High Power Multilevel Converters - Analysis, Design and Operational Issues
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Lecture - 03
Basic Understanding of Converter - (Sinusoidal pulse width modulation and three phase circuit)

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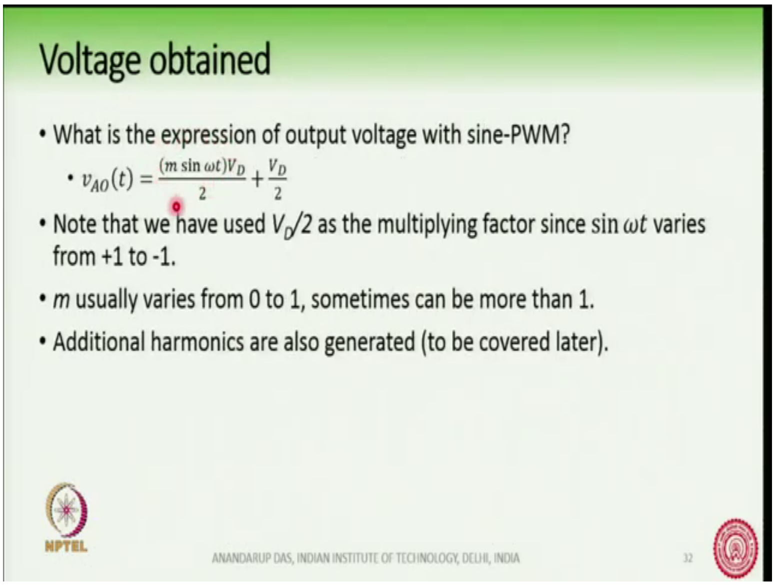

So, in the half bridge, what is the expression of output voltage and it is given by this formula present here V AO t is m sine omega t into V D by 2 plus V D by 2. Now, this factor here V D by 2, this factor is because we have taken the reference point of the pole voltage as the lower side or negative pole of the DC bus.

If we take the reference point for calculating the pole voltage as the midpoint or the imaginary midpoint of the DC bus, then this V D by 2 will cancel out and the AC output or the AC component inside the pole voltage is given by this expression here m sine omega t into V D by 2. So, the pole voltage or V AO has two parts; one is the AC part and one is the DC part. The DC part comes because of the choice of the reference point.

If the choice of the reference is say it can be made in such a way that the DC part vanishes and then, we can say that V AO t is m sine omega t into V D by 2. Now, so, if we see here the AC component of the voltage, we find that it is proportional to m.

Now, m is called the modulation index. So, m can vary, but usually it will vary from 0 to 1. Under some circumstances, it can go beyond 1. When it is varying between 0 and 1, we call it linear modulation. When it is more than 1, then we call it over modulation because if m is more than 1, then the sine wave, the height of the sine wave is more than the height of the triangular wave.

Now, apart from this expression, here I have talked about the fundamental AC as well as the DC, but there are some other high frequency harmonics also generated and these harmonics we will cover later.

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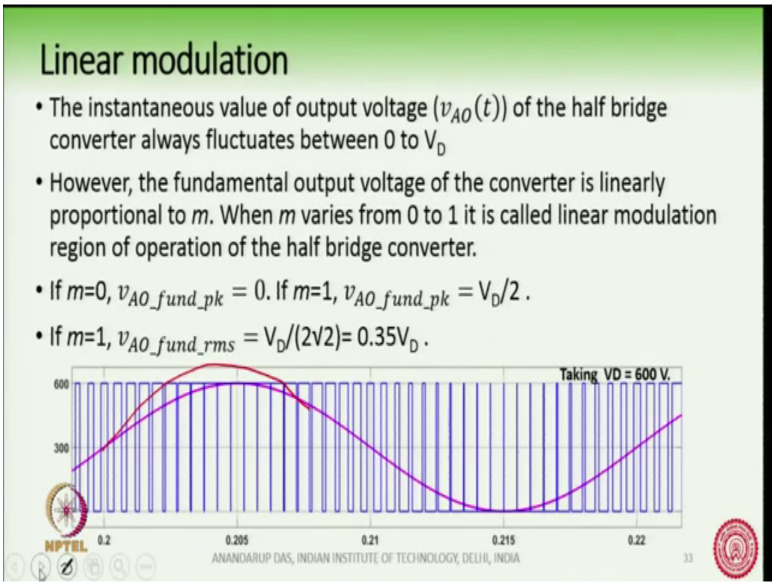

So, how does the waveform look like? See it is shown in this curve here. The blue curve here is the instantaneous pole voltage or that means, V AO t with respect to the negative of the DC bus and we can see that this V AO t is varying between 0 and 600, where V D is taken as 600 as I have shown it here, V D is 600 volts DC bus. This is typical for 400 volt, 415 volt, three-phase AC.

So, the 600 volt DC bus, so the V AO t is varying between 0 and 600. The pink curve here, this curve pink curve is the AC which is embedded which is embedded inside this instantaneous PWM waveform. And why it is embedded? We can understand it intuitively by observing the width of the pulses. As we can see the width of the pulse is narrow here and the width of the pulse is large here and progressively, it becomes narrow until it becomes very narrow here.

So, of course, it means that the average voltage is going down here and then, it progressively increases as I can see here and it becomes maximum at this point. So, the AC is embedded inside this PWM waveform or the Pole Voltage Waveform. Here, as I have also written it here the fundamental output voltage of the converter is linearly proportional to m and this is very important.

As I have shown it in the previous expression, the AC component in this waveform is m sine omega t into V D by 2. So, V D being a constant so, the output voltage is linearly proportional to m. So, this is the advantage of the linear modulation, linear sine triangle PWM or linear sinusoidal PWM that the output voltage can be controlled, the output voltage can be controlled by varying m and it is linearly proportional ok.

So, if m is equal to 0, the fundamental V AO peak of the fundamental voltage in V AO is equal to 0. If m is equal to 1, then the peak of the fundamental voltage inside A O or the peak of the fundamental voltage in the pole is V D by 2. Because m equal to 1 means and at sine omega t sine omega t equal to 1 that is omega t equal to 90 degree.

This V AO fundamental peak is V D by 2. So, if m is equal to 1, the fundamental RMS voltage in V AO is V D by 2 root 2; 1 by root 2 of the previous value, 1 by root 2 of this value. So, V D by 2 root 2 and that will be equal to almost 0.35 V D. So, the output voltage of the pole voltage output from the half bridge converter can be controlled between 0 and V D by 2 root 2 or in the RMS and in the peak, it is 0 and V D by 2; between these 2 values linearly with the change of m.

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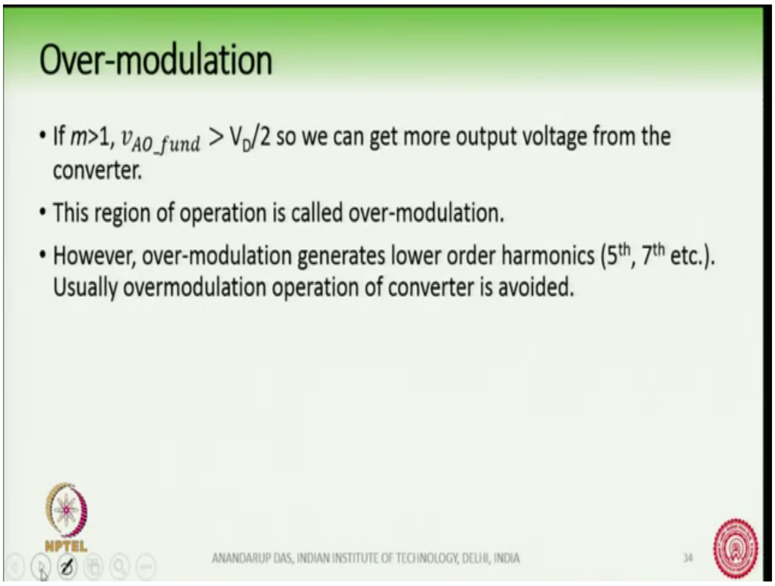

What will happen if m goes beyond 1, which means that the AC voltage here is in more than 1 is something like this. What will happen if m is more than 1? So, if m is more than 1, then the fundamental voltage output from V AO is more than V D by 2. So, we get more output voltage.

However, this region is called the over modulation region, but in this case we have a drawback and a serious drawback and that is the over modulation generates many lower order harmonics fifth-seventh etcetera. So, it is generally avoided; low over modulation operation of a converter is usually avoided because lot of fifth, seventh and other lower order harmonics are generated from the converter.

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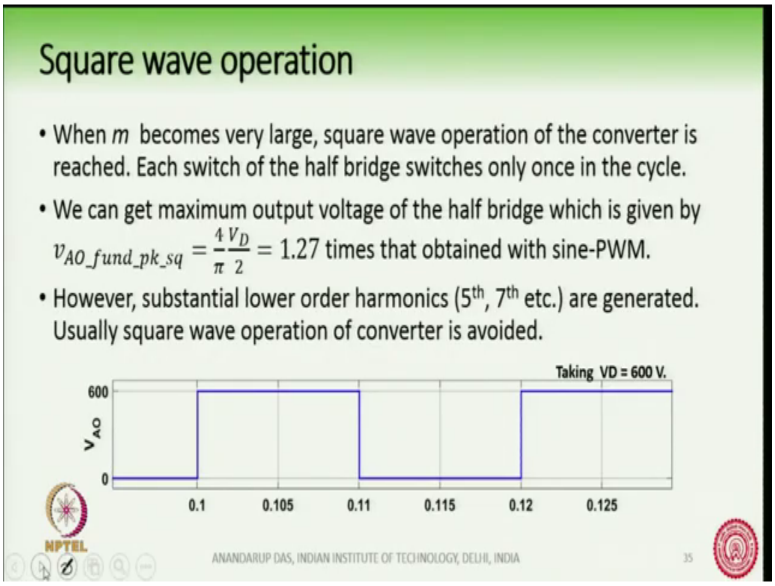

If we go on increasing the value of m, even further at one point of time, the square wave operation of the converter is reached. So, what is meant by square wave operation? In square wave operation, as you can see here the each switch of the half bridge switches once in the cycle.

So, the top switch is switched for 50 percent of the cycle and the bottom switch is switched for rest of the 50 percent of the cycle. So, here you can see that the bottom switch is switching for half the cycle. Here, so, we get 0 voltage and for half the cycle the top switch is switched. So, that we get the 600 volt output. Here, 600 volt output.

So, if we do the Fourier analysis of this waveform and if we ignore or take out the DC part, there is a and that if we take out the DC part out of this waveform, then the fundamental peak voltage which is inside this squared wave is 4 by pi into V D by 2; 4 by pi into V D by 2 as we see and which is equal to 1.27 times that obtained with sine PWM. So, because 4 by pi is 1.27.

So, in sine PWM the maximum fundamental peak voltage that we got was V D by 2. While in square wave, the maximum fundamental we could get is 1.27 4 by pi times V D by 2, that is 1.27 times that what I we can obtain from sine PWM. So, this region between 1 and 1.27 is part of over modulation.

Later, we will see that it is possible by injection of triple n harmonics or third harmonic, it is possible to extend the linear modulation by 15 percent more. We will come to that later. But as of now we can understand that the peak fundamental voltage that we can obtain from a half bridge converter with sinusoidal PWM is V D by 2 that is the maximum voltage peak.

While in square wave, it is 1.27 times this value. Again with a square wave, we get the same problems as we get in over modulation that is a large number of lower order harmonics are generated. So, we usually avoid the square wave mode of operation of the converter, we usually avoid this operation.

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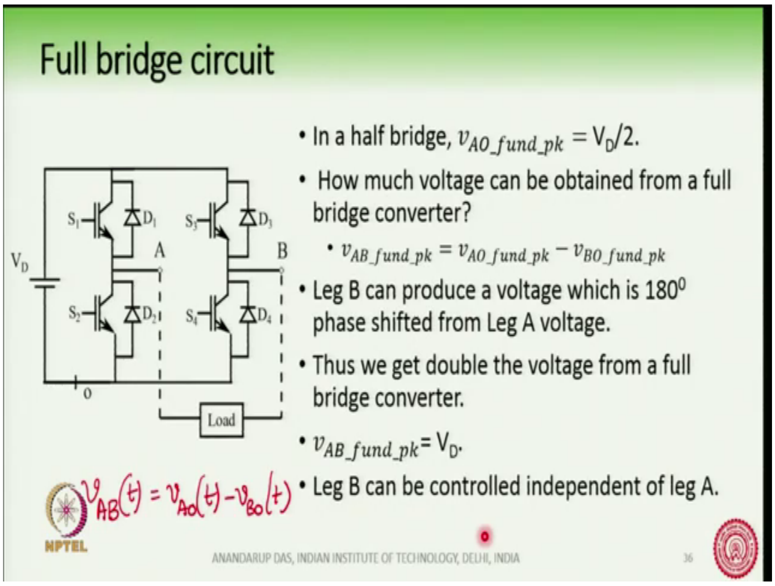

Now, once we have understood the half bridge that is now turn our attention to the full bridge circuit. Full bridge is nothing but an extension of half bridge. That is as I had told you that there is a there are 2 switches here, which is forming 1 leg of the converter and you can see V AO voltage is present here.

In a full bridge, we introduce 1 more leg here and these 2 legs are independent of each other. So, they do not know about each other ok. So, leg B can be controlled fully independently of leg A. So, what is the benefit, if I use a full bridge suppose I connect my load between point A and point B. So, there are 2 legs; leg A and leg B and these are their 2 outputs, A and B and the load is connected here across AB.

So, from one half bridge that is for example, from leg A, I can obtain the peak fundamental voltage as V D by 2 if I use sine PWM from 1 leg that is leg A. Now, how much voltage can be obtained from the full bridge? Now, this voltage which is applied across the load we can term it as V AB. Now, this voltage V AB is nothing but V AO minus V BO ok.

So, I can write like V AB is equal to nothing but V AO minus V BO ok. So, therefore, the total voltage which can be obtained across A and B is nothing but the difference of voltage between what I obtained from A leg and the B leg. So, if now I produce a voltage where leg B, the voltage produced by leg B is 180 degree phase shifted from the voltage produced by leg A ok. If I do like that, then I we can get double the voltage from a full bridge converter ok. So, if the voltage of phase B is 180 degree from phase A.

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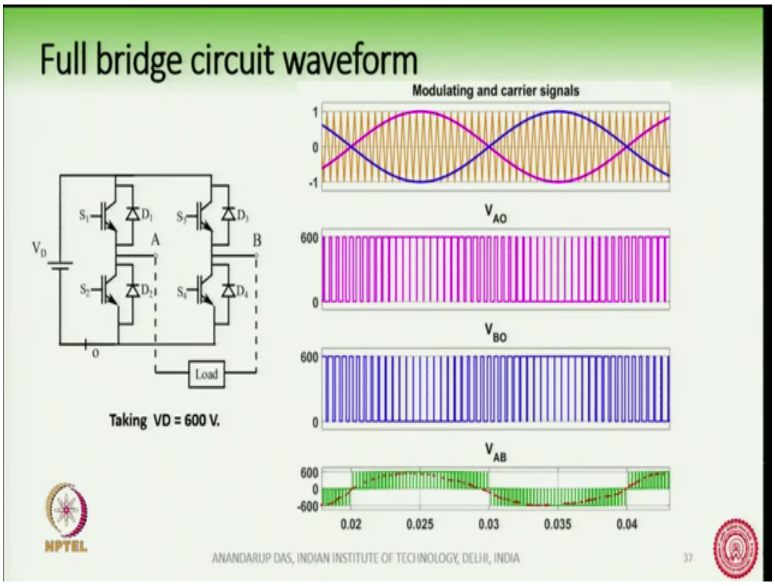

So, here you can see this in this curve that suppose the voltage of A phase is this; the voltage of A phase the fundamental voltage inside A phase is this much the voltage produced by B phase B the fundamental component of it is shown by this blue curve. So, what happens then?

If there are 180 degree phase shifted, we can get double the voltage from the full bridge converter.

Therefore, this is what is written here V AB fundamental peak is V D and this is exactly double than the fundamental peak voltage produced from the half bridge ok. So, here we saw the half bridge is producing V D by 2 and here, we see that the of the full bridge is producing voltage of V D. Now, remember that leg B is fully independent of leg A. So, it is not necessary that leg B voltage is always at 180 degree to leg A voltage. We can set any other voltage from leg B also and then, the load voltage can be accordingly controlled.

So, leg B voltage and leg A voltage, they may be 180 degree, but they can be any other value also. The differential voltage basically falls across the load. So, here we are showing you some of the waveforms. So, as I told, so this is the full bridge converter. So, V, so that the sine wave which controls or the modulating wave for A phase is the pink waveform and the modulating wave for the B phase is the blue one and they are 180 degree phase shifted. So, and they are compared with a high frequency triangle which is spanning between minus 1 and plus 1.

So, the output voltage V AO is again between 0 and 600 and it is a PWM waveform the output voltage from. The leg B is again a PWM waveform like this and the differential voltage falls across the load. And so, if we see here that the differential voltage, this is the green one here, it is varying between minus 600 and plus 600 and the waveform looks like this.

The fundamental component inside this waveform lies here. This is the fundamental which is present inside this waveform and the fundamental component inside this waveform is double the magnitude as compared with what can be obtained from the half bridge.

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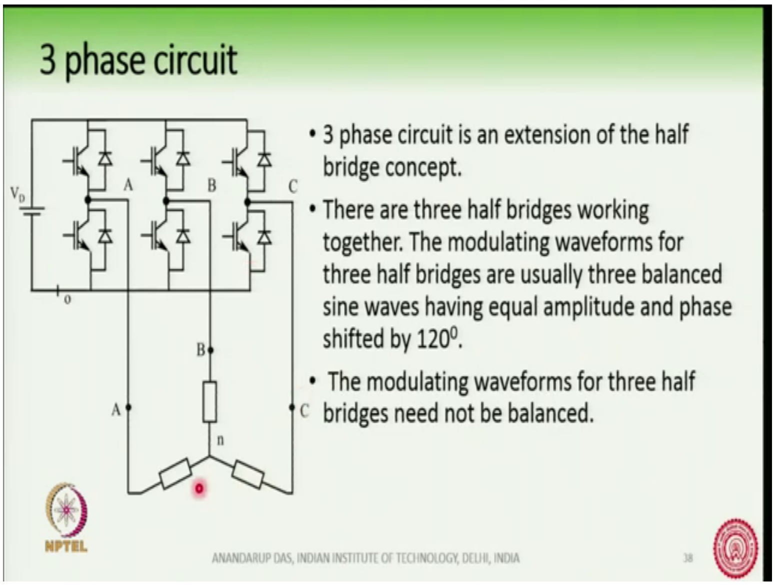

Now, we go to the next step. We have seen that this leg A and leg B can be operated independently. So, let us put a third leg and that is this leg C here, let us put it. Again, these three legs leg A leg B and leg C are completely independent of each other ok. They do not know that there is there exist one more leg. So, these three legs is by putting these three legs, we are basically extending the concept of the half bridge ok.

And in this converter which is a three phase converter, it is nothing but three half bridges working together ok. So, how will you control the three half bridges? Of course, if you want to get a balanced output voltage from this converter, we will give three balanced sinusoidal reference to the three legs and they will be equal in magnitude and phase shifted by 120 degree that is the balanced amplitude.

Although this is true, but I must mention that the three modulating wave forms need not to be balanced ok. There is no requirement that these three wave forms has to be balanced, it can be unbalanced also. In fact, when such a converter is used in unbalanced system, then it may be required to produce unbalanced voltage waveforms from this converter.

So, these three half bridges usually operate with balanced reference waveforms. But they can also operate with unbalanced waveform. Now, we have a star connected load here which is where we are placing equal impedances here.

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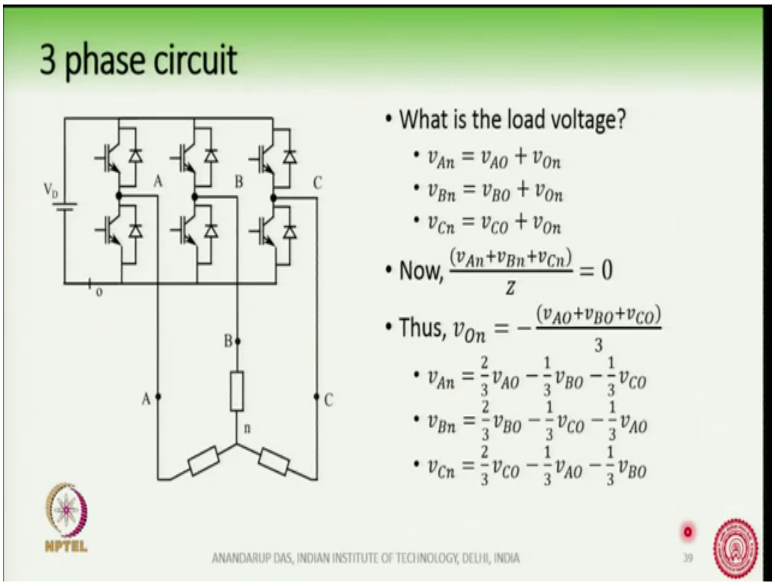

So, if we have such a circuit, then we would like to know what is the voltage across the load because that is what we are interested to find out. Because ultimately the converter is supplying to a load and we are interested to know that how much voltage can be applied to the load, what is its relationship with the converter voltages.

So, in order to find it, we write the Kirchhoff's law. So, we see that let us focus on this first line V An that is this voltage V An is nothing but V AO that is this points voltage to this point plus V On. You can see this is the voltage here V On. So, basically V AO plus V On is V An this voltage. If you just apply the Kirchhoff's voltage law, it is imagine there is a potential between this point O and n, then we can write this equation.

Similarly, V Bn is also equal to V BO plus V On and similarly, V Cn. V Cn is V CO plus V On. Now, in this converter we see that the star point is isolated and so, the sum of the three currents which is coming to this star point must be equal to 0 and so, V An plus V Bn plus V Cn divided Z, where Z is the impedance of the load, but phase is equal to 0. So, if I sum the left hand side and the right hand side.

Therefore, I can see that the sum on the left hand side will be equal to 0 and therefore, by equating I will see that V On is equal to minus V AO plus V BO plus V CO divided by 3. So, this V On that is this voltage between point O and n, we see that there exists a voltage between point O and n. This is an important observation. What it tells us is that there is always an instantaneous pole the instantaneous voltage difference between point O and point n.

So, we cannot short the points O and n; if we short them because there is a voltage difference there will be a dead short circuit. So, we cannot short this point to this point. We cannot also short this end point to the midpoint in this DC bus, this is also not possible. Because there is always an instantaneous voltage difference and why is it so?.

Because you see the V AO voltage V BO and V CO; V AO, V BO, V CO can take only 2 values. V AO can take values 0 and V D. V BO, 0 and V D and V CO, 0 and V D. So, for so, these out of these three, one will always be V D. If all of them all three are 0, then there is nothing no output voltage from the converter. But in order to get some output voltage from the converter, one of them must be V D. And therefore, there is an instantaneous voltage difference between points V O and V O and point n. This voltage is also sometimes called the common mode voltage ok.

The sum of V AO, V BO, V CO divided 3. This voltage is also called the common mode voltage. The common mode voltage exists for such converters because there is switching on this voltages and V AO, V BO, V CO are not the sum is not equal to 0. This is unlike the case; this is unlike the case, if there were sinusoidal voltage sources here.

For example, if there were synchronous machine connected to the three-phase load here. Synchronous machines produce sinusoidal voltages ok. And the instantaneous sum of if it is a perfectly balanced sinusoidal voltage that is produced by the synchronous machine, the instantaneous sum is always equal to 0.

But here this converter the instantaneous sum of pole voltages is not equal to 0 for all of the switching states, it is not equal to 0 and therefore, or a common mode voltage exists between point O and n. The common mode has many implications ok. For example, for high switching frequency inverters common mode causes varying currents in motor drives. Also we will see that this common mode voltage is something which can be utilized in order to increase the linear modulation range. We will see that later.

So, once we know that there exists a V On voltage and it there is an instantaneous voltage difference between O and n, but no current is flowing because the n point is completely isolated from the O point. So, no current can flow. So, we can also find out therefore, the instantaneous voltage expressions of these phases A, B and C and these instantaneous voltage expressions are by substituting V On here and V AO, then we can see that V An is two-third V O minus one-third V BO minus one-third V C O.

So, which means that the instantaneous phase voltage across the load is now expressed as the combination of 3 pole voltages. So, this is the expression which expresses the instantaneous phase voltages as a combination of the 3 pole voltages again in turn V AO can be 0 or V D; V BO can be 0 or V D; V CO can be 0 or V D.

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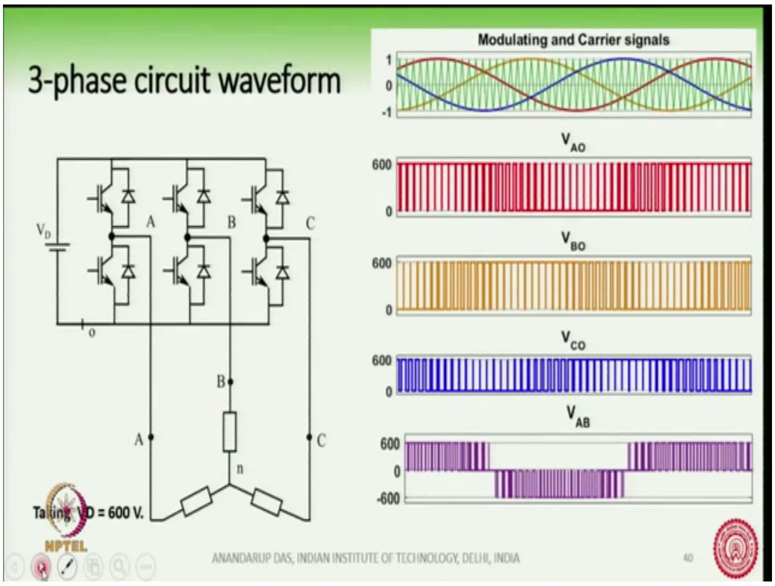

So, therefore, we have now we are now showing you the voltage waveforms. So, as you can see here, the more if you see the modulating and the carrier signals. We see that there is a high frequency carrier here and then, there are three waveforms for A phase, B phase and C phase. But the red one, the orange one and the blue one here and they are perfectly balanced. Their amplitudes are equal and the phase shift is 120 degrees. So, this is the V AO waveform, V BO waveform and V CO waveform.

Each of them fluctuating between 0 and 600 and the line voltage is again, if you do the line image what is the line voltage? The line voltage is V AB for example, is equal to V AO minus V BO. So, therefore, V AB here is equal to V AO minus V BO and we can draw it like this ok. The fundamental voltage inside this lies somewhere, the fundamental voltage which is embedded inside this V AB waveform is somewhere here ok.

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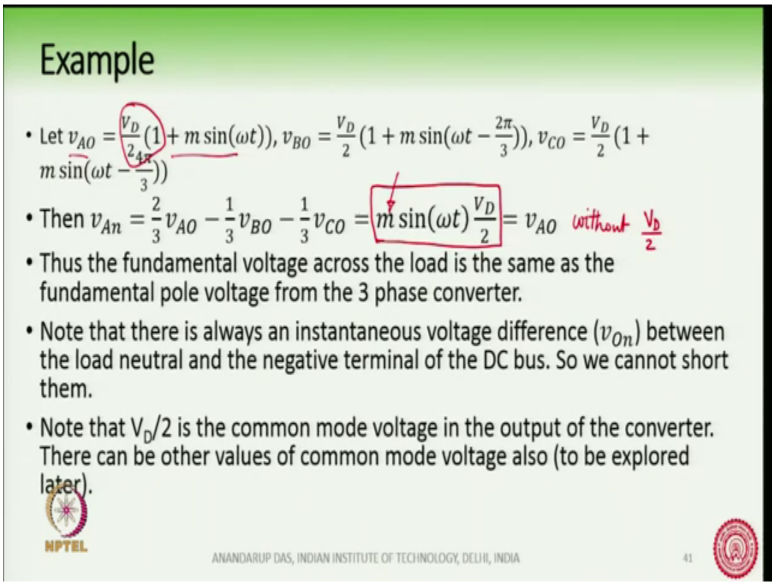

So, the here is the fundamental voltage available. So, now, we can see what is the; what is the expression of V An, we can find it out. So, V AO here can be written as V D by 2 into 1 plus m sine omega t. From the previous slide, we have seen it is we have said that this is the fundamental AC voltage and there is also a DC voltage in V AO.

So, V AO is equal to V D by 2 into 1 plus m sine omega t and V BO is will be equal to V D by 2 and then, V D by 2 into m sine omega t minus 2 pi by 3 and V CO will be V D by 2 m sine omega t minus 4 pi by 3 because we are giving three balanced modulating wave forms to the three-phases.

And then, by applying the formula that V An is equal to two-third V AO minus one-third V BO minus one-third V CO, if we apply that formula. Then, substituting these values into V AO, V BO here and V CO here, we get that V An voltage that is the instantaneous phase load phase voltage V An is equal to m sine omega t into V D by 2 ok. M sine omega t into V D by 2 which is exactly equal to the fundamental voltage present in the pole voltage.

So, we see that the pole voltage whatever the fundamental voltage inside the pole voltage is exactly equal to the fundamental voltage that gets impressed across the load. So, the fundamental voltage inside the pole voltage will come and impress across the load and this is expected because there is no loss, there is nowhere some nothing is lost. So, the fundamental component inside the pole voltage comes across the load. But we also see that V D by 2 the DC part which we had assumed is no longer present in V An expression.

So, that V D by 2 x part. So, the DC part inside the pole voltage that we had assumed earlier is no longer present on the load. So, the load will only see a pure AC voltage and that we can see here V An is equal to V AO. V An is equal to V AO or without the AC part, I should write it here. This is the V AO without V D by 2. So, it is only the V An is only this expression, the V D by 2 that the DC part here, the V D by 2 that part vanishes.

So, therefore, by changing the value of m, by changing this value here by changing the value of m, it is possible to change the output voltage. So, m by say if m is equal to 0.5, then you get some voltage on the load; if m equal to 1, you get more voltage on the load in this way ok. There is also a common mode voltage between V O and n.

So, there is a common mode voltage or the voltage is available between O and n, but since n point is isolated from O point, so that common mode voltage can be utilized in adding some third harmonic. We will use this concept in some slides later.

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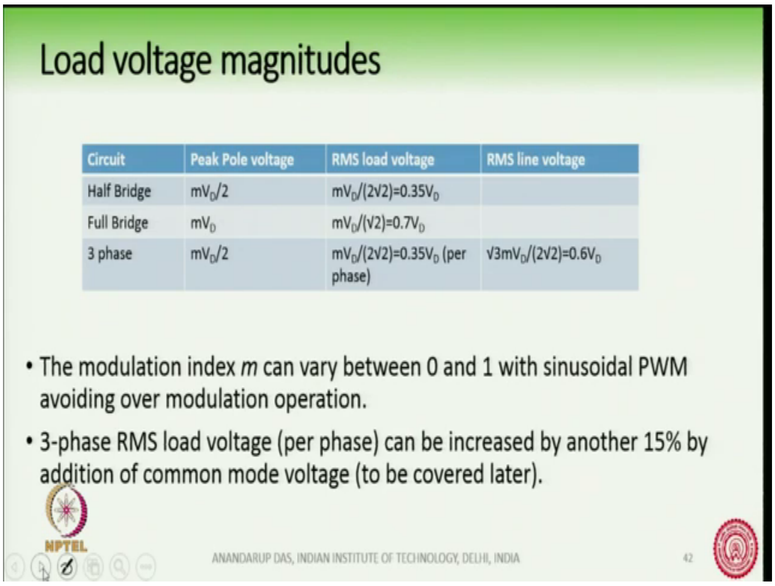

So, let me see therefore, let me summarize what are the load voltage magnitudes possible. So, from a half bridge, the peak pole voltage is equal to m V D by 2; m can vary between 0 and 1. So, the RMS load voltage that can be obtained is m V D by 2 divided by root 2 that is 0.35 V D. In case of a full bridge, we can get double the voltage from what we can get from the half bridge. So, therefore, from a full bridge, we get m V D that is the peak pole voltage possible.

And the RMS load voltage is m V D divided by root 2 and that is 0.7 V D that much of voltage we can get the AC voltage from the full bridge. Now, in case of a three phase, in case of a three phase system the peak AC part of the pole voltage is again m V D by 2. The AC component of the peak pole voltage and so, the RMS load voltage is m V D by 2 root 2 that is 0.35 V D per phase and the RMS line voltage, the peak value will be root 3 times this value and which will be equal to 0.6 V D ok. So, the three phase RMS load voltage can be increased by another 15 percent by addition of a common mode voltage.