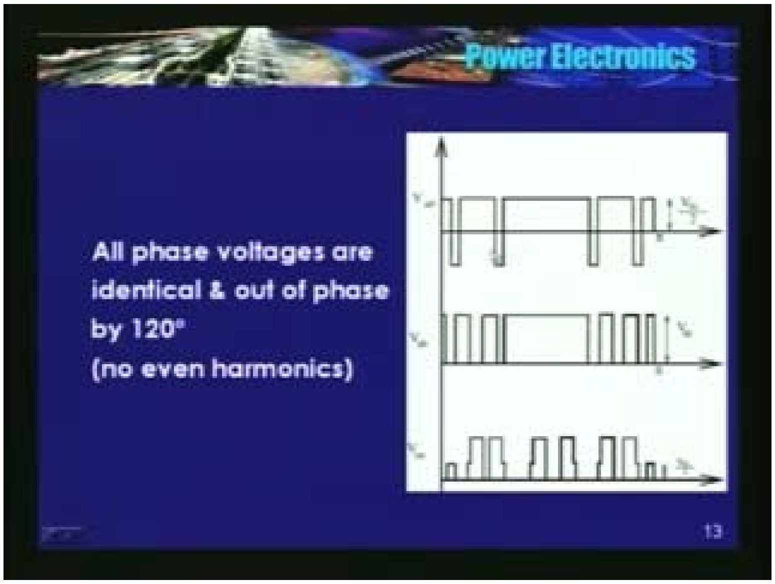

All phase voltages are identical & out of phase by 120°
(no even harmonics)

From pi to 2 pi, again I will have a negative half cycle. So, magnitude is V_{dc} here and phase voltage is again, there are 2 steps; one is V_{dc} by 3, another one is 2 by 3 V_{dc}. Whatever that happened in a 6 step converter, there also 1 third V_{dc} and 2 third V_{dc}. Even here, in a PWM inverter, the phase voltage waveform; there are 6 steps or no no i there are 6 steps in the sense, 1 third V_{dc} and 2 third V_{dc}. This is pole voltage, line to line and the phase voltages. Now, these 3 phases are identical and are out of phase by 120 degrees. There are no even harmonics

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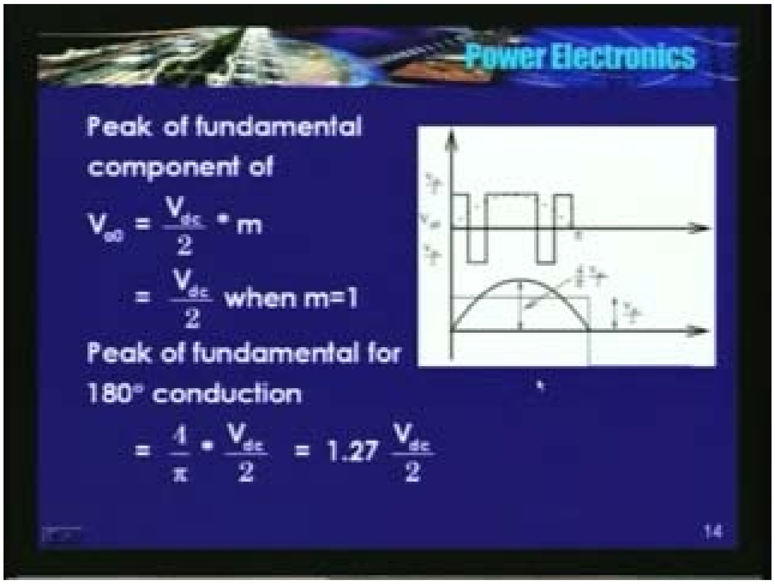

Peak of fundamental component of

$$V_{a0} = \frac{V_{dc}}{2} * m$$

$$= \frac{V_{dc}}{2} \text{ when m=1}$$

Peak of fundamental for 180° conduction

$$= \frac{4}{\pi} * \frac{V_{dc}}{2} = 1.27 \frac{V_{dc}}{2}$$

What is a peak of the fundamental component in a PWM inverter and what is the peak of the fundamental component in a square wave inverter? See in this figure, I have just shown a few number of pulses. Now, it can be proved that the peak of the fundamental peak of the fundamental is V_{dc} by 2 itself, is the input voltages itself. See here, as I have written Va_0, the peak is this. So, V_{a0} the fundamental component is V_{dc} by 2 into m. If m is equal to 1, modulation index is equal to 1; I have peak of the fundamental component of V_{a0} is V_{dc} by 2. How about in 180 degree conduction? It is 4 by pi into V_{dc} by 2.

See here, we have already drawn this, 180 degree conduction, V_{dc} by 2. So, this is 4 by pi into V_{dc} by 2. Whereas, in a pulse width modulated waveform, it is just V_{dc} by 2 itself. So, in other words in other words, the peak of the fundamental in 180 degree conduction is higher is higher, is 1.27 times V_{dc} by 2.

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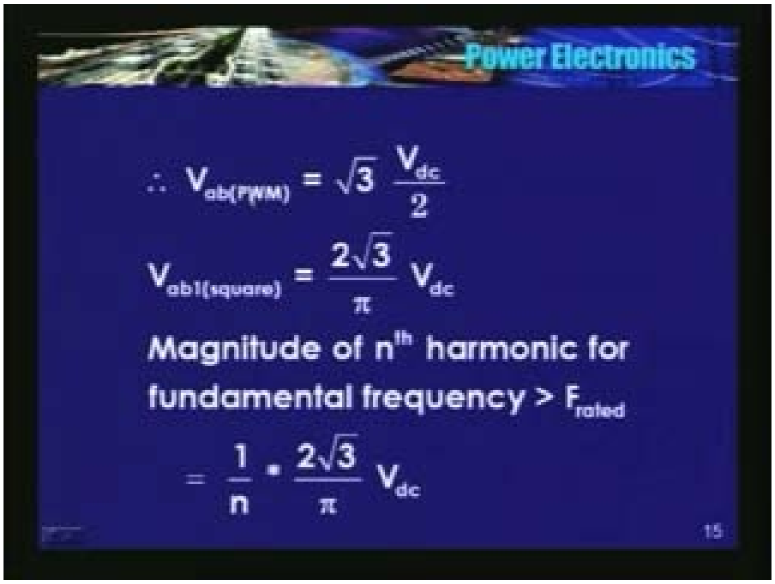

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$$\therefore\ V_{ab(PWM)} = \sqrt{3}\,\frac{V_{dc}}{2}$$

$$V_{ab1(square)} = \frac{2\sqrt{3}}{\pi}\,V_{dc}$$

Magnitude of n^{th} harmonic for fundamental frequency > F_{rated}

$$= \frac{1}{n} \cdot \frac{2\sqrt{3}}{\pi}\,V_{dc}$$

So, what is the line to line voltage in the PWM waveform? It is again root 3 times this, V_{dc} by 2. Whereas, square wave, it is 2 root 3 by pi into V_{dc} 2 root 3 by pi into V_{dc}. What is the magnitude of nth harmonic for the fundamental frequency greater than F rated? I did show this expression in the beginning of my lecture. I have shown you the the Fourier series for the line to line voltage waveform.

So, I can so, what is the, what is the magnitude of the nth harmonic in a 6 step operation? It is it is 1 over n into the peak of the fundamental. I will repeat; the magnitude of the nth harmonic in a 6 step operation is 1 over n into the peak of the fundamental, remember, peak of the fundamental.

Now, what are the various frequency components that are present in the output voltage waveform which is controlled using pulse width modulation or in other words, what is the frequency spectrum? Now, before writing the various components, I will define a factor, what is or which is equal to F_N.

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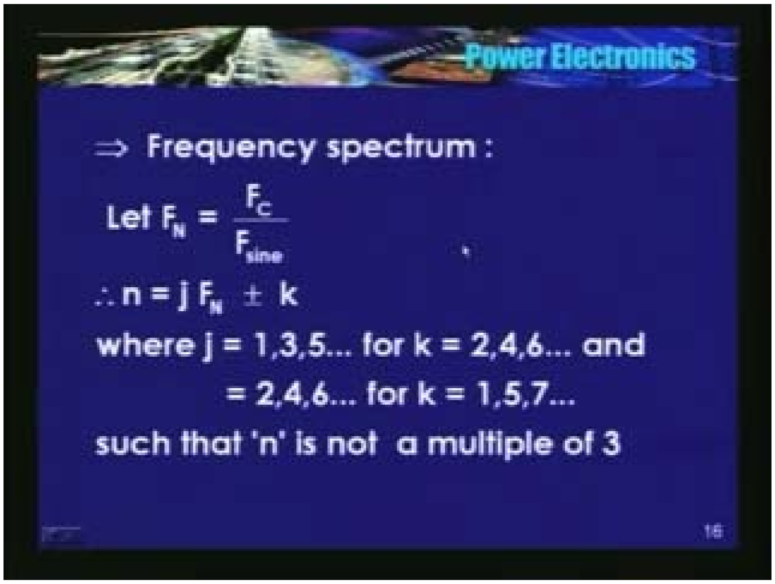

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⇒ Frequency spectrum :

Let $F_N = \frac{F_C}{F_{sine}}$

$\therefore n = j F_N \pm k$

where j = 1,3,5... for k = 2,4,6... and

= 2,4,6... for k = 1,5,7...

such that 'n' is not a multiple of 3

I will define F_N which is equal to F_C divided by F_{sine}. F_C is the carrier frequency carrier frequency and F_{sine} is the frequency of the fundamental component. So therefore, the frequency of that are present are j into F_N, for a sinusoidal PWM technique, j into F_N plus or minus k plus or minus k where where j is equal to 1, 3, 5 so on for k is equal to 2, 4 and 6 and when j is even j is even, at the time k is 1, 5, 7 such that n is not a multiple of 3. Why it is not a multiple of 3?

In a line to line waveform, you cannot have or there are no triple N harmonics in a line to line waveform there are no triple N harmonics or it can be that can be they can be ignored. So, this is the frequency spectrum. So, if F_N is equal to 45; I have taken the ratio of ratio of the carrier frequency of the triangular wave to the frequency of the fundamental, I have taken 45 number.

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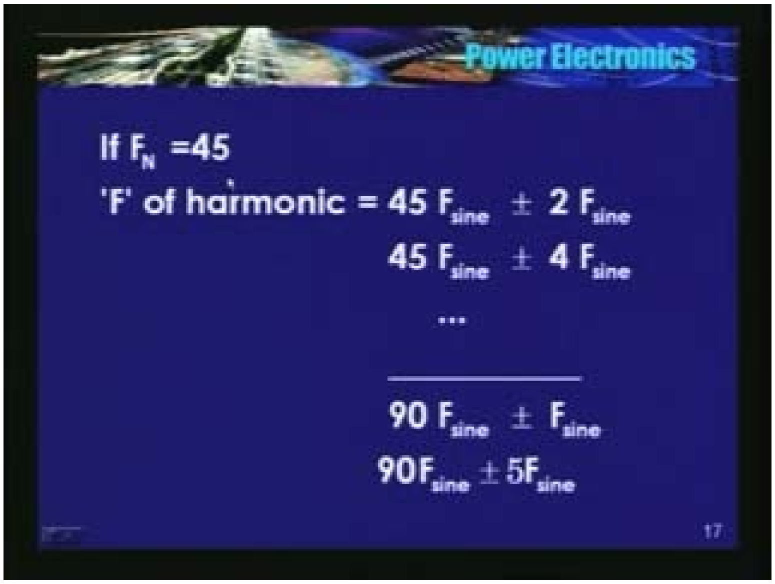

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If F_N =45

'F' of harmonic = 45 $F_{sine} \pm 2 F_{sine}$

45 $F_{sine} \pm 4 F_{sine}$

...

90 $F_{sine} \pm F_{sine}$

$90F_{sine} \pm 5F_{sine}$

So, frequency of the harmonics that are present is 45 into sine plus or minus 2 F_{sine}. See here, 1 F_N plus or minus k, k is 2. So, twice F_{sine} and second we have plus or minus F_{sine}. When j is equal to 2, k is equal to 1, 5, 7 so on. So, it is like 90 F_{sine} plus or minus F_{sine}, 90 F_{sine} plus or minus 5 F_{sine} so that none of them are multiples of 3 none of them are multiples of 3 none of them; though I have given the frequency spectrum. The predominant harmonic is 45 F_{sine} plus or minus 2 F_{sine}

In other words, there are 2 frequency components; at 43 F_{sine}, 45 F_{sine}, remember. So, if I maintain a ratio of 45, carrier to fundamental, we have a fundamental component whose frequency is equal to the frequency of the modulating wave and there are 2 components at 43 F_{sine} and 47 F_{sine}. These are the 2 predominant harmonics.

Now, what happens as m tends to 1? In other words, as the output voltage increases, you need to increase the magnitude of the sine. In fact, as the magnitude of the sine increases, output voltage changes. V_0 is proportional to the modulation index V_0 is proportional to modulation index. The magnitude of the carrier or the magnitude of the triangular wave is held constant. So, output voltage is varied by varying the magnitude of the sine.

So, as m approaches 1; see, we have a very interesting case, just see in this waveform, I have just shown the intersection at the center.

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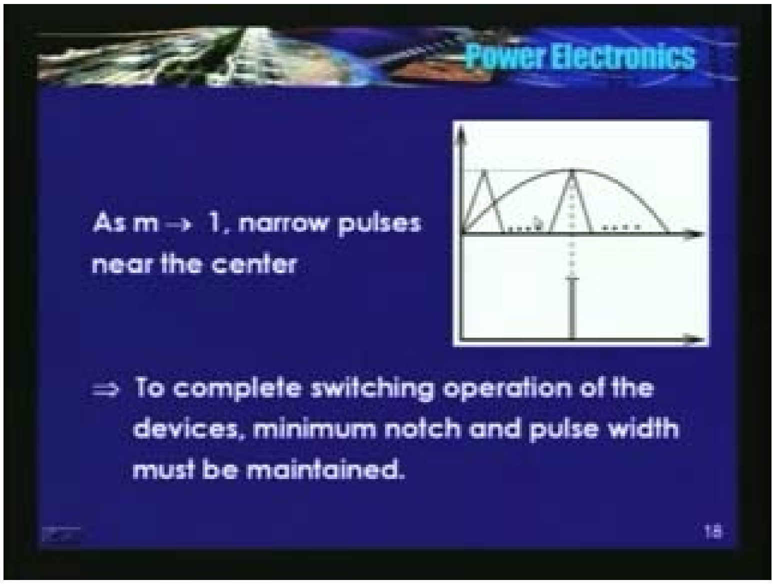

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As m → 1, narrow pulses near the center

⇒ To complete switching operation of the devices, minimum notch and pulse width must be maintained.

We have no problem near the 0 crossing; both, at these two 0 crossings. See, at the center, m is equal to 1 means triangular wave as well as sine wave is equal to 1, we have a very narrow pulse. See, we have a very narrow pulse.

Now, what is the problem in this narrow pulse? See, what does this intersection indicate? So, device has to be turned off at the falling edge and at the rising edge, again, device has to be turned on or vice versa. You have a very narrow pulse there, but then general philosophy is that a device having turned on or having turned off, it should be maintained in that state for some time.
I repeat; having turned on or off the device, it should be maintained in that state for at least for some time. So therefore, if there is a very narrow pulse; so, that pulse has to be blocked. It should not be applied to the control circuit of the inverter which turns on and off the devices. It is something like this, see here.

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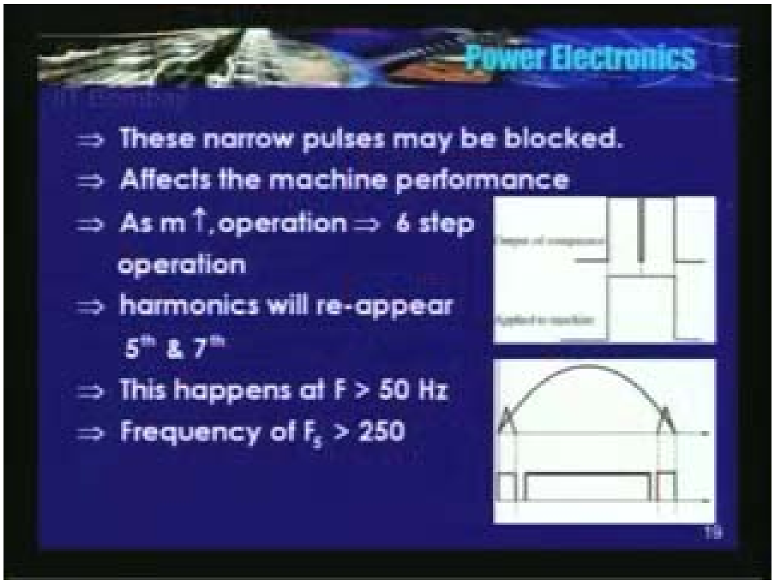

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- ⇒ These narrow pulses may be blocked.
- ⇒ Affects the machine performance
- ⇒ As m ↑, operation ⇒ 6 step operation
- ⇒ harmonics will re-appear 5th & 7th
- ⇒ This happens at F > 50 Hz
- ⇒ Frequency of F_s > 250

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So, this this is a very narrow pulse, is an output of the comparator; wherein, a sine wave and a, and a carrier wave, they are compared. Since, this is a very narrow pulse, this should be blocked and this waveform, that should be applied to the inverter. This is an over rider here. Now, this this is also known as the pulse dropping pulse dropping. We are dropping the pulse or we have blocked this pulse. So, what is the effect of the pulse dropping in the machine?

Definitely, it has to affect the machine performance. See because, it was supposed to be turned, the device, supposed to be turned off here and on, again here. So therefore, for some time, so that particular phase, there is change in the voltage applied to the motor. Now, we are not turning on and off. We have kept the device completely on here. So definitely, there is a slightly a higher voltage applied to the motor. So, it will definitely affect the motor performance.

Now, what happens if I try to increase the magnitude of the the modulating wave above 1, what is known as the over modulation over modulation? Now, you will have intersections only at the 0 crossing, may be, only near the 0 crossing and you will have a very broad pulse in the center. See, as m tends to increase above 1, you will have intersections near the 0 crossing and a broad pulse in the center.

So, in other words, inverter is slowly going in from pulse width modulation to a square wave operation. Now, the conduction period is approximately 180 degrees. We had, till modulation equal to 1, we had pulse width modulation. Now, above modulation index equal to 1, now we have a 6 step operation 6 step operation. Till or in PWM mode, frequency of the predominant is approximately equal to the frequency the carrier. See, I did tell you that frequency of the frequency of the predominant harmonic is F_C minus or if the ratio is 45, I have at 43 and 47.

Now, if a switching frequency, switching frequency is of the order of of the order of say, 5 kilo hertz 5 kilo hertz, 2 FM or 2 twice the fundamental frequency. That is 100 hertz; 100 hertz this side and 100 hertz that side, so 4.9 kilohertz, 5.1 kilohertz, something like that.

So, I can say that in PWM mode, frequency of the predominant harmonic is approximately equal to the frequency of the carrier. This is true till m is equal to 1 or m is equal to less than 1. As m goes above 1, we are going in for 6 step operation. 6 step operation frequency spectrums is 6 N 1 plus or minus 1 harmonic. So, when m is equal to 1? When F is equal to F rated, approximately is equal to 50 hertz for Indian condition.

So, till, say, below 50 hertz, we have a frequency spectrum or frequency the predominant harmonic is approximately equal to the carrier and above 50, there is fifth harmonic, seventh harmonic. What is the solution? What is the, see, the fifth and the seventh, they will appear only above 50 hertz only above 50 hertz. Now, if you wish, you can design a filter to filter out 250 hertz component.

See, below 50 hertz, the frequency of the predominant harmonic is approximately equal to the frequency of the carrier which is high and therefore, those harmonics get filtered by machine inductance, machine leakage inductance. Above 50 hertz, fifth and seventh are reappearing. So, may be at 51 hertz or so, there is fifth harmonic that is approximately 255 hertz or so. So, that is why I said, if you wish, one can design a filter to filter out a harmonic of 255 hertz. It is possible now, it is possible.

Another question is if it is not possible, you have no choice. You got to live with it you got to live with it because you cannot have pulse width modulation in the entire range, may not be possible.

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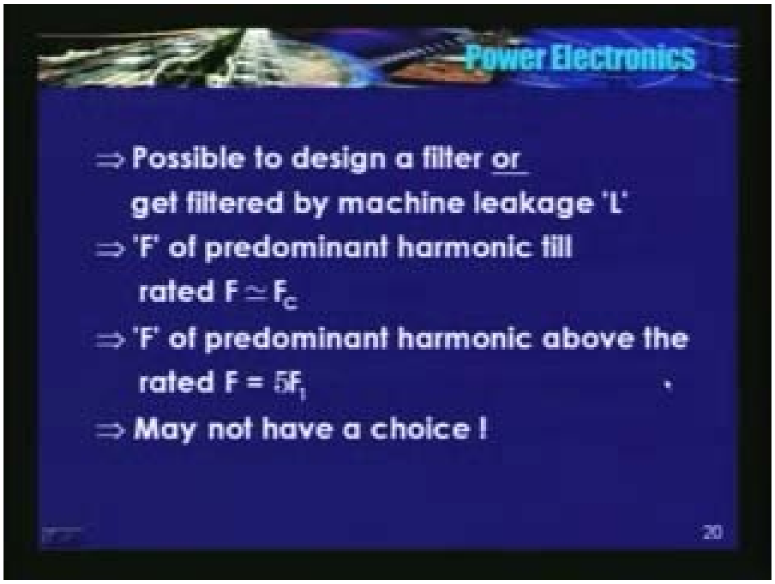

Power Electronics

⇒ Possible to design a filter or
get filtered by machine leakage 'L'

⇒ 'F' of predominant harmonic till
rated $F \simeq F_c$

⇒ 'F' of predominant harmonic above the
rated $F = 5F_1$

⇒ May not have a choice !

20

So, that is what I said here, frequency of the predominant above the rated F is 5 times F_1. One way is one can design a filter whose cut off frequency is 250 hertz. Now, it if you can filter 250 hertz; definitely, it will filter the component which are above 250 hertz. Now, second way to argue is that is no choice but to live with it but to live with it. That is about sinusoidal PWM technique.

What do we find? We found that the peak of the fundamental using sinusoidal PWM technique is 78.55% of the peak of the square wave. It is V_d by 2, second is 4 by pi V_d by 2. So, the ratio is 1 divided by 1.27. That is equal to 78.55%.

So, using sinusoidal PWM technique, the peak of the fundamental that can be obtained for a given DC link voltage has come down. In other words, utilization of DC link voltage or utilization of input source has come down. See here, utilization of DC link voltage source has reduced.

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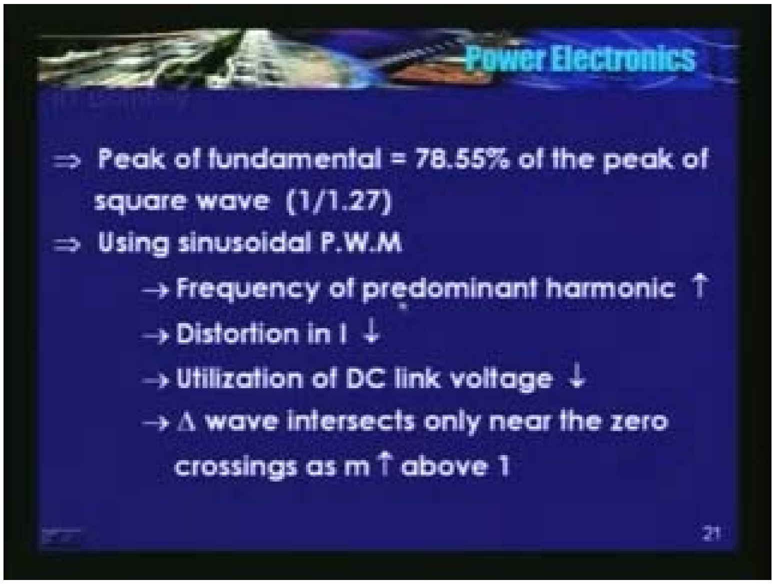

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⇒ Peak of fundamental = 78.55% of the peak of square wave (1/1.27)

⇒ Using sinusoidal P.W.M

  → Frequency of predominant harmonic ↑

  → Distortion in I ↓

  → Utilization of DC link voltage ↓

  → Δ wave intersects only near the zero crossings as m ↑ above 1

What did we gain? In the PWM mode, the frequency of the predominant harmonic has increased. So, if the frequency of the predominant harmonic has increased, they can they do get filtered out by machine leakage inductance. So, there is an improvement in the input current waveform. In other words, the distortion in the current has come down.

Another observation is that the triangular wave intersects only near the 0 crossing, as m increases above 1. As m increases above 1, that the intersections are only near the 0 crossings; near the peak, there are no intersections.

Now, there is a question. See, harmonics are are are appearing only at the only at the only at m is increases above 1, because there are no intersections there. Now, the question is; is it possible to change the modulation waveform, modulating waveform without increasing the harmonic content and simultaneously increasing the DC link utilization?

I will repeat; using sinusoidal PWM technique; see, the peak wave fundamental is only 78.55% that is the reduction now. The peak of the fundamental goes on increasing as m increases towards 1. See, there is a problem as m increases above 1. So, the question is I will repeat again, is it possible to change the shape of the modulating wave without changing the harmonic content and simultaneously increasing in the DC link utilization?

In other words, the peak of the fundamental should be higher than this 78.55%. It should be higher. See, in a in a it was V_d by 2, Some I should get slightly higher here with the new wave modulating waveform. But then harmonic content should not change harmonic content should not change. What I will do is or what is being done is a third harmonic component is being added to the modulating wave, see something like this.

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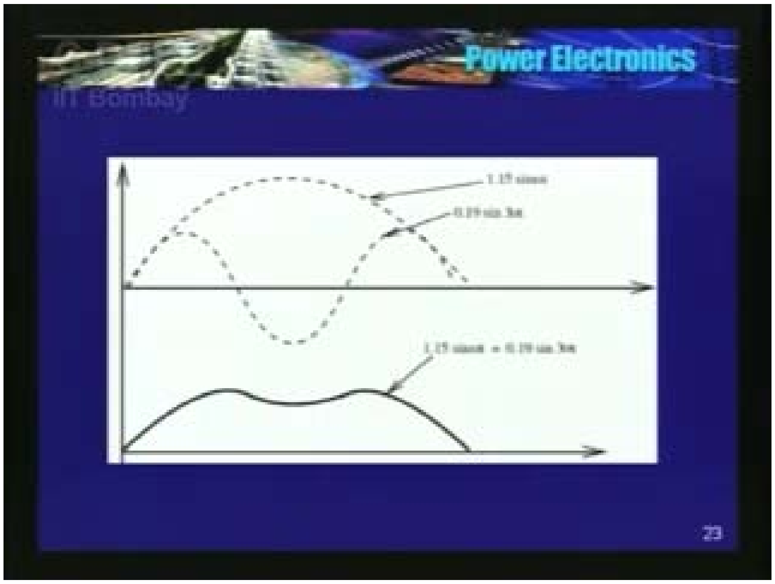

See, a third harmonic component is added to the modulating wave. See, the modulating wave is now 1.15 times this sin omega t. It was only sin omega t. I took 1 as a sin, 1 a 1 per unit, sin omega. I am adding 0.19 times sin 3 omega t to this waveform and the resulting waveform is something like this. See, now the peak has gone. We do not have a sharp peak here, we had a problem here; sin, the triangular wave, of a it was, maximum I can have m is equal to, modulation is equal to 1 here.

So, now there is no peak here. Now, area of this, the modulating wave when I have a purely sinusoidal wave is less compared to this waveform. See, 1.15 sin omega t plus 0.19 sin omega t. I have added a third harmonic component to the modulating wave. This third harmonic cannot appear in line to line waveform, remember this third harmonic cannot appear in line to line waveform.

So, what is the result? I have only sin omega t, whereas, here I have 1.15 times sin omega t. In other words, there is a 15% increase in the fundamental component of the voltage using a third harmonic injected sinusoidal PWM technique.

See, the goal was to increase the DC link utilization. Goal was to keep the harmonics spectrum same, if not improve it by changing the modulating waveform. What did I do? We added a third harmonic component of some magnitude. Simultaneously, we increased the magnitude of the modulating waveform by 15%.

Now, the peak has vanished, the peak of the sin wave. So, now if I compare the resultant waveform with the triangular with the same triangular waveform, I can get the maximum value of the output voltage waveform is 15% higher compared to a sinusoidal PWM technique. So, this is known as third harmonic injected PWM technique. More about it, we will discuss in the next class.

Thank you.