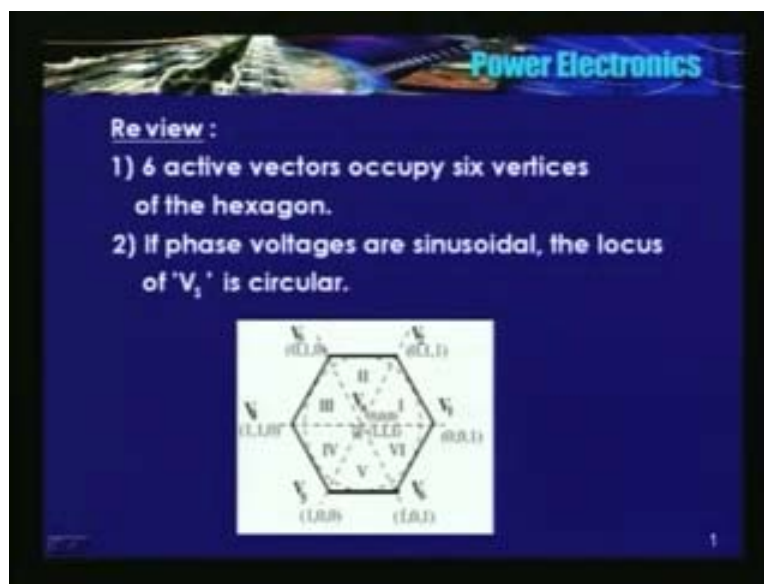


Power Electronics
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Lecture - 40

In my last class we found that 6 active states in the inverter occupied 6 corners of the hexagon and two 0 vectors which are also known as null vectors, they are at the origin.

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See in this figure, see, 000 or 111 corresponds to the origin. Just by turning on the upper switch of phase A or 001, the magnitude of the phase vector is V_S at an angle 0; magnitude of the space vector is V_{dc} at an angle 0. Now, turning on the upper switch of phase B; the space vector moves by an angle 60. See 011, the magnitude remains the same is equal to the magnitude of the DC link voltage V_{dc} but it moves by 60 degrees.

Now, by turning off the upper switch of the phase A; it moves by another 60 degrees. See here, it is 010 and now turning on the upper switch of phase C, it moves by another 60 degrees and so on. So, another observation that we made was that if all 3 phase voltages are sinusoidal, then the locus of V_S is a circle.

Now, what about the space vector PWM technique? In space vector PWM technique, the space vector, the required space vector is synthesized using 2 adjacent vectors and the null vector.

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3) In space vector PWM technique, 2 adjacent vectors and the null vector are used to synthesize V_s^*

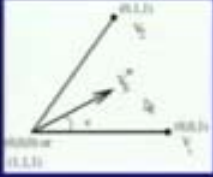
$$V_s^* T_c = V_1 T_1 + V_2 T_2$$

$$T_1 = T_c \alpha \frac{\sin(60-\theta)}{\sin 60}$$

$$T_2 = T_c \alpha \frac{\sin \theta}{\sin 60}$$

$$T_z = T_c - (T_1 + T_2); T_c = \frac{T_s}{2}$$

$T_s \rightarrow$ Sampling time
 \rightarrow During this time V_s^* remains stationary at that point



See in this figure; assume that the space vector is in quadrant 1 or in between V_1 and V_2 and making an angle theta. The length of the space vector is determined by the V by F curve. Now, we need to synthesize using V_1 V_2 and this null vector in such a way that volt second balance is satisfied.

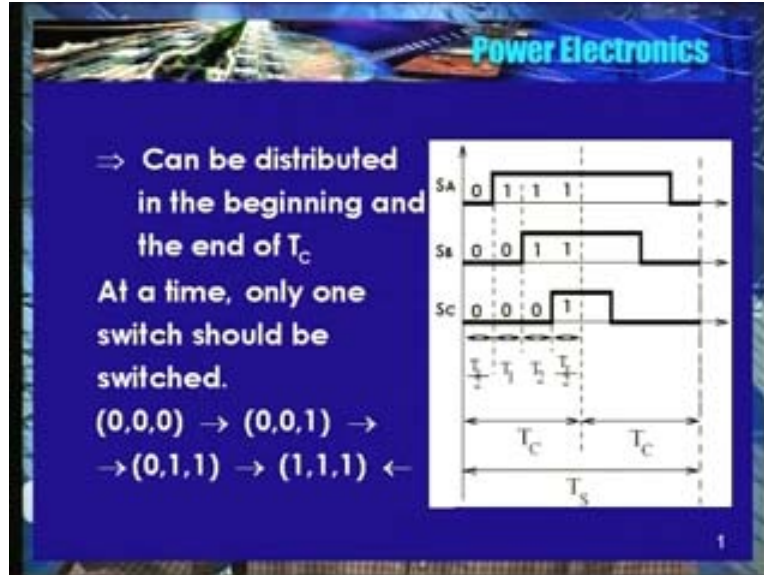
In other words, V_s into time T_c equal to V_1 and T_1 plus V_2 into T_2 where **where** T_1 is the time for which V_1 is applied, T_2 is the time for which vector V_2 is applied and the relationship between T_c T_1 and T_2 is given by this equation. T_z is the time for which 0 vector is applied, is T_c minus T_1 plus T_2 and T_c is T_s by 2 where T_s is the sampling time. During this time, it is assumed that V_s remains stationary at that particular point.

I will repeat; T_c is T_s by 2 where T_s is the sampling time. During this time, the space vector V_s is assumed to be stationary at that particular point. So, by solving these equations we found that T_1 is given by this equation and T_2 is given by this equation. So, to determine T_1 and T_2 , I need to know only theta or the position of the space vector in the sector. I need to know only this angle theta.

Now, T_z can be applied either by using 000 or 111. The time for which or the way 000 or 111 is applied is not going to affect the volt second balance. It is only during the active vectors or is only when the vector, active vectors are applied; the inverter supplies power to the load. So, **so** duration for which 0 vector is applied or duration for which 000 or 111 is applied can be chosen as per convenience.

Now, coming to the implementation part; at any given time only one switch is turned on or off. That is the space vector requirement, space vector PWM technique requirement. So, we will start with 000.

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In other words, we are at the origin; by turning on phase A alone, the upper **upper** device of phase A alone, space vector moves along the X axis. See here, 000 is applied for T_z by 2 duration. I have taken this for as convenience, it is not a must that I should apply this 000 vector or for T_z duration. See, after sometime I am turning on the upper device of phase A. See, phase B, phase C; the upper devices are still off, the lower devices are on. So, this is nothing but 001.

So, **so** V_1 , this is the V_1 vector is applied for T_1 duration. So, at the end of T_1 I am turning on the **upper phase of** upper device of phase B. So, that is 110 or C phase is 0, B phase is 1, A phase is 1 and at the end of T_2 , I am turning on the upper device of phase C also. See, now it is 111 **so** and this is entire T_c period.

So, see the sequence, 000 to 001 and from that 011 and again, 111. Now, this is T_c period and the relationship between the sampling time T_s and T_c is twice T_c is T_s . Now, again at any given time only one switch should be turned on or off. So, we were at this point with 111, I will continue to apply the same vector for another T_z by 2 period. I will apply the same vector 111 for another T_z .

So, after sometime I will turn off the upper phase, I will turn off the upper device of phase C. I have turned off here, the upper device of phase C **C**. Phase A is 1, phase B is 1, phase C is 0. So, this is for T_2 period, this is for T_2 seconds. At the end of that period, I will turn off the upper device of phase B.

See here, A phase is 1, B phase has become 0 and c phase is 0. This is 001 and after T_1 seconds, I will turn off the upper device of phase A. So, I have 000. So, one complete cycle I have completed or sampling period. So, I started with 000, 001, 011 and to 111 and again backwards. So, this is about the space vector PWM technique, wherein **wherein** only one device is being turned on or off.

Now, what is the maximum value of m for which the space vector is sinusoidal? How do I determine the maximum the length of the vector for which all 3 phase voltages are sinusoidal?

I told you that if all 3 voltages are sinusoidal, the locus of V_s is circular. So, for lower **modulating** modulation index value, V_s will always remain within the hexagon. Now, what is the maximum value of V_s for which or beyond which the voltages are going to be a non sinusoidal? How do I determine?

See here, the maximum value of V_s for which the locus is circular is a diameter of the inscribing circle. So, the radius of this circle is the length of V_s for which the space vector or for which all 3 voltages are sinusoidal. Now, what is the value of the **the** radius of this circle? This is nothing but see, this is the hexagon, inscribing circle. So, the length of or the radius of this circle is V_{dc} into $\cos 30$. Now, see this angle is 30 degrees. So, that is equal to root 3 by 2 into V_{dc} .

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⇒ All voltages are sinusoidal (locus of V_s is circle)
 ⇒ Max. value of V_s for which locus is a circle = radius of the inscribing circle

$$= V_{dc} \cos \frac{\pi}{6} = \frac{\sqrt{3}}{2} V_{dc}$$

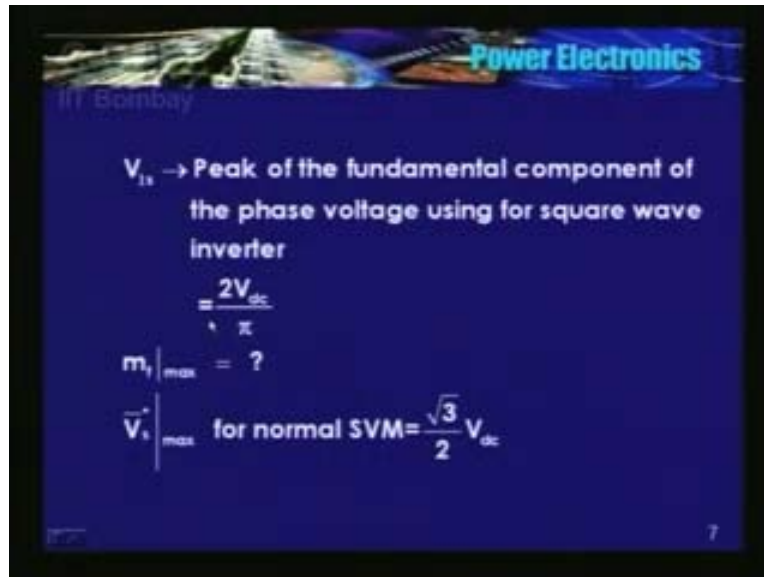
Let $m_f = \frac{V_{1sp}}{V_{1s}}$

V_{1sp} → Peak of the fundamental component of the phase voltage using space vector PWM technique

Now, I will define a term m_f is equal to V_{1SP} divided by V_{1S} where V_{1SP} is the peak of the fundamental component of the phase voltage using space **space** vector PWM technique, where V_{1SP} is the peak of the fundamental component of the phase voltage obtained using a PWM technique and V_{1S} is the peak of the fundamental component of the phase voltage obtained using square wave operation. So, m_f is the ratio of V_{1SP} divided by V_{1S} .

Now, what is V_{1S} or in other words, what is the peak of the fundamental component of the phase voltage got using a square wave operation? That we have already calculated, in may be, two, last lecture or before that. We found that it is $2 V_{dc}$ by π , **$2 V_{dc}$ by π** .

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Now, what is V_{1SP} ? See, V_S star maximum or the maximum value of V_S is root 3 by 2 into V_{dc} . I will repeat; **maximum value of** maximum value of the space vector is root 3 times V_{dc} because **this is the** this is the radius of the circle which lies inside the hexagon. Under that condition, all 3 voltages are to be sinusoidal.

Now, what is the relationship between V_S and the phase voltages? If V_{an} , V_{bn} , V_{cn} are known, you can calculate V_x and you can calculate V_y and therefore, V_S . I will repeat; if I know V_{an} , V_{bn} , V_{cn} ; you can calculate V_x and V_y , the X axis component and the Y axis component of the all 3 phases and therefore, you can calculate the length of the space vector V_x . But I have not told you how to determine V_{an} , V_{bn} , V_{cn} if V_x and V_x and V_y are known.

See, because I need to calculate 3 values; V_{an} , V_{bn} , V_{cn} and I know only V_x and V_y . How do I calculate V_{an} , V_{bn} , V_{cn} ? There exists a relationship, see here is the relationship.

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Now $V_{an} = \frac{2}{3} V_x$

$$V_{bn} = -\frac{1}{3} V_x + \frac{1}{\sqrt{3}} V_y$$

$$V_{cn} = -\frac{1}{3} V_x - \frac{1}{\sqrt{3}} V_y$$

at (0,0,1), $V_s = V_x = V_{dc} = \frac{3}{2} V_{an}$

$$\therefore V_{an} = \frac{2}{3} V_s$$

V_{an} is equal to 2 by 3 into V_x . So, there is a way to derive this. I am not going to tell you how to derive this relationship. So, but then it can be derived. So therefore, V_{an} is equal to 2 by 3 into V_x , V_{bn} is given by minus 1/3 V_x plus 1 over root 3 into V_y and V_{cn} is equal to minus 1/3 V_x minus 1 over square root 3 V_y . So, if I know V_x and V_y ; using these 3 relationship, you can calculate the value of V_{an} , V_{bn} and V_{cn} .

Now, what is the peak value of the phase voltage that I can get using the space vector? We found that for 001 or in other words, only the upper device of phase A is on, the length of the space vector is V_{dc} and for this position; Y - component is 0, we have only the X - component.

See see I will show you, this position corresponds to 001 somewhere here. See here, this is the 180 degree conduction - V_{a0} , V_{b0} , V_{c0} and these are the 3 phase sinusoids. For 001, we found that V_{an} is 2 by 3 V_{dc} and V_{bn} and V_{cn} , they are same; minus 1 third V_{dc} . Recall, for 001; V_{an} is 2 by 3 V_{dc} and V_{bn} and V_{cn} , they are same but minus 1 third V_{dc} .

Now, in this figure, in this 3 phase ... where this point corresponds to? I said V_{bn} and V_{cn} are same. Both are negative and the value is 1 third V_{dc} . V_{bn} and V_{cn} are both are same and they are negative. Definitely, this point is this. See, V_{bn} and V_{cn} , they intersect at this point and both are negative and at this point, V_{an} is at the peak V_{an} is at the peak. So definitely, 001 position at that point phase A is at that peak.

Now, what is the relationship between V_s and the phase voltage? So, V_s is equal to 3 by 2 times V_{an} . Now, so for 001, V_s is equal to only V_x and that is equal to V_{dc} and in my last class, I have derived an expression, wherein, V_x is equal to 3 by 2 times V_{an} .

See, I will repeat; for 001, V_S is equal to V_x V_a by 0 and that is equal to V_{dc} itself and the relationship between V_x and V_{an} is this; V_x is equal to 3 by 2 times V_{an} . So therefore, V_{an} is equal to 2 by 3 times V_S . So, what is the peak value of V_{an} ? It is nothing but 2 by 3 times the peak value of V_S that can be obtained.

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The slide displays the following equations:

$$\therefore \text{Peak of the phase voltage } V_m = \frac{2}{3} \cdot \frac{\sqrt{3}}{2} V_{dc}$$

$$= \frac{V_{dc}}{\sqrt{3}} = 0.577V_{dc}$$

$$\therefore m_f = \frac{0.577V_{dc}}{\frac{2}{\pi} V_{dc}} = 0.907$$

So, it is 2 by 3 into 3 by 2, square root of 3 by 2 into V_{dc} . So, the peak of the phase voltage V_{an} that can be obtained using space vector PWM technique is $0.577 V_{dc}$. I will repeat; peak of the phase voltage V_{an} or that is also equal to V_{bn} that is also equal to V_{cn} is 0.577 times V_{dc} . So, what is the value of m_f ? It is nothing but the peak of the phase voltage using space vector PWM technique to the peak of the fundamental component using square wave operation. What is this? $0.577 V_{dc}$ divided by 2 by π into V_{dc} . That is equal to 0.907 **0.907**. So, how do I interpret this result?

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⇒ 90.7% of the fundamental of square wave is available compared to $\left(\frac{V_{dc}}{2} \right) / \left(\frac{2}{\pi} V_{dc} \right) =$

78.55% in sinusoidal PWM

⇒ 3rd harmonic injected PWM = 78.55 * 1.15 = 0.907

⇒ SV. PWM = 3rd harmonic injected PWM

I can say that 90.7% of the fundamental of square wave is available using space vector PWM technique. I will repeat; 90.7% of the fundamental of a square wave is available compared to **compared to** only 78.5% in sinusoidal PWM technique.

See, I will repeat; I found the ratio of the fundamental in space vector to a square wave is 0.907. So, if I take the peak of the fundamental that is obtained using a square wave is 1 per unit. So, I am getting 90.7% in space vector. How much have we getting in sinusoid PWM technique, sinusoidal PWM technique or what is the peak of the sinusoidal PWM technique or peak of the fundamental using sinusoidal PWM technique? It is V_{dc} by 2.

See, peak of the fundamental component to the phase voltage in sinusoidal PWM technique is V_{dc} by 2. See, I will repeat; peak of the fundamental component of the phase voltage in sinusoidal PWM technique is V_{dc} by 2. So, this ratio comes up to be 78.55%. So, in space vector it is 90.7; in sinusoidal PWM technique, it is 78.55%. So looks like, in space vector PWM technique, it is possible to get higher value of the fundamental component.

By the way, we have also done third harmonic injected PWM technique. What did you find? See, we added 15% more for the fundamental. In addition, we added a third harmonic component also; 0.19 times $\sin 3 \omega t$. So, our modulating wave was 1.15 $\sin \omega t$ plus 0.19 into $\sin 3 \omega t$. So, I said third harmonic components do not appear in line to line voltage wave form. So, fundamental component is proportional to the **the** sinusoidal modulating wave. Since it is 1.15, so there is going to be a 15% increase in the phase voltage.

So, if I take this ratio in third harmonic injected PWM technique, it is sinusoidal is 78.55 into 1.15. So, it is comes out to be 0.907 **0.907**, same as **same as** space vector PWM technique, same

as space vector PWM technique. In other words, the peak of the fundamental component of the phase voltage that can be obtained using space vector PWM technique is the same as the peak of the fundamental component of the phase voltage using third harmonic injected PWM technique.

So, in other words, space vector PWM technique is almost the same as third harmonic injected PWM technique. I had told you that if you complete 1 cycle in 6 steps, you will get 6 step operation. Wherein, the space vector moves by an angle 60 degrees at a time. To have smooth operation, I said we need to divide the entire 360 degrees by large number of parts. I said we need digitize a sine wave.

In other words, the sampling time T_s should be as small as possible. We have assumed that during that period or during T_s seconds, space vector is stationary. Now, how many samples in 1 second? How do I decide on the number of samples in 1 second or what is the rule to be followed? The rule to be followed is that all sectors should be equally used in the entire cycle for producing symmetric line voltage. I will repeat; all the sectors should be equally used in the entire cycle for producing this symmetric line voltage.

So, in other words, the samples are positioned symmetrically about the each sector with 1 sample at the cycle **at the centre**. I will repeat; the samples are positioned symmetrically about each sector. This number of samples should be symmetric about each sector with 1 sample at the centre **with 1 sample at the centre**. So therefore, if there are 3 samples in 1 sector, they should be positioned at; one at 10 degrees, another one is at 50 degrees because this should be symmetric, one at the centre. That is at 30 degrees.

So, in every sector if I have one pulse at 10, I should have another pulse at 50 and **at** another one is at the centre, 30 degrees. So, this is the rule should be followed; all the sectors should be equally used in a entire cycle, only then I can have symmetrical line voltage. Samples, they should be positioned symmetrically about each sector; one pulse here and one pulse here and one at the centre **one at the centre** and **it should be** number of pulses should be odd multiple of 3 **odd multiple of 3**, 3, 9 and so on. Now, this rule has to be followed while implementing space vector PWM technique.

So far we discussed 4 different types PWM techniques. What are they? One is sine triangle, third harmonic injected PWM technique, harmonic elimination and last one is space vector PWM technique. All these PWM techniques, they control the output voltage of the inverter. In other words, the voltage applied to the load is being controlled. Now, current will flow depending upon the circuit condition. So, voltage is depended variable and current varies independent, **depending upon** depending upon the circuit condition.

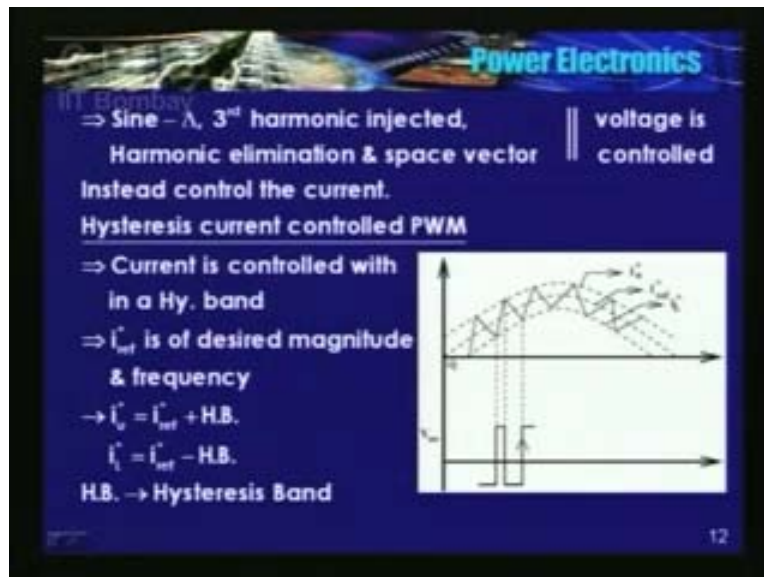
By the way, you cannot control both voltage as well as current in one circuit. Now, if it is possible to control the output voltage, it is also possible to control current that is flowing in this circuit. So, there is a PWM technique which is known as hysteresis current controlled PWM technique and **I repeat** I will repeat; hysteresis is current controlled PWM technique. What it says?

It says, take a reference a sinusoid current of required magnitude and required frequency. See, magnitude depends on the circuit condition or load requirement, frequency of the sinusoid or frequency of the reference current is the same as the frequency of the fundamental component of low voltage applied to the machine. Now, you have generated a reference sinusoid which is the required current that should flow in the machine.

But then in a power electronic equipment if there is switching, it is just not possible to have a pure sinusoid current flowing into the machine. It is rather impossible to have a pure sinusoid current flowing into the machine because there are switchings. So, the moment when you close a switch, current may increase or decrease. But then you can always control the variation in current.

So, in hysteresis current control PWM technique; there is a reference sinusoid, there is an upper band and there is a lower band. See here, I will show you.

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This is the reference current $i_{reference}$ for which is the sinusoid, a full sinusoid of required magnitude and frequency. Then I will take an upper band i_u star i_u star which is equal to $i_{reference}$ plus some hysteresis band HB. HB stands for the hysteresis band. Similarly, the lower limit i_l star is i_{ref} minus the hysteresis band. In other words, current is controlled or current that is flowing in the load is controlled within these 2 bands.

I told you, it just cannot have an ideal sine wave, pure sine wave – current. But then you can always control the variation in the current. So, I have taken an upper band and a lower band and current should be controlled within this band. How do I control this current? By the way, I have covered this in AC to DC conversion, unity power factor conversion; I had covered this, I will just repeat this. There may be the reference current that I have taken may be, a rectified sine

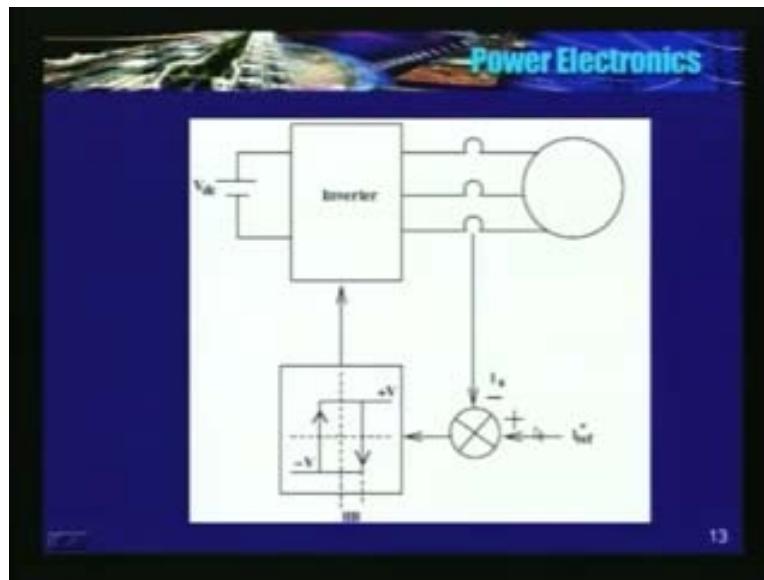
because we control the DC link current. We had placed the inductor in the DC side and we have controlled that current.

Here, the current that is flowing into the load or output current of the inverter: that we are controlling, remember. We are controlling the output current of inverter flowing into the load: that we are controlling. Definitely, it has to be AC. So, how to control the current within the hysteresis band?

So, when the actual current touches the lower band **lower band**, you close the upper switch and open the lower switch. See, when I close the upper switch, V_{a0} is plus V_{dc} by 2, remember and if I close the lower switch V_{a0} is minus V_{dc} by 2. So definitely, when I close the upper switch, current should increase. So, I will close the upper switch till this current or the current flowing into the load increases and touches the upper band and when it touches the upper band, I will open the upper switch and close the lower switch. Now, the voltage applied is minus V_{dc} by 2, current reduces.

See here, **when you touch upper switch sorry when you touch the upper lower band**, see, this is a lower band and this is the upper band and when you touch the lower band, I will close the switch. So, V_{a0} is become positive here, current increases. When it touches the upper band, you open the upper switch and close the lower switch. This is it, closed lower switch. Voltage applied is minus V_{dc} by 2 to wait till this current comes and touches the lower band and so on.

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So, in the block diagram level, it looks something like this. I have shown a motor here, does not matter, it could be anything. Inverter, this implies that we are sensing the current flowing into the load. There is the I_a actual and this is the reference current, a reference sinusoid. This is the actual; plus, minus. What do I get? I will get the error and this error should lie within

the hysteresis band. This is HB, this is also HB and the signals go to the driver circuit to turn on and off the switches.

By the way, **this made** this hysteresis band is nothing but a Schmitt trigger. So, this is a subtractor, op-amp again, op-amp circuitry, this is another Schmitt trigger. I have shown you here only for 1 phase and I have showed you there are 3 sensors or 3 current sensors to measure the instantaneous current that is flowing into the machine, remember, it is the instantaneous current that is flowing into the machine that this controlled.

See, you do not need to have 3 current sensors. You can do with just 2 current sensors because in 3 phase 3 wire system, the current that is flowing in the third wire is the sum of these 2. In other words, i_a plus i_b plus i_c is equal to 0, so i_c is minus of i_a plus i_b . So, you can implement this circuit using just 2 current sensors. So, what is the advantage of this scheme over the other PWM techniques, wherein voltage is being controlled?

See here, we are controlling the current. It is the current that is flowing into the machine will determine the torque. See, for example, **in in a** in a DC machine, the armature current that is flowing will decide the torque that produces; T is $k \phi$ into i_a , not the armature voltage. So, by controlling the current that is flowing into the machine, it is possible to control the torque directly.

So, in other words, a current controlled machine responds faster compared to a voltage fed machine because I am directly controlling the current. No, I am not applying the voltage and thereby, current increases, no. Here, the current is directly being controlled. So, current fed load responds faster compared to voltage and the second advantage is; so, there is inherent overload protection **there is inherent overload protection**, we are sensing the current and controlling within a reference value **within a reference value**. There is nothing like current in rush as in the case of voltage fed machine.

Here, current is directly being controlled; there, see, when I am changing the modulation index, **you** there could be inrush current because voltage applied to the machine has changed or if modulation has suddenly increased, however low it may be **however low it may be**, so applied voltage has been increased. The other circuit conditions may not change that fast. **There could be** or there is inrush current in almost all the voltage fed PWM techniques. This is absent in current fed machine or hysteresis current controlled PWM technique.

What could be the other advantage of current controlled PWM technique? See, the input to the inverter is a voltage source and this V_{dc} voltage source is being derived by rectifying the input AC. So, if input AC fluctuates **which generally is**, so DC link also will fluctuate and if DC link fluctuates and assuming that I have already programmed my V by F curve in the controller, the flux in the machine will change now.

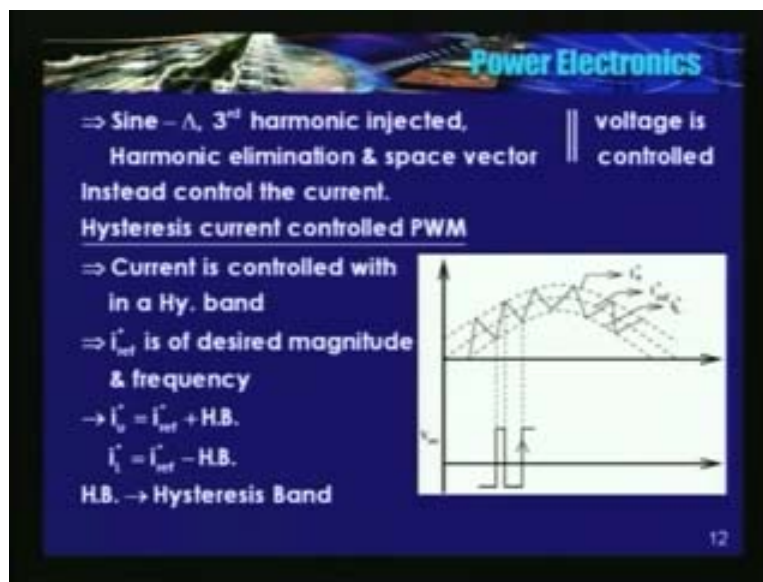
See, I will repeat; I have programmed some V by F curve in the micro controller used in the inverter and assume that I am not sensing the DC link voltage. I am assuming that DC link voltage is held constant because of the variation in the **input voltage** input AC voltage; the

rectified DC voltage also has reduced. So therefore, the input voltage to the inverter is also reduced and the controller does not know anything about the reduction in the input DC.

So definitely, there is going to be a change in the flux in the machine because I may be keeping V by F constant, you may be keeping V by F constant; but then that V itself has changed because V_{dc} itself as changed. Whereas, in current controlled PWM technique, what happens? It does not matter whether the DC link voltage is fluctuating or not; we are controlling the current, current is being controlled within a hysteresis band.

So, as long as the current touches the upper band switch is being closed and when it is and as long as current touches the lower band, the bottom switch is closed. So, an inverter with current control is almost insensitive to the fluctuation in the DC link, whereas, any other voltage controls PWM techniques; if you do not sense the DC link voltage, the V by F ratio or even if you keep it constant, the value of V itself as changed. Therefore, flux may not be the rated value flux may not be the rated value.

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Now, how do you choose this hysteresis band? Smaller the band, the waveform will be superior because current that is flowing into the machine is controlled within the hysteresis band. So, that means the band itself is very small. So, you may have an approximate here a sin wave itself, almost an ideal sin wave. But then smaller the band, higher will be the switching frequency because see in this figure, this band is very small; current touches the lower band, immediately I need to close the upper switch, current increases, band is very small, it touches the upper band immediately, I need to open that switch and close the lower switch.

So, smaller the band, waveform is superior but then switching frequency is higher switching frequency is higher and just the opposite or higher the band, waveform deteriorates, switching

frequency is low. So, it depends on the power level. The devices that you are using will decide the height of the hysteresis.

So, a last point to be noted here is that **so** this is an inverter, a voltage source inverter, input is an ideal voltage sources, assumed to be ideal voltage source. But then you are controlling the current flowing out of the inverter. So, it is a voltage source with current control, **voltage source with current control**. This is quiet popular in electric drives, especially high performance electric drives; voltage source with current control is quiet popular. So, more about or more on inverters we will study in our next class.

Thank you.