High Power Multilevel Converters – Analysis, Design and Operational Issues
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Lecture – 20
Modular Multilevel Converter- Arm Currents

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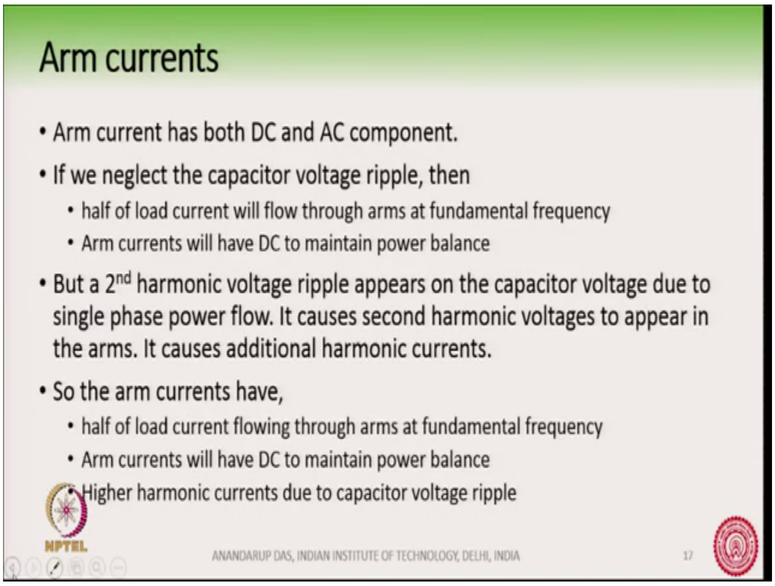

So, the Arm Currents have half the load current and a DC component these are essential, but then some higher harmonic predominantly second harmonic component which comes from the power oscillation due to a single phase voltage interacting with a single phase current. So, that comes also we will talk about it sometime later.

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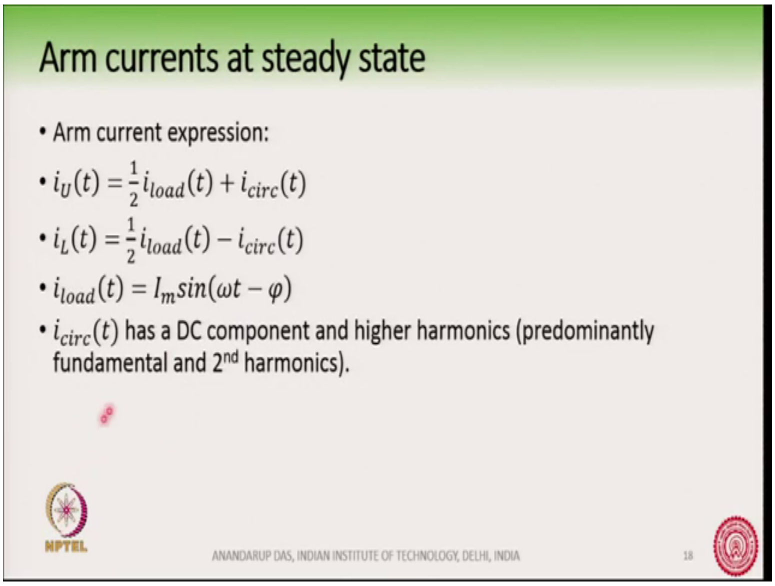

So, let us first look into the arm current expression. So, we say that i U is half i load plus i circulating and i L is half i load minus i circulating ok.

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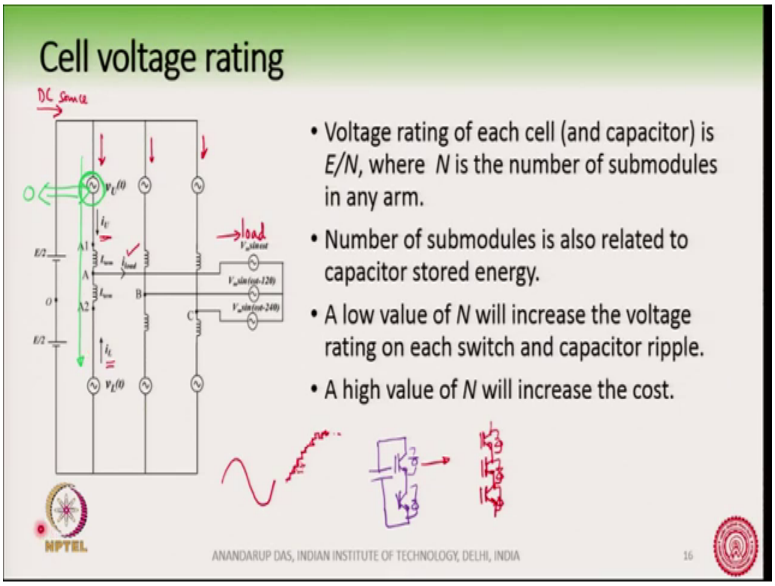

So, in this; so this is the circulating and i U is half the upper arm current is half of the load current plus the circulating current, while the lower side is half of the load current minus the circulating current right. So, therefore, we can write it like this, so that the sum of i U plus i L is equal to i load right which is given by i m sin omega t minus phi; phi being the power factor angle of the load. Now, i circulating t as I told you it must have the DC component and some higher harmonics, second harmonics is there we will talk about.

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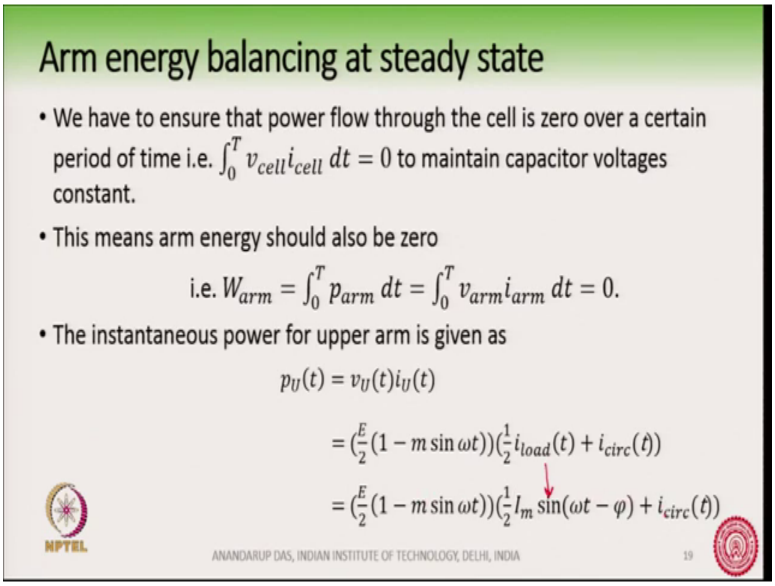

Now, first we would like to see how much is this DC current; how much, because the major component of the circulating current is the DC which is essential. So, now we would like to find out what is its magnitude, what is the magnitude of the DC current that will flow? In order to understand or in order to find out what is the magnitude of the DC current we will see that we will mathematically write what I said earlier that to maintain the capacitor voltage constant, the power flow through the cell must be 0 over a certain period of time ok.

The net power flow to the capacitor if we can ensure that this net power flow through the capacitor is 0 over a certain period of time, then the net energy taken from the capacitor is 0 and so there will be no net change of voltage over that time period ok. Of course, there will be instantaneous fluctuations on the capacitor voltage because of second harmonic component or the DC, there will be instantaneous fluctuation, but the overall voltage over this time period t will be 0. And so this one this x this is mathematically written like this, v cell into i cell dt is equal to 0, the cell next energy from the cell is taken to be zero.

So, this means that if we extrapolate like this way for the arm ok; for the arm also a similar conclusion can be drawn, like v arm I arm dt is 0 over this time period t ok. And if we can ensure this one then the net arm energy is 0 over a certain time period and then the arms can maintain the same voltage.

Just for just to tell you one thing i mean those who are familiar with mmc I will just say a word here we will explain it later that when we go ahead with this equation saying that the v arm into i arm over a period of time should be zero. We are ensuring that the arm voltage is fixed over a period of time ok.

However, this does not ensure that individual capacitors are balanced within an arm ok. So, for example, with this equation we say if suppose the arm voltage is 100 kilo volt and we say that the arm voltage is 100 kilo volt we have ensured that and there are suppose hundred cells each cell keeping a certain voltage.

Now, this equation only ensures that the arm voltage is maintained at 100 volt, but individual cells whether they are at e by n that is not ensured ok, that is not maintained, that we do not have a we do not have we cannot say that individual cells inside the arm is exactly keeping the rated voltage we, that is equal to e by n we cannot say that. Because one capacitor in one cell can go up voltage on the capacitor, voltage on other capacitor can go down, but their sum can be made same ok, one is going up one is going down, but their sum may be same ok.

So, when we go ahead with this equation we just ensure that the arm voltage is same. In order to ensure that individual cells have the same voltage, we will use something called as a sorting algorithm later not now we will talk about the sorting algorithm later, but it is necessary ok, because we are just ensuring that the arm voltages are like fixed. So, if we see that we have to make this equation satisfied v arm i arm dt 0 over a time period.

So, let us see the upper arm, we try to find out what is this upper arm. So, we see what is the upper arm power ok, this is v Ut into i U t fine. Now, what is v U t? We have earlier found out that, v U t is e by two one minus m sin omega t we had said this earlier in one of the equations.

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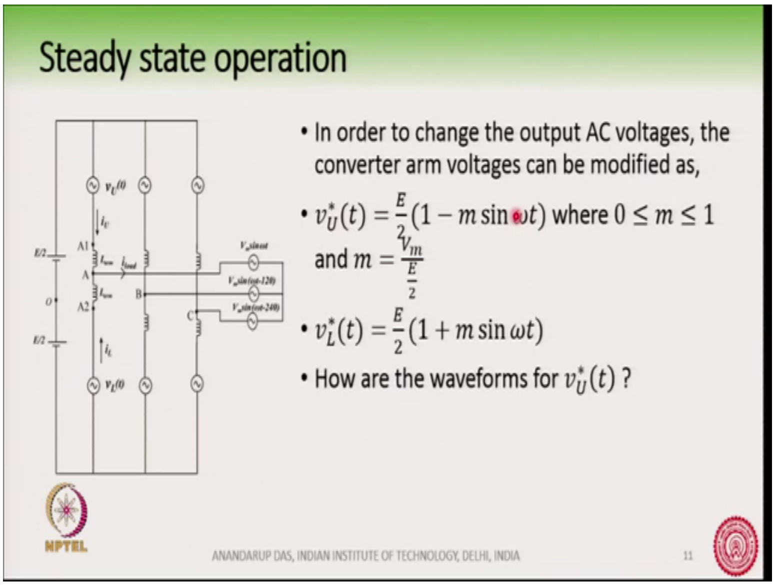

Yeah, this here we have said where m is the modulation index m v m into by E by 2, sowe have substituted this there. So, this is the; so this is where v U t comes here right. What is i U t? Just now we had it is half i load and the i circulating ok. So, we have two expressions here and we multiply them term by term for each one, we expand them and multiply them term by term that is after substituting i load as half i m sin omega t. So, we substitute this one this i load we substitute as half sin omega t phi and then again multiply them term by term.

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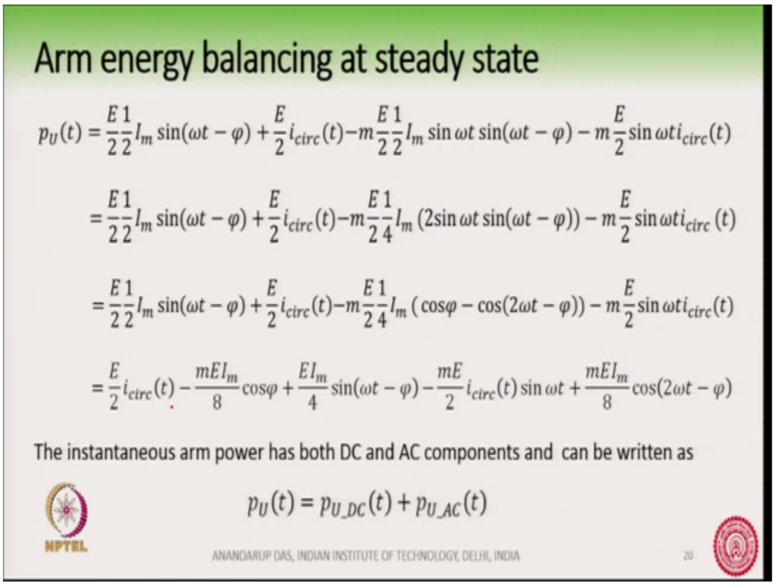

So, what do we get? We get a big expression like this here in pU t where we have multiplied them you can also do it yourself. So, you multiply them all of them one by one and you get a big expression here which you can. So, that you can see that there is one sin omega t and sin omega t minus phi this kind of sin a sin b format and we can this product term we can split it into two additive terms which is like this. So, two sin a sin b is cos a minus b minus cos a plus b and that is what we have written here like this ok.

So, once we do this one; so we have now all terms which are in plus i mean additive terms no multiplicative terms. So, we have this term here and then we see these terms so we expand all of them just get all of them outside their brackets and all, so we see this several terms here coming. Now, there are some terms with the sin omega t, there are some terms which is cos two omega and there are some sin omega and there are some terms without any omega ok.

So, we see that in this upper arm as we had expected earlier this upper arm power has some DC component and some AC component and the AC component has the fundamental frequency component as well as the second harmonic component ok. So, let us see the first the, so that is what we have said in pU t this pU t has a DC component as well as an AC component ok, which is present here this DC component and AC components are present in this big expression here.

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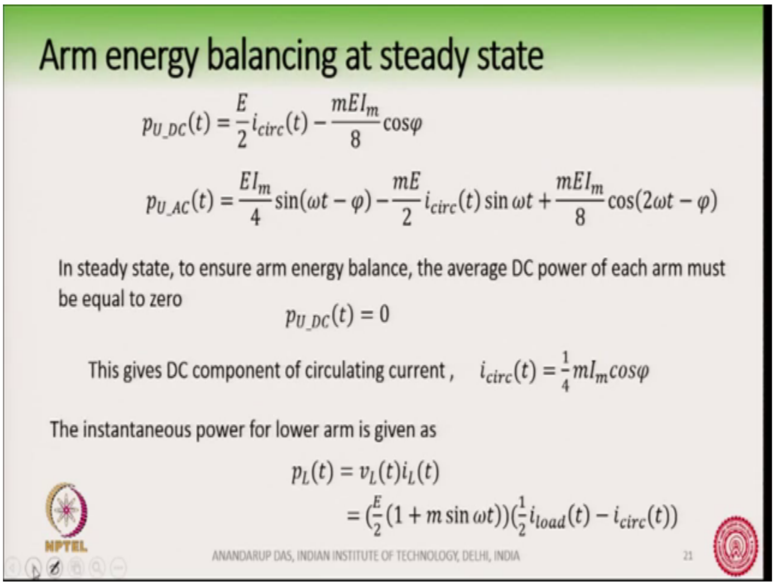

Now, let us collect the DC terms ok. So, what are the DC terms here? So, we collect this one here, this is the DC component and then we have the AC components here. So, we see that the DC component is this much and the AC component are these ones right these are the AC components.

Now, you have to be a little bit careful why this is DC component is because in this i circulating t the DC component of the circulating current is what we have taken. In this one in this i circulating t the DC component of i circulating t has been taken ok. So, this is like the only the DC part of the i circulating well these are the AC components here. So, if this is the DC component of i circulating and we have already said that the net DC should be 0 in steady state, to ensure that the arm energy balance is maintained.

So, the DC power of each arm must be equal to 0 only then the capacitors will maintain their voltage if the DC power flowing to the capacitor is not 0, then either it will the capacitor voltage will fall or it will rise. So, therefore, this term must be equal to 0 here ok. So, if you make this equal to 0 the DC component of the circulating current comes out to be like this ok, one fourth m i m cos phi fine.

So, this is the DC component of the circulating current ok, this must flow through the arms in order to ensure that pU DC is equal to 0. This component of the circulating current, so, we had said that in the circulating current there is a DC component, there is half of the AC load component and there are some other high frequency or the second harmonic component.

So, first component that we said the DC is this one, this is the DC in the. Of course, here you see that something interesting kind of like it is dependent on cos phi ok. So, if the phi is equal to 90 degree ok; if phi is equal to 90 degree, then the DC component of the circulating current becomes 0. So, there is no DC component of the circulating current when the phi is equal to 90 degree or the cos phi is equal to 0. Why will it happen? Because if cos phi is 0, that means, the load is a fully reactive load.

So, the fully reactive load will ideally under ideal conditions, the full reactive load will not draw any real power ok. So, it there will be a power exchange between the converter and the load, but the net real power flowing through the converter will be 0 and if the net real power flowing from the converter is 0. So, I circulating the DC component should also become 0 ok.

So, this circulating component will be as can be seen from the expression also 0 ok. Of course, the circulating component is again dependent on m, so if you increase m then the circulating component will also go on increasing. So, this cos phi 0 suppose you connect the mmc the converter as a statcom and you are using the statcom purely to supply reactive power to the grid ok.

So, of course, you can use it if it is an ideal statcom and it is only supplying reactive power to the grid, you will see that this will be 0 cos phi will be 0. And hence the circulating current vanishes from the mmc anyway that is a different thing. Now, in the upper arm the energy is now balanced ok, what about the lower arm? In essence the same exercise can be done for the lower arm also.

So, you see this is the pL t and you multiply vL t with iLt the lower arm voltage multiplied by the lower arm current. You substitute the lower arm voltage here and substitute the lower arm current here ok. So, you substitute this and again like the previous case fully expanded.

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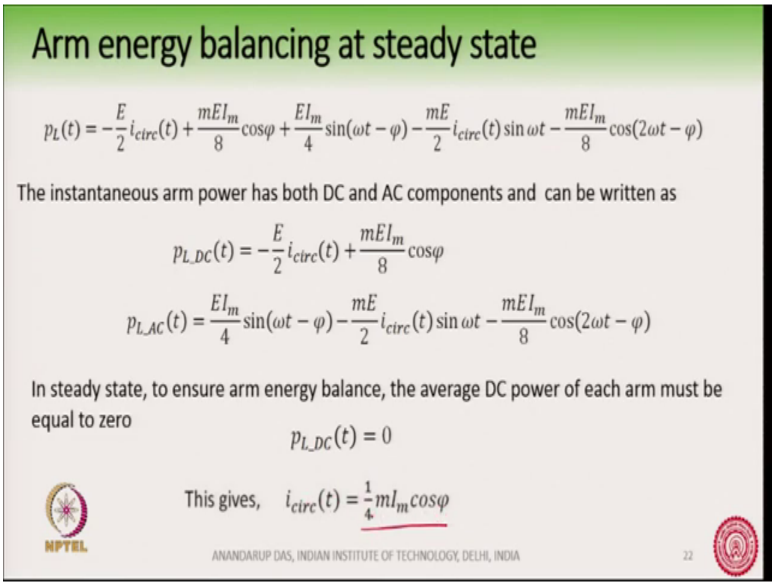

So, then this when you expand it fully, then again we see that in this lower arm power there is a DC component and there is an AC component just like before ok. So, this DC component again here, this DC component for the lower arm should again be equal to 0 to ensure arm energy balance for the lower arm.

So, this PLDC should be equal to 0 and so this gives the same value of the i circulating current here for the lower arm ok. Indicating that this DC component whatever is flowing in the upper arm is also flowing in the lower arm and that justifies the current that i have drawn here ok. The DC is actually flowing from the upper arm and through the lower arm and going back ok. So, and going back to the source here ok, so, this DC is the same DC which flows from the top through the bottom and goes back to the source ok.

So, the same circulating current, so, that is why it is a circulating current flows from the top and bottom and goes out. And so, this is what is that circulating current one fourth mI m cos phi ok. Now, this AC component of the upper arm and lower arm this component here this one, this will lead us to the second harmonic voltage or second harmonic voltage ripple on the capacitor energy fluctuation.

We will talk about this second harmonic sometime later, but remember that we have out of this pU and pL we have only taken the DC component and have made it to be 0, we have not analyzed fully the AC component of the power we will analyze it sometime later. I want to just highlight the sum of the DC component, the sum this is the DC component of the circulating current. So, there is one current flowing through this a phase, one current through the b phase and one current through the c phase right.

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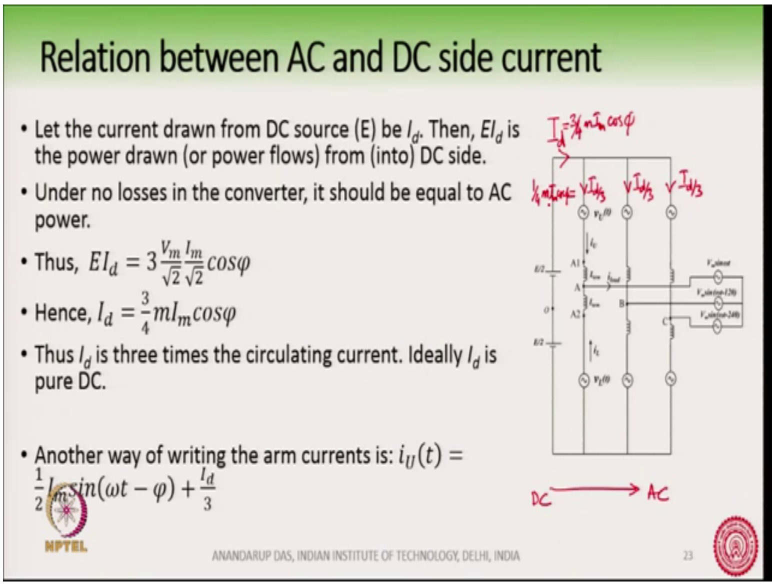


So, the sum of these three DC current is the current which is drawn from the DC bus right. So, this the current which is drawn from the DC bus, suppose this current we denote by I d ok. So, this gets split into this, this and this ok. So, this is like this and this is like this and this is like this ok. So, the this DC current the I d by 3. So, therefore, the upper arm current can also be written something like half I m sin omega t minus phi plus I d by 3 here ok. It can also be written something like this i U t and similarly i L t will be half i m sin omega t minus phi minus I d by 3 ok.

Now, this I d by 3 if it can also be obtained in a different fashion by seeing the power balance ok. So, the let the current drawn from the DC source, so, let us see the power balance from the DC side and the AC side of the converter. So, the current drawn from the DC source let the current drawn is I d which I have mentioned here. Then what is the power flowing from the DC side? The DC side power is flowing is I d ok. So, we are assumed that the power is flowing like this way from the DC side into the AC side ok.

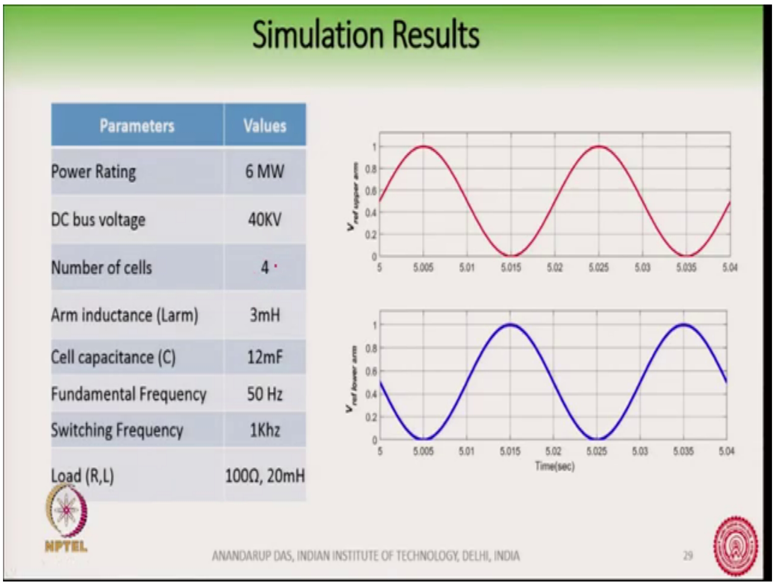
Now, if the converter is ideal if there are no losses in the converter, then this will be equal to the AC power which is flowing out here from the converter. So, what is the AC power which is flowing out of the converter is equal to three times this voltage and current and cos phi right the three times VI cos phi, where VI means V the voltage is V m by root two the rms voltage i m by root two is the rms current and cos phi is the angle between the pole voltage and the current.

So, the AC power that is flowing out of the converter is this much three times VI cos phi right and the DC power which is flowing in into the arms is equal to EDI d right. And these two must be equal because if you are assuming an ideal converter and the capacitors are perfectly balanced, there is no energy loss anywhere then these two must be equal to they must be equal. And so this id is three fourth in I m cos phi ok, this id here is equal to three fourth m I m cos phi and. So, this I d by three this value will be equal to one fourth m I m cos phi seeing from the power balance right.

So, this is the DC component of the current the same value one fourth m I m cos phi we have already obtained, you see here this is also one fourth I m m I m cos phi. So, and we found out from the power balance ok, that the DC component of the circulating current is one fourth m I am cos phi, we got it from the power balance we are also getting it from the overall power flow of the converter from the DC side and the AC side ok. Both ways we find that one fourth m I m cos phi this much of DC current is flowing through this here ok. So, we are very sure that what we are doing is correct ok.

So, one fourth m I am cos phi is the current which is flowing here. So, that sum of this 3 is the three fourth m I m cos phi. So, E times I d E times three by four m I m cos phi this is the power which is taken from the DC source. And this 3 VI cos phi is the power which is flowing through the to the AC side.

So, by knowing this also we will be able to find out what is the DC current. As I told you we have not discussed this AC component of the power we will do it ok, because there is something interesting that comes from there also. (Refer Slide Time: 24:44)



So, far we have just talked about the DC component we will do it. But before doing going there of the AC component of the power, let us see few simulation results for this converter we have made a very small simulation here with number of cells as 4 ok. Now, this is not very realistic generally mmc's with 4 number of cells are not much used and also at this power level 6 mega Watt for some drives application, some manufacturers are making drives with at this power level, but this is not the most prominent application of mmc.

We have taken this as with four number of cells, we can always increase it to higher number of cells, but it gives you more insight into how the converter operates, if when we say there are four number of cells you will see this one. So, and there are certain parameters which have been chosen and so this is the upper arm reference and this is the lower arm reference that v U star and v L star ok. And you can see that both these references are between 0 and 1.

So, there is a DC shift, but the AC are 180 opposite ok. So, as I told E by 2 minus E by 2 into 1 minus m sin omega t and in other words E by 2 1 plus m sin omega t. So, this is where the phase difference can be seen in the reference.

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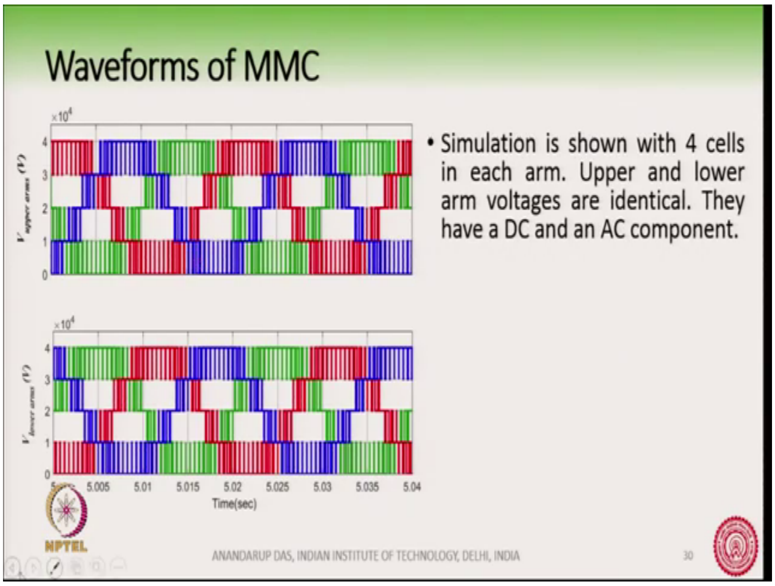

And accordingly the actual upper arm and lower arm voltages are something like this. So, since there are 4 number of cells you can clearly see the levels here. So, this is so that should be 5 levels because this is made up of half bridge. So, this is the first level 0 and there is a second level 1000 volt, 2000 volt, 3000 volt and 4000 volts right. So, each DC bus is 1000 volt there are a total DC bus voltage is 440 KV. So, each is 10 KV I was mistaken not 1000 volt 10000 volts. So, this is 440 kilo volt divided by number of cells e by n. So, that each voltage is 10 kilo volt and so this is 10 kilo volt not 1000 volt; this is 10 kilo volt.

So, 0 t10 KV, 20 KV, 30 KV and 40 KV. So, there are five levels because there are four half bridges in each arm and these are the steps. Of course, when you increase this number 4 to a very high value hundred, this waveform will become like close to sin wave this blue waveform or the red waveform on the green waveform will become very close to sin wave with very small steps in between them. So, with 4 cells we can clearly see the 5 steps in the waveform ok.

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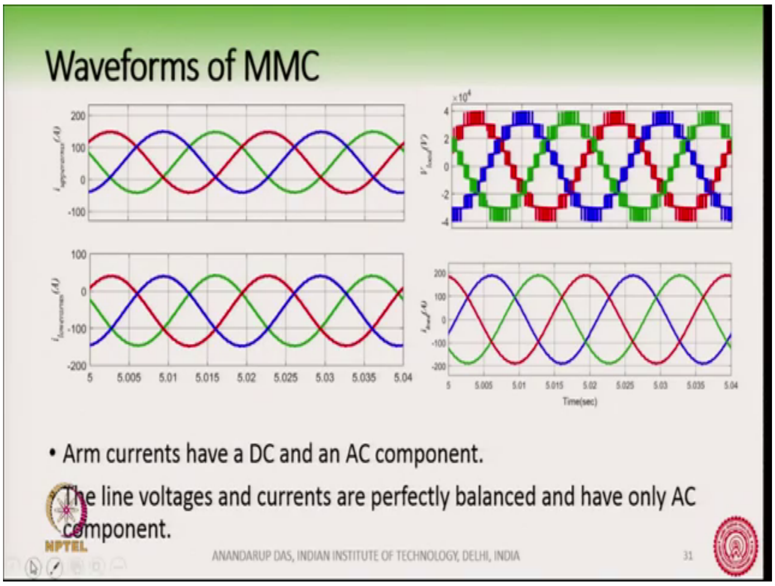

And the arm currents ok, so, this is the upper arm current and this is the lower arm current and this is the load current here ok. The load current is perfectly sin wave almost like a perfect sin wave with no DC component, but the arm current here both the upper arm and the lower arm you see these are shifted from the 0.

So, this means that there is a DC component here ok, this DC component as I as we have discussed is essential for the operation of the converter. So, there is a DC component here and there is a DC component here, but these two DC components they do not come in the load current waveform ok, load does not get the DC component. The DC component flows from the upper arm through the lower arm and goes back to the DC source, it does not flow to the load. And the load voltage is here you can see there are we have to see how, many we can calculate how many levels will be there. So, you can find out that this is a very close to a sin wave. So, therefore, the load current is also sinusoidal.

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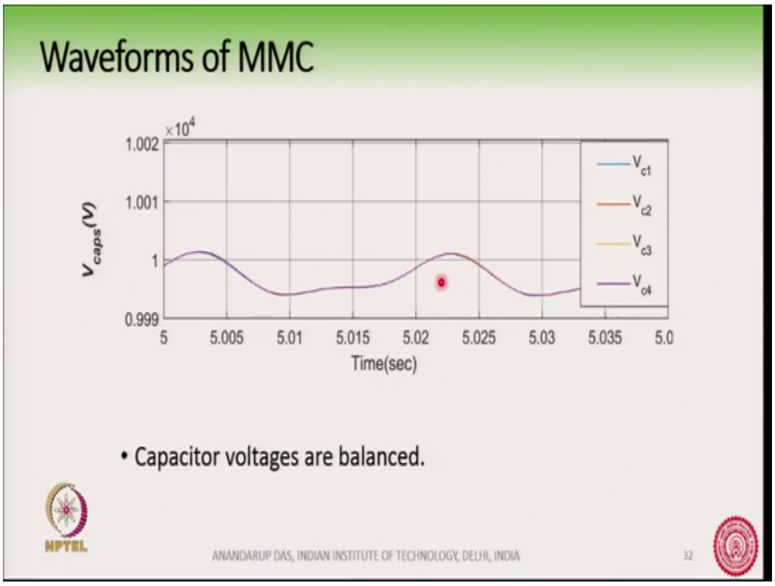

And the capacitor voltages; the capacitor voltages in these 4 cells these are pretty balanced ok, so, this is the 10 kilo volt. So, there are 4 capacitor voltages here probably you are not able to see the four distinct capacitor voltages here we see 1, 2, 3, 4 here there are 4 capacitor voltage, but they are pretty balanced actually there within the, there is a fluctuation here on the capacitor voltage, but they are pretty much balanced ok.

So, how do we balance it we need something called as a sorting algorithm we will talk about it later, but just to give you a brief understanding an idea that these are the waveforms this is what actually happens actually it looks like this. We have shown you some simulation results here and in the subsequent class we will start with the AC component of the power and there we will see something interesting coming up here we have left it because we.

So, what we did today was something like we understood the operation of the converter, we saw the arm voltages their expression arm currents their expression and we found out from reasoning that the arm current must have a DC as well as in some part of the load current that DC we found out an expression. And we verified it by the power balance also, but there are something like second harmonic component of the arm current which we have not touched till now we will touch it in the next lecture, but we have also shown you and some simulation results here.