High Power Multilevel Converters – Analysis, Design and Operational Issues

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Lecture – 19
Modular Multilevel Converter- Arm and Cell Voltage Ratings

So, hello everyone, in the previous lecture we had covered the basic circuit topology of MMC. In today's lecture, we will talk about the modeling mathematical model of the converter from which it will be possible for us to know about the voltage and current ratings of the arm of the converter and the IGBTs or the transistors, DC bus voltage on the capacitor etcetera. So, the steady state model of the converter will be covered in today's class.

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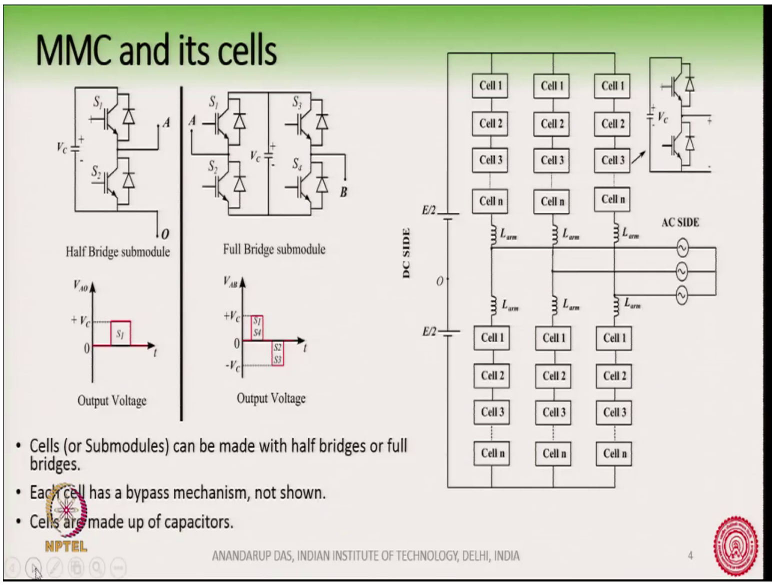

In the last lecture so, we were talking about MMC and then we talked about the drawback of CHB from where we said that the MMC had a capacitor on the DC bus and some of the features we discussed.

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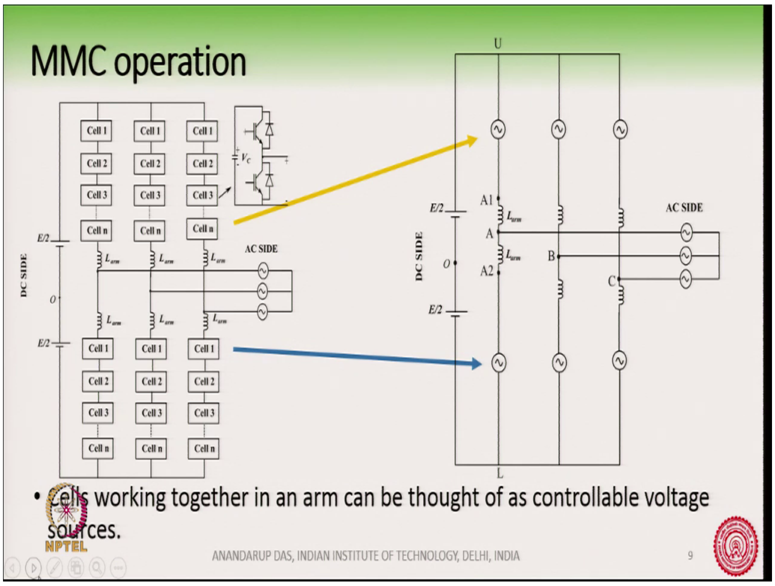

And from where we said that the equivalent circuit of an MMC can be thought of as controllable voltage sources I mean there are 6 arms and so, these six arms act as 6 controllable voltage source the operation. So, the operation is dependent on how we tweak this controllable voltage source.

So, how well we modify the controllable voltage source or we can alter the controllable voltage source. This controllable voltage source is made up of transistors inside the cells and having a capacitor as the DC bus ok. So, how will we change, modify alter this controllable voltage sources and that is how the operation of the converter can be controlled.

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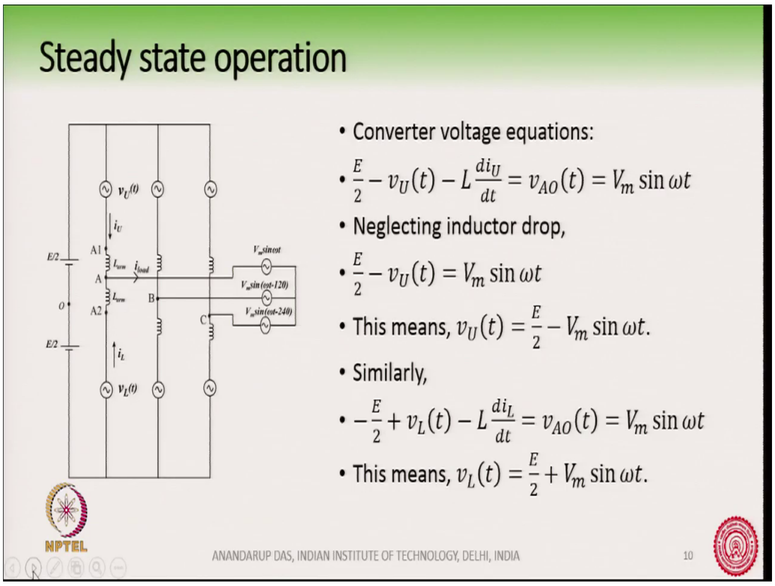

So, we also said about this steady state equations where we found out that the upper arm voltage has a expression like this and the lower arm voltage has an expression of like this in neglecting the inductor drop which is a reasonably good approximation.

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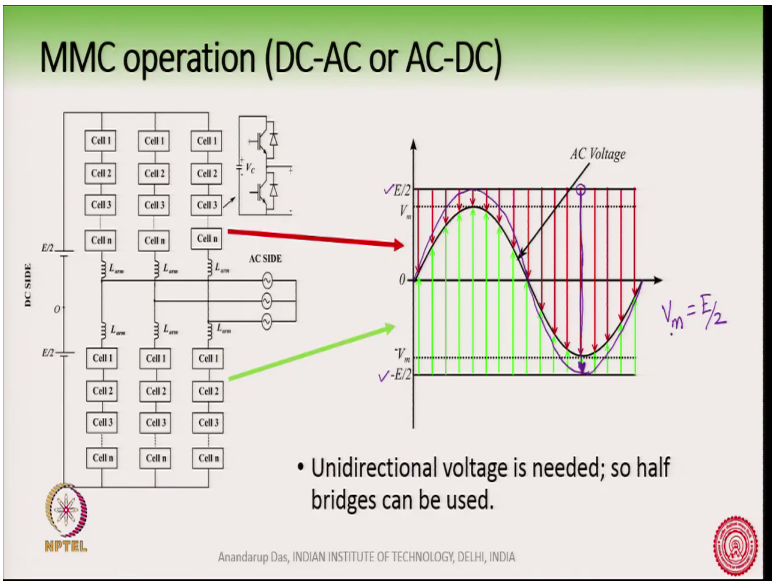

So, from here we talked about this particular waveform, which is the waveform for example, for AC to DC application, the equation which we had written earlier or in the previous slide. Now is diagrammatically represented here in this waveform, where these arrows the red and the green arrows represent the instantaneous voltage magnitude of the upper arm and the lower arm. So, these are the controllable voltage sources made up of these cells.

So, we said that the converter can be you can think of the converter both sides both ways like you can think of an AC source present and then you want to produce a DC, which is the rectifier mode of operation or if you have a DC and you want to produce a variable AC, then it becomes a inverter mode of operation. So, the same circuit remains only the arrows flip that direction ok. I mean at one point of time, you can we had discussed about it.

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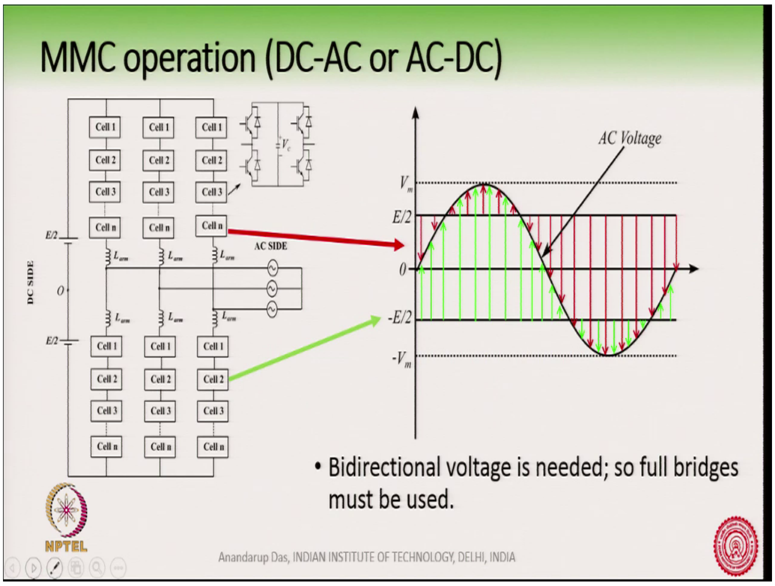

So, it is also possible that the DC bus is less than the peak of the AC bus AC voltage magnitude and an extreme case we said about the short circuit in the DC bus.

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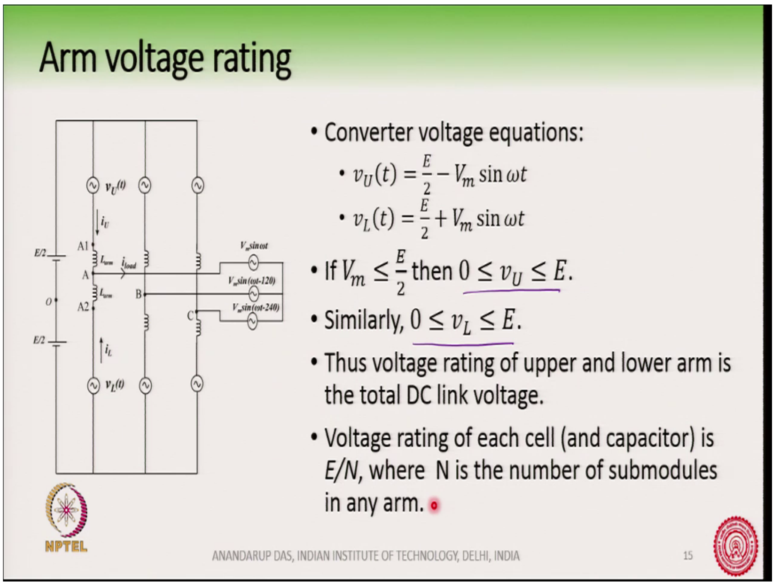

So, today first we will see, what is the arm voltage how much arm voltage needs to be produced from the converter or how much is the blocking capacity of the arm. So, if we see the equation and we will rewrite the equation here, we have seen this equation earlier v U is E by 2 minus V m sin omega t and v L is E by 2 plus V m sin omega t. V u is the upper controllable voltage source this one and v L is the lower controllable voltage source in any particular phase.

Now, if V m is less than equal to E by 2. This is the most common type of operation like when you are for example; converting from AC to DC there is an e v DC for e v DC application V m is usually less than equal to E by 2. So, if this is true and if you substitute it here, then you see that this E by 2 minus E by 2 sine omega t and so, please find that the v U the v U voltage it is between 0 and E. In a similar fashion, we can also see that the lower side voltage is between also 0 and E by substituting this V m as E by 2 here ok.

So, therefore, the voltage that needs to be produced by the upper and the lower arm is equal to the total DC link voltage ok. So, which means the this arm here and this arm the total voltage that needs to be produced by this arm as well as this arm is equal to the DC bus voltage ok. So, this E is the total DC bus voltage ok. So, the upper arm as well as the lower arm and the voltage that needs to be produced from them is capital E or the total DC bus voltage. This is also understood from this waveform here. It is also understood that suppose the AC voltage is reaching this place.

So, let me draw it, if the AC voltage is something like this here if the AC voltage is something like this that is this is the condition where V m is equal to E by 2 this is the condition I have drawn. So, if V m is equal to E by 2 you can see the length of for example, the maximum length of this arrow the maximum length of this arrow becomes this much. So, this is the length of the arrow. So, this is the maximum instantaneous voltage, that the upper arm has to produce right and of course, this is also the voltage that a lower arm lower arm has to block right.

So, what is the length of this maximum arrow? The length of this is equal to E because you see this is E by 2 and this is minus E by 2. So, therefore, this maximum length of the arrow is equal to E and hence during this condition where V m is equal to E by 2, then the voltage that needs to be produced is equal to E. So, that is what we have seen here 0 less than equal to v U less than equal to E. Now so, this means that the arm which is consisting of many number of cells ok. Suppose there are N number of cells or sub modules in each arm capital N this capital N is the number of sub modules or arms in any some models are cells in any arm, if N capital, then this whole E has to be supported by these N number of cells.

So, the voltage rating of each cell the voltage rating of the capacitor in each cell as well as the voltage rating of the switch in each cell all of them must be equal to E by N that is what here shown here this E by N here ok. So, the voltage rating of the cell as well as since the voltage rating of cell is capital E by N. So, therefore, each cell has its own capacitor that must be rated for that much voltage E by N and so, because it is having say half bridge or full bridge, each transistor will also be rated for E by capital N, the voltage rating of the cell is dependent on how many sub modules we choose in any arm ok.

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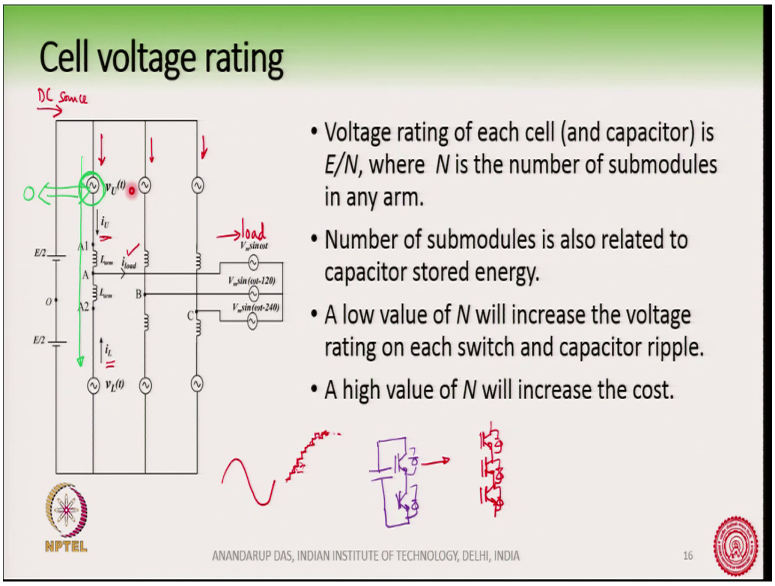

Now, here comes a choice here comes the choice because you see if you. So, suppose we are thinking of about a edge vDC line edge v DC converter MMC acting as an edge v DC rectifier. So, then for example, we can have the DC bus as say plus minus 200 kilo volt; that means, this capital E which will be equal to 400 kilo volt.

In that condition how many number of cells or how what is the value of N that we should choose? Of course, the first criteria that we should follow is what is the available rating or what is the available voltage rating of the transistor that we have. Now we can choose 3300 volt IGBTs, we can choose 4500 volt IGBTs even we can choose six thousand four 6500 voltage IGBTs also these are usual values, but then exactly which IGBT to be chosen is not so, straightforward ok.

If you increase the voltage rating of the IGBT, then we will require less number of IGBTs right. But it will increase the voltage rating on the switch and the capacitor if you increase the number of sub modules then the voltage rating of the IGBT will go down so, but then if you increase the number of sub modules, then the cost the complexity because you have to control so, many so, many IGBTs together. So, say if you instead of 100; 100 cells in each arm if you increase it to 200 cells in each arm of course, the voltage rating will go down.

But now, you have to instead of 100 cells in each arm we have to now control 200 cells in each arm which increases the complexity, which increases the size and also the controller the because the gate drive requirement, the fiber optic the isolation requirement many other things will be affected. So, this is not a very straightforward choice ok. So, even some manufacturers some manufacturers use the half bridge as like this, some manufacturers even use half bridges like what we have discussed like this as the half bridge.

Ok, but some manufacturers do not have a single IGBT here they have something like this there is no single IGBT, but a series connection of several high IGBTs ok. So, some manufacturers have this. So, this one IGBT is not a single IGBT, but several series connected IGBT. Now it this cannot be directly said it needs to be simulated and we have to find out what is the complexity, what is the loss. Remember the loss is very much important because you we are having a large number of series connected devices.

So, the conduction loss the conduction switching loss will not be so, important here because with so, many cells in series the output waveform is almost close to sine wave ok. So, we do not need very high switching frequency for individual cells, but the conduction loss is substantial because whatever current is flowing, it is flowing through several cells in series and all of them are coming in series. So, the on state voltage drop is kind of adding up this case. So, this high value of n increases the conduction losses in the converter.

So, we have two kind of like see what is available in the market, how much expertise we have again as I said earlier, we have more expertise on a 1200 volt IGBT rather than a 6500 volt IGBT ok. So, there we have to make a choice like which IGBT which rating IGBT we have more expertise whose gate drive we know very precisely how it functions, how is the fault performance of such an IGBT and many other factors come in and then we can say that by considering all these factors as well as the laws and many other dynamic performance then we choose this value of capital N how many cells. But the starting point of this calculation, it comes from the fact that the rating the minimum rating of the voltage, but the minimum voltage rating is capital E by N. So, this is the starting point of the design.

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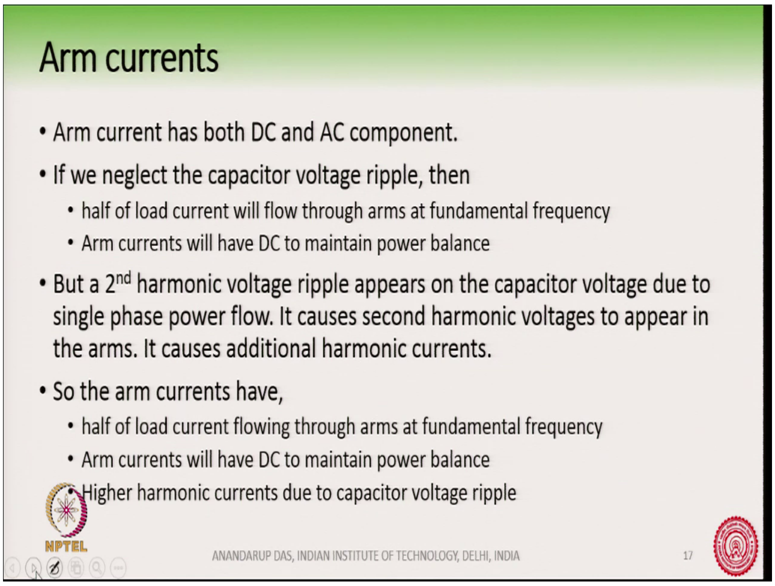

Next is the current flowing through the arm this is a little bit tricky the arm current ok. Now let me first tell you what does the arm current contain. So, primarily the arm current has a DC as well as an AC component ok. This feature of the converter where the arm is containing both DC and AC is what makes this converter unique and sometimes it is sometimes it is difficult to fully appreciate the operation of this converter.

So, the arm current has both DC and an then AC component. Now why first of all the question comes up why? Why there is a DC as well as an AC. So, if you see the circuit of the converter now this is the arm current ok. So, this i U here and this i L here. So, upper arm current and lower arm current. Of course, you can see here that the sum of i U and i L is what is making the load current here this is the load current. Now the voltage produced by this converter is almost like a sine wave. So, the load current for this converter we can assume that it is almost like a perfect sine wave.

And can be represented by the equation i load equal to i max into sine omega t minus phi or something like sinusoidal function we can write. And since this is fed from both the upper and the lower arm of course,; that means, both the upper arm and the lower arm will contain a fraction of this load current and that is evident from the Kirchhoff's current law. So, the i U and i L will have a fraction of the load current and generally because of the balanced operation of the converter the i U and i L upper arm and the lower arm in each phase contains half of the load current. This is a this is understood from the symmetry and the balanced operation of the converter.

That i U and i K contains half of the load current and the load current can be safely assumed to be a purely sinusoidal current. So, that AC component of the i U and i L is understood pretty easily now why is there a DC component? Ok as I told you i U and i L has not only an AC component, but also a DC component now why DC? This is where this converter is unique why there is a DC component? Now if you see how we have made this upper arm and lower arm remember that the upper arm and lower arm these two voltage sources they are made up of capacitors, capacitors are different from rectifier fed that but because they dont have their inherent energy supply ok.

They can temporarily store the energy in the form of half c v square, but they do not have a. So, these capacitors in the upper and the lower arm they do not have a source of energy which is connected. Now you see here this upper arm when the load current is flowing through the upper arm and the lower arm of course, the real power suppose we are taking it as a let us take an example of a DC to AC converter ok. So, DC to AC converter. So, the real power is flowing from the DC bus into the AC load ok.

This is how it is flowing this is the load here and this is the source here DC source from the source to the load it is flowing. Of course, it gets divided into the three phases. So, this gets divided into three phases and then it flows to the load one third one third one third. Now this DC source is the source of energy and the source of like the real power is flowing from this DC source into the load via these capacitors, these are made up of capacitors these are all made up of these sources are capacitor. So, the real power is flowing from this DC source via these capacitors into the load it is flowing like this via the capacitor.

Now, when real power flows through the capacitors what happens? This comes from the basic circuit understanding when real power flows through capacitors either the capacitor energy will go up or the capacitor energy will go down depending on the direction of the power flow. So, either you will increase this half c v square or you will decrease the half c v square because you are allowing the real power to flow through the capacitor. If reactive power flows through a capacitor over a cycle we give some energy to the capacitor and get it back from the capacitor.

So, over a cycle the net energy which is supplied or which is taken from the capacitor becomes 0 when there is a reactive power flow, that is the voltage and angle voltage and current having 90 degree angle. But when real power flows through a capacitor then the energy of the capacitor will either go up or it will go down unless we take some precautionary measure ok. Now you see here; when the real power is flowing from this DC through the capacitor through the load ok. So, this arm which is made up of capacitor several capacitors in series the arm will lose its energy because or it will gain energy when the power is flowing from here to the load.

So, in order that the energy in the arms is at a steady value it has to be at a steady value otherwise what will happen? Why these arms are needed? Because they are creating this multi level or they are creating this sinusoidal voltage source multi level sinusoidal voltage source, they are very much needed and it is important for us to keep the capacitor voltages to a fixed value. If the capacitor voltages are going up or going down then we will not be so, easily getting the sine wave output right.

If the capacitor voltages is diverging we will have a non sinusoidal output. This we have seen earlier also that if the voltages are not kept at a particular value if the capacitor voltage are not kept at a particular value. So, instead of a sign. So, if you want to because they are trying to create a sine wave from the arm voltage and this is made up of like this. So, greater is the number of steps closer is we are to the going to the sinusoidal waveform. So, this is what we are trying to achieve. So, this is the sine wave here ok.

But this will be this will be possible only if this tips these steps are kind of like steady steps over a period of time, these are very stiff steps. If the capacitor voltages are going up or down these steps will no longer be very discrete steps it will I increase decrease or it will fluctuate like that. So, it is important that the capacitor voltage in these arms they are at a particular value within of course, we will have a tolerance, there can be a slight fluctuation in the capacitor voltage, but it should be within the acceptable limit. Only then we get this kind of like a stiff steps in the output waveform. So, it is important that the capacitors hold their voltage.

Now, when this real power is flowing through the capacitors, it will not be able to hold that voltage because the energy the energy corresponding to this real power will cause the capacitor voltage to either go up or go down depending on which direction the energy is flowing based on the half c v square. So, therefore, the AC component of the current the AC component which is flowing through here this AC component must be compensated it must be compensated; compensated for what? So, that the capacitors hold their voltage ok.

So, the capacitors do not divert the voltage on the capacitors do not diverge either up or down ok. So, how can it be compensated? It can be compensated by a circulating current. It can be compensated you can say by a DC current this is the DC current why it is DC that we will come I can mathematically we will show why it is a dc, but there must be a circulating current ok. This circulating current ensures that the net energy taken from this source over a certain period of time the net energy is 0. So, we do not take or give any. So, this is 0 here ok. This circulating current is essential for the operation of the converter.

Without the circulating current the voltage on the arm will either go up or mean I mean diverts the voltages will go wayward it will go very high or it will go very low either to the DC bus or to 0 because the real power is flowing through the arms and we do not have a mechanism because so, the arm is losing the energy or gaining the energy and we do not have a mechanism to compensate that compensation mechanism is provided by the circulating current ok. We can find out how much is the circulating current and it is predominantly DC.

The circulating current is predominantly DC because this circulating current is in fact, the DC component is what makes sure that the energy is over a period of time is 0. So, let us now see. So, therefore, this statement arm current has both DC and AC, this can be understood from the operation of the converter ok. So, half of the load so, this what we have written if we neglect the capacitor voltage ripple, then half of load can be flow through the arms at the fundamental frequency.

So, that is the load current frequency and arm currents will have a DC to maintain the power balance or the energy balance ok. So, that the arm energy is fixed. However, in addition to this there is a second harmonic voltage also that comes on the capacitors ok. So, the curve capacitor has a ripple and this causes us this is actually a second harmonic voltage ripple on the capacitor. This is not very high the second harmonic voltage ripple is not very high it has some second harmonic additional currents which flow through the converter, but it does not come on the DC side neither it comes on the AC side.

There is an additional second harmonic we will talk about this additional second harmonic ok. The origin of the second harmonic can be understood from the fact that this voltage source here this voltage source here this one, this voltage source is a single phase voltage source and the single phase current is flowing. Note that these three voltage sources are completely independent of each other, they do not know about each other, then they do not even know that there is a lower arm.

So, these are single phase six single phase voltage sources and we know that when through a single phase voltage source a single phase current flows with a phase difference between them, then there the power which flows through this voltage source has a DC component and the second harmonic component v i cos phi if you multiply it, you will get one DC component and a 2 omega t 2 omega component that second harmonic component in the power causes a second harmonic voltage fluctuation on the capacitor.

So, that will cause some additional harmonic currents in this. We will talk about it, but we will talk about it sometime later we will first talk about the DC component. The DC component is essential the second harmonic component comes because of the power fluctuation.