High Power Multilevel Converters – Analysis, Design and Operational Issues
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Lecture – 22
Modular Multilevel Converter – Different Circuit Topologies

Hello everyone and today we will start another session on Modular Multilevel Converters. So, in today's session we will mostly talk about the different circuit possibilities with MMC or Modular Multilevel Converter.

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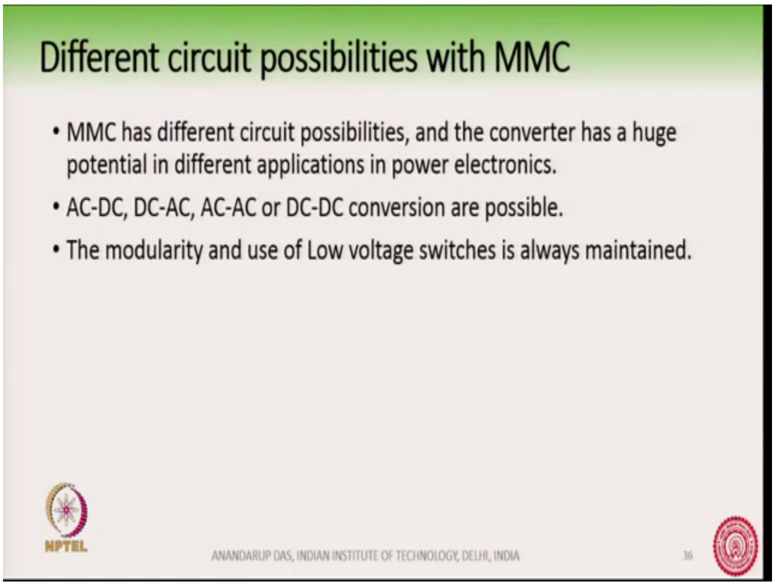

So, in this lecture session the usefulness of MMC for a wide variety of applications in power electronics can be understood by observing that this converter with the help of these controllable voltage sources can be manipulated in a wide variety of fashions.

And we will see why this converter is so, exciting both for researchers as well as for the industry. Because it opens up a lot of possibilities in terms of different types of circuit topologies that are possible using this controllable voltage source approach. And so, AC to DC, DC to AC, AC to AC and even DC to DC all applications of power electronics, they can be explode with the application of MMC as the main or the main principle idea based on that principle idea.

Now, usually MMC is applied for high voltage and high power applications because we would like to have many number of low voltage switches working together and we would also like to have the modularity feature where there are large number of identical sub modules working together. So, these two features are very promising and interesting for MMC. So, we would like to preserve both these features the modularity feature and the use of low voltage switch this feature both of these features we would like to preserve when we talk of other applications, when we talk of say DC to DC MMC or we talk about AC to AC MMC based topologies.

So, modularity and low voltage features are preserved or maintained and so, earlier or like means MMC has now been popular for high voltage DC transmission. So, where you convert the AC into high voltage DC for HVDC transmission and then at the inverter station who convert back the HVDC into AC. So, AC to DC and then again DC to AC that is how MMC has been commercially implemented, but people see a lot of possibilities with other types of applications say AC to AC direct AC to AC converter or DC to DC converters. So, these are some of the things that we will talk today.

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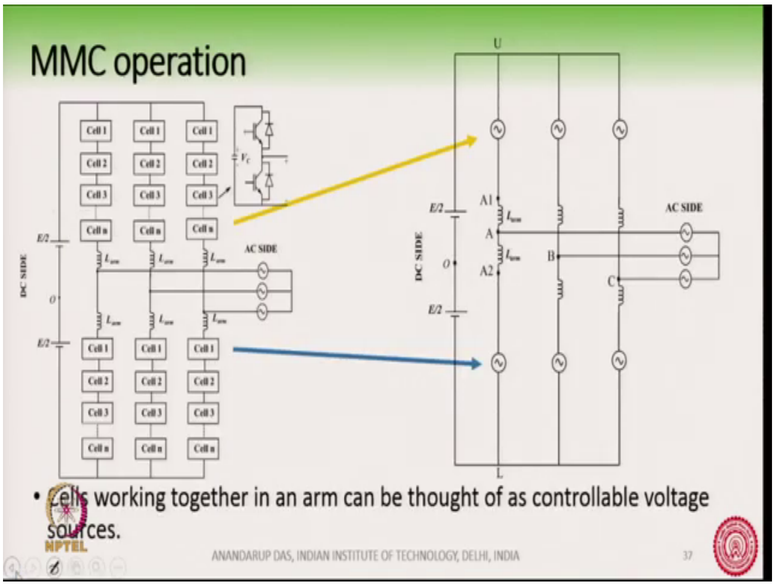

So, before I go into these different circuit possibilities with MMC let us again recap once more what is the circuit. So, this circuit MMC circuit has many cells and these cells are as you can this is. So, these are the cells here and these there are large number of cells in the upper and the lower arm and we had said that these cells can be made up of half bridge or full bridge circuit and these cells can be treated as a controllable voltage source. So, you can see here three controllable voltage source in the upper arm and three controllable voltage source in the lower arm and then you have the grid or the AC side or the motor here and you have a DC side here.

So, you can send the power from the grid into the DC side for HVDC applications like for power flowing from this AC to DC for HVDC and power can also flow from DC to AC when you want to invert it back. So, these 6 controllable voltage source is or these 6 controllable voltage sources are the are something which we can manipulate because these are controllable voltage source and they can be controlled easily by giving a certain reference wave form and using pulse width modulation multilevel pulse width modulation say level shift PWm.

So, these controllable voltage sources are something which we can manipulate at our own will and this is the basis of exploring the different circuit topologies. So, you have controllable voltage sources in your hand which you can manipulate and obtain the desired result. So, this is what we will explore now.

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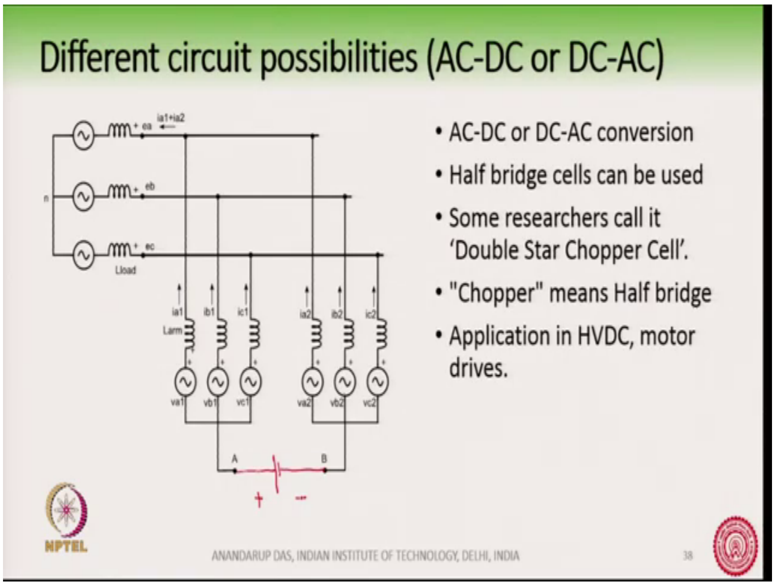

Now, the first one which we will see is the same control the same MMC, but now I have drawn it in a slightly different fashion why have I drawn it like this fashion we will understand a little bit later. But you can see the same converter I am now redrawing it in a slightly different fashion. You see here in this one we have this side this is the AC source or load whatever you may, this is the AC side which may be the grid or the motor load and which corresponds to this here and we have put an additional inductor.

So, let us not talk about that inductor, but you have the AC side here and this AC side is here; now these are the six controllable voltage sources ok. So, these are the this is the three controllable voltage. So, this is the upper arm and this is the lower arm and these are the arm inductors ok. So, this here corresponds to this upper arm here ok. You just see that I have this I have drawn this circuit only, but now in a slightly different fashion this is the circuit here. So, this is the upper arm here and this is the lower arm here. So, the upper arm for example, is connected to one point of the incoming or outgoing AC and here you see the lower arm is also connected to this point here.

This is the common point which is same as this point here. So, this is the upper arm this is the lower arm which is going to the AC side and here also this is the upper arm, this is the lower arm and they are going to the AC side. I have put an additional inductor here just yeah this you can ignore for the time being. So, this is here and this is upper arm and lower arm.

Similarly, in the B phase also this is the upper arm and this is the lower arm. So, this is the B phase here upper arm and lower arm and in the C phase you have upper arm and lower arm ok. Now, these upper arms are shorted here the lower arms are shorted here. So, you see here the upper arm three upper arms are shorted at this point and the lower arms are shorted in this point, two isolated neutrals right. And these two are these two are the terminals which say for a DC to AC converter is connected to the DC source and for an AC to DC converter we produce the DC here ok.

So, in a similar way see this these are the two neutral points isolated neutrals of the upper arm and the lower arm and they are taken out and shown by this A and B. So, this circuit here the way I have drawn it is same as the previous circuit only it has been redrawn in a separate fashion. So, in this one so, this circuit as we have already discussed in length, they can be used for AC to DC or DC to AC application. So, if you have sorry if you have say DC to AC application, then here is your DC bus that is what we have seen in the this circuit here this is the same circuit the DC to AC converter you have a DC. So, if you want to create the VDC.

So, you will say that between the point A and B are the positive and negative terminals of the HVDC line. So, half bridge cells can be used in this controllable voltage source.

Now, some researchers. So, you will see in literature when you explore the MMC different circuit topologies, you can see many literatures available in online libraries. For example, if you see in I triple E explorer, then you will see a lot of circuit topology variants of MMC. Now some researchers call this as double star chopper cell ok.

Now why it is double star and why it is a chopper cell? So, chopper means half bridge. So, they use the word half bridge for chopper and full bridge for bridge ok. So, its a different nomenclature meaning the same thing; however, you will see both these both these terms use frequently in literature. So, I would like to introduce you that sometimes people call the half bridge as chopper and full bridge as bridge ok.

So, some researchers call this topology that is the conventional MMC for AC to DC or DC to AC application as double star chopper cell converter. So, chopper cell you can understand because it is made up of half bridge, but why double star? The reason of double star is, you can understand here that there are two star connected as if there are two star connected converters here ok. Remember that this is the upper arm and this is the lower arm and they are fully controllable voltage source ok.

So, if you see that the point A, the point A here or this point here rather I will say this point and this point these are two isolated neutrals ok.

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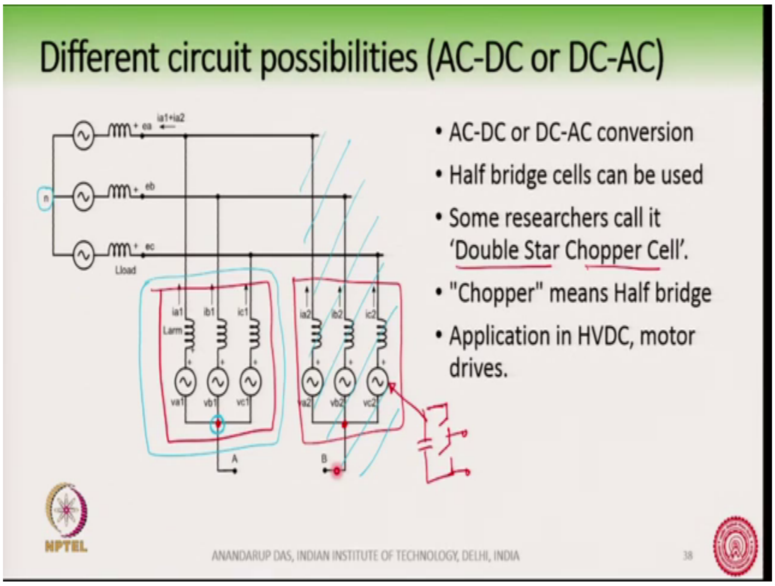

So, this here this one this is as if a star connected voltage source and this is another star connected voltage source right. So, these two star connected voltage source are working together and that is why this word double star is used. There are two double stars there I mean there are two star connected voltage sources working together and they are made up of chopper cells means inside this; this is made up of half bridge like this ok. So, that is what is meant.

Now, if you note it carefully you will understand that the cascaded H bridge converter which we had discussed earlier, cascaded H bridge converter is nothing, but a subset of MMC ok. In case of cascaded H bridge converter we had sorry in the cascaded H bridge converter we had actually only this much only one of this ok. The second one was not there this second one the second controllable voltage source was not there. So, you can see that if I just erase this point. So, this was not there in a cascaded H bridge.

So, cascaded H bridge can be turned as single star bridge cell because in a cascaded H bridge we usually have full bridge here we will have full bridge, but it is a single star and then in that cascaded H bridge we had earlier seen that this neutral point here was floating it was floating with respect to the load neutral point here ok.

So, and we also understood that during fault condition, the voltage difference between this neutral point and that neutral point these this voltage difference makes it possible to produce balanced line voltages in spite of having unbalanced bowl voltages. So, the there will be then a voltage difference between this neutral point and that neutral point here. So, this one and this one.

So, the cascaded H bridge is nothing, but subset of MMC where this this this star is absent. So, there is a single star. So, this was only present ok. So, the if you analyze it in that way, you will feel that we have already analyzed one single star we have analyzed this cascaded H bridge, now we are connecting one more star ok. So, this is also another way of looking at MMC as if like you have, so yeah. So, therefore, this is where the DC voltage is available this point between A and B. Now this converter. So, this we have studied in details and we have seen that it can be applied for HVDC and motor drives etcetera ok.

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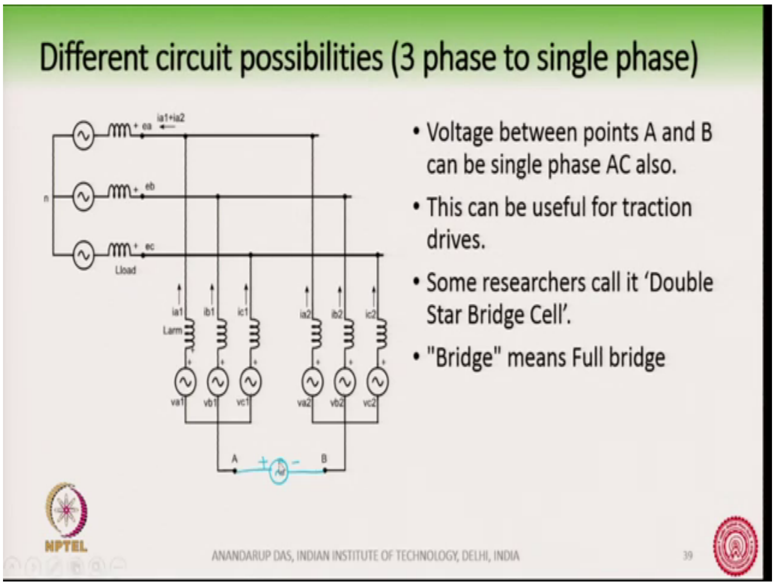

Now, if you go one step ahead. We have so, far said that the point the voltage between points A and B are DC ok. We have analyzed it in details that the voltage between point A and B is a fixed DC a straight line and then we have the AC which is being produced here ok.

Now, the next step is can I have a single phase AC between points A and B? That means, I will try to put a single phase AC here is it possible? Yes, in fact, it is possible how do you how do you understand the operation? So, in order to understand the operation you see here you see that how did we analyze yes this slide.

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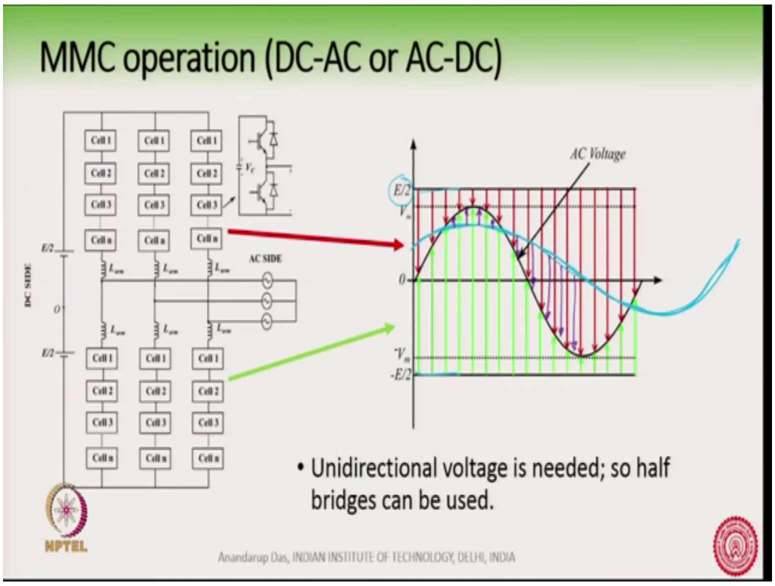

So, here we said that there was a DC here and the DC minus DC here and the AC was inside and the upper arm and the lower arm they were producing voltages which are given by these arrows ok.

Now, if instead of this flat DC, if we have an AC I mean to say that instead of this line being a flat line can we have a fluctuating line. So, for example, not this one see we have we have a flat line here, if I say that let me have instead of this flat line instead of a flat line I have started to vary this line ok. So, what will happen then? Two three things will happen simultaneously first thing it will be possible to operate the converter because now, if the line is something like this, then the arrows can produce this blue line with the help of the arrows, arrows are nothing, but the controllable voltage source.

So, the arrows will be now changing like this something like this sorry I yeah we will change this. So, the arrows can produce this voltage the arrows must be bi directional in nature because sometimes the arrows will be positive and sometimes the arrows will be negative. So, just we will change this slide.

How the AC quantity how we can get an AC from a three phase AC? How can we get a single phase AC from a three phase AC can be understood from this diagram here ok. So, here we had assumed that there was a DC source which was represented by this line here and this line here and there was an AC, which we were trying to produce or which we were getting from this AC side.

Now, now we are saying that this AC this DC here is no longer a fixed line and it has started to vary. So, I can draw this variation. So, for example, I can say something like. Ok this is the AC its a single phase AC ok. So, the this flat line here and this flat line is no longer a flat line. So, its not a fixed DC, but the, but this has started to vary slowly suppose you could start to vary flow slowly what will happen then? You see the arrows can still produce this blue line ok.

So, here how will the arrows look like? So, the arrows will look like say. So, the arrow is the instantaneous different difference between this blue one and the black one. So, here you see for example, some arrows will be like this say the green one will become like this ok. So, these indicate that we need a we need a bidirectional voltage capability from the arm ok. So, but it is possible to have a single phase, AC from a three phase AC that is what I we were we were looking here.

So, here we were saying that we have a single phase AC and we have a three phase AC, now earlier we had got a constant DC source and now we are getting a we are getting a single phase AC source so; that means, single phase means the voltage magnitude here will vary.

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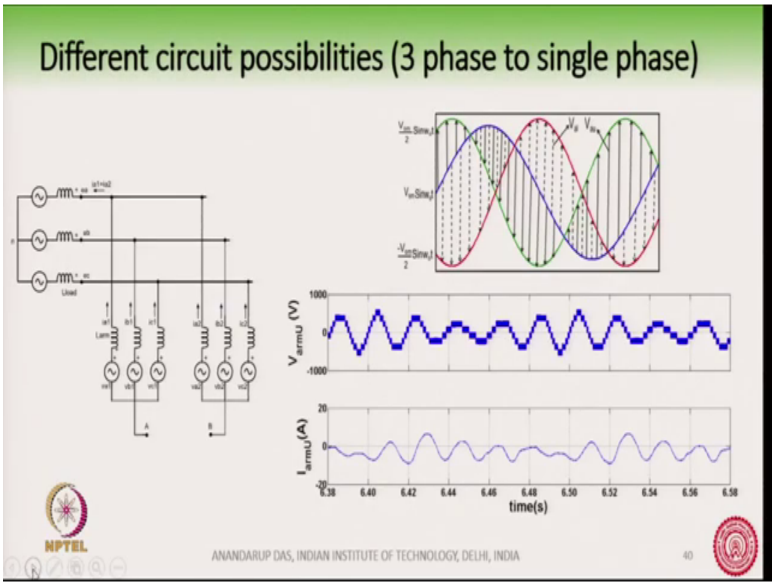

So, this is what also is shown here. So, the voltage is varying; right voltage is varying at this point. So, what we understand that blue coloured waveform which we had drawn if the voltage starts to vary there, then we will be using full bridge cells inside this we will be using full bridge cells here and here. So, that the instantaneous voltage difference between this voltage source here and this voltage source here can be supported by the arm voltages here and here the.

So, you we are basically applying the Kirchhoff's voltage law and we are seeing; that means, I mean neglecting the inductor drop, you can find out yourself that what will be the expression of the voltages of the upper arm and the lower arm when this side is a single phase AC and this side is a three phase AC.

Note that this single phase AC can be a different frequency compared to this three phase AC frequency. So, this side can be 60 Hertz this side can be 50 Hertz ok, but here what we are seeing is a direct conversion of a single phase AC to a three phase AC with bidirectional power flow. Power can flow seamlessly from this side to this side or this side to this side because it is an inherent feature of the converter.

So, what we are understanding is that, this voltage point voltage between A and B is not necessarily will be kind of like a DC, it is not necessary to have this DC. The voltage between point A and B can be a single phase, AC also and where can be where can it be applied it can be applied in case of say traction drives. For example, suppose in India we have 25 k V single phase50 Hertz traction drives 25 k V single phase available on the traction lines and suppose we want to drive a three phase load ok. So, it is possible to use such a converter directly ok.

Now, as I as I told you if we want to run under such a condition then we will need full bridge cells because I had just now drawn it because you will need bidirectional arrows, we need bidirectional arrows. So, if we need bidirectional arrows; that means, we will need full bridge full bridge feature. So, we cannot use half bridge. So, we have to use full bridge in this in this voltage source. So, therefore, some researchers call it double star bridge cell because there are double stars. So, there is one star and this is the second star and we are using full bridges. So, they are calling it bridge cell. So, double star bridge cell full bridge ok.

So, the earlier one where we had used only we had used only the half bridges, there the word double star chopper cell was used. So, you can see here that we have actually done some simulation as well as experimental work on this and you see that during this condition the ah. So, suppose this is the one phase of the three phase source or load I mean this does not have any yeah [sing/single] means the power can flow from the single phase AC to three phase AC or three phase AC to single phase AC.

So, suppose this is one side of the three phase AC one phase of the three phase AC and you can see here this are the this arrows are indicated this V a u; that means, and this dotted arrows at V a l that is the upper arm voltage waveform instantaneous upper arm voltage waveform and instantaneous lower arm voltage waveform. What are these green and red ones? This is kind of like the voltage between point A and B ok. We have drawn two of them just to show that how the upper arm and the lower arm instantaneous voltages can be obtained there is basically only one of this waveform. So, there is one single phase AC and there is one three phase AC, but at a different frequency.

So, if you see the armed voltage here, if you see the armed voltage you can see the armed voltage has many steps because it is a multilevel converter having many steps, but there is a there are two frequency components here because we had simulated it with 50 Hertz single phase I mean 50 Hertz and 60 Hertz both. So, one side was 50 Hertz and the other side was 60 Hertz. So, the armed voltage has both these frequency components and this is expected because when we were converting from DC to AC, the armed voltage has a DC component and an AC component.

Now, the armed voltage has both components; both AC components no DC component one 50 Hertz and one 60 Hertz for example, ok. So, and the arm currents will also have a similar feature ok. So, this is something which is very interesting because just by analyzing and just by looking at the circuit in a slightly different fashion, we see that a possibility exists for converting a single phase to a three phase or a three phase to single phase at different frequencies and different amplitudes both are possible.

Now, we see the next possibility ok. What is the next possibility? I mean there are many possibilities I am just showing you some of the possibilities and you can yourself understand why the converter looks to be a very promising solution for many power electronic application.

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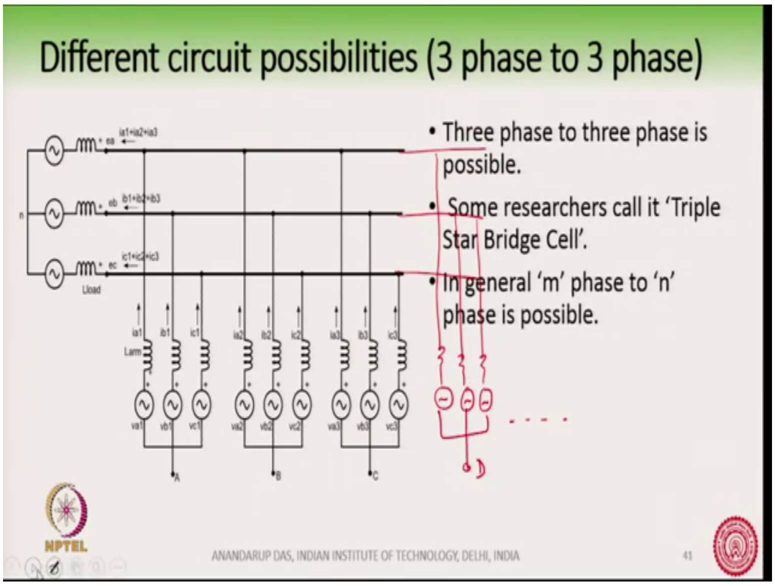

Now, here. So, far you see we have considered a double star configuration. So, we had upper arm three upper arms and three lower arms. So, there were double star two stars star 1 and start 2.

Now, if I add one more star here one more star like this ok. So, we will say it as a triple star bridge cell; triple star bridge cell. Now this is something which is very interesting because now we are seeing a possibility of you see three phase to three phase converter, direct three phase to three phase converter direct three phase to three phase converter one three phase. So, this is one three phase, the word incoming and outgoing does not have impact here. So, there is ones three phase system here, there is another three phase system here ok. So, it is a direct integration of two three phase systems through this converter.

Now, what is done nowadays when you want to convert from one three phase to another three phase system? Say for example, you have a three phase 50 Hertz incoming and you want to drive a three phase motor at say 10 Hertz. So, this is a basically a three phase two three phase three phase two three phase system ok. So, one side three phase is at 50 Hertz at a certain voltage the other side is another three phase at this other voltage and other frequency.

So, what do we do? We basically first rectify the incoming three phase with many times we use a diode bridge rectifier and we get rid of the frequency component the AC component because diode bridge rectifies it. So, we get rid of the AC component. So, we get rid of the 50 Hertz and we get a DC and by using say any inverter or on the output of that DC bus, we get a variable AC which we will feed it to the motor.

So, first the idea is get rid of the AC component make it DC from that DC you produce whatever AC you want to produce through the help of the inverter that is the basic idea. But again you see this is a two stage conversion you can instead of using a diode bridge rectifier you can also use a front end rectifier ah. So, that you can get some additional benefits like unity power factor operation and something like that and bidirectional power flow.

Now, this is a different way of looking at it, where you see this is one side is an AC and the other side is another AC. The with this front end converter a DC bus and the inverter, the drawback is as the voltage level goes higher and higher this central DC link is something which making that central DC link is somewhat challenging ok. And because as the voltage goes up you have to build a capacitor which is able to sustain that high voltage and the energy stored in that capacitor also becomes very large because it will be proportional to half c v square.

So, MMC does this in a slightly different fashion as I am showing you here MMC is doing it, but then instead of that central DC link, it divides the DC link inside the cells as if it is doing like that. So, that central DC link is split into several small DC links inside the cells ok. So, this may be useful at high voltages when you directly want to convert high voltage to high voltage for two different frequencies, this may be quite useful ah, but it has also some drawbacks ok. As you have seen that there will be a circulating current MMC is inherently because there is a circulating current flowing and the capacitors must be designed so, that their voltages do not fluctuate too much in presence of the circulating current.

And so, although we split the capacitor into cells, the each individual capacitor the voltage rating and the energy inside the capacitor goes down, but the total energy of all the capacitors is much more than the capacity the energy stored in the central DC link concept ok. Because in a central DC link concept the ripple part goes through the capacitor the DC or the net energy flows from the rectifier into the inverter side, but the ripple part circulates inside the capacitor it is not the case here this is different.

So, we see that MMC gives us another possibility of using such three types means three star cells for conversion from an three phase AC to another three phase AC here bidirectional power flow at different voltage and frequencies. So, this can be connected to a motor and this can be connected to a grid and or vice versa.

So, some researchers call it as a triple star bridge cell and it is also called sometimes Modular Multilevel Matrix Converter MMMC that is also used this word is also used. There is yeah, but going one step ahead we can also see that if we connect one more of this star cell. So, I can connect many more starts cells like this. So, I can also extend. So, one more here I can also do like this. So, A BCD and so, on.

So, in general I can say that an m phase two in phase system is possible yeah it is possible to do like that ok. So, this is also something which may be interesting for certain application ok. So, a three phase, two three phase possibility exists with MMC.

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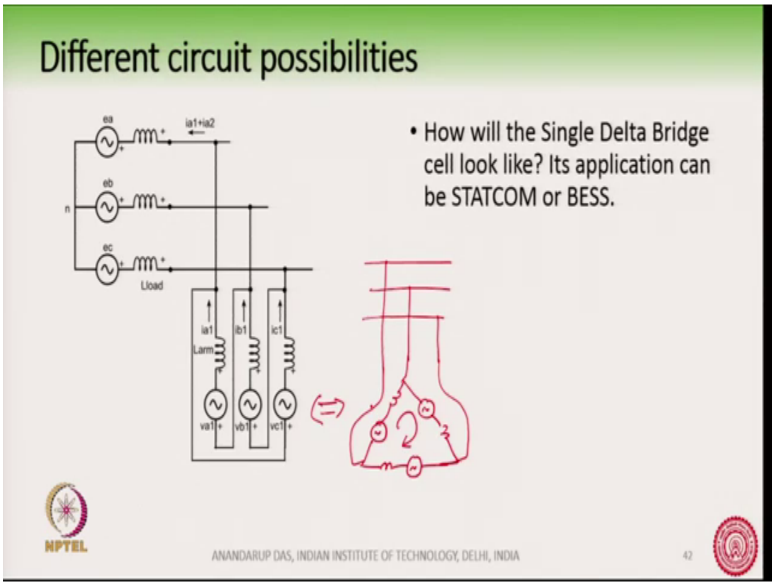

So, far we were talking about only star connected cells how will it look like with the delta connected cell? So, this is what it looks like in a delta connected cell delta connected.

So, where do we use delta connected configuration? Sometimes we use it in STATCOM or energy battery energy systems ok. So, with the STATCOM. So, this is how you can also connect the MMC convert the arms in a delta connected. So, this is a delta connected system here. So, I mean what we have drawn here is something like this this is what is. So, this is the same thing I am drawing it like this is the same thing which I have drawn. So, this is the delta connected system the same thing these are same.

One feature of the delta connected system is that you can have a circulating current flowing inside the delta which may be useful when you have to compensate unbalanced loads for example, in a STATCOM application. So, this can be kind of like a delta connected STATCOM ok.

You can similarly have multiple delta connected systems that is also possible like double delta, triple delta that is also possible, but all these features I mean we have to see what are the unique advantages of going into such topologies what is what is exactly the advantage that we get. One advantage is always there for MMC is that we use modular low voltage devices, but connect many of them connecting together to produce a controllable high voltage source that is the inherent feature of MMC.

Now, how do we play around with that? How do we play around with these controllable voltage sources is how we make different topologies suitable for different applications ok. So, that is what is something interesting about an interesting and also unique feature of the converter.

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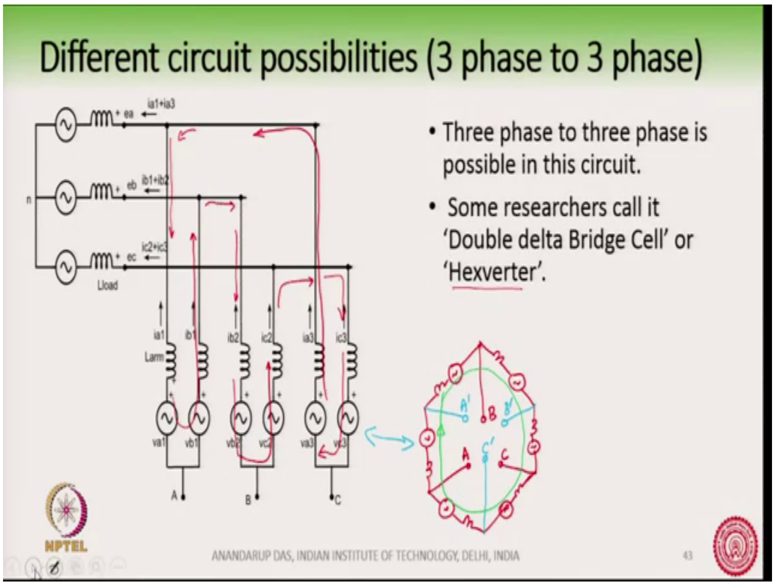

Now, another variant is possible this is called double delta bridge cell and sometimes it is also known as a Hexverter ok. So, this is also possible to have a three phase to three phase circuit. So, as I told you like you see this circuit is. So, basically we are giving a circulating current path in this double star bridge cell sorry double delta bridge cell.

So, how does it look like? See earlier there were three cells connected now we are connecting two, but it is connected in a slightly different fashion. You see this is one the upper see the upper arm and the lower arm ok. So, the upper arm and the lower arm and the upper arm and the lower arm for each phase, but there is a circulating there is a path for the circulating current because remember the circulating current must flow inside the convertor to maintain the energy balance.

So, the path of the circulating current is something like this going like this. So, this is the circulating current path goes like this, goes like this, like this and goes like this this and then again goes back, sorry I have done mistake not like this not this one it does not go back here. So, then and then it goes back through here, through here and through here ok. So, this is the path of the circulating current.

So, here also what is the advantage here? In this earlier version we had 9, we had 3 plus 3 plus 3 total 9 controllable voltage source or 9 arms that we had to do ok, but here in this configuration we have 6; 6 controllable voltage source or 6 arms and in with this 6 arms it is possible to have a three phase to three phase converter. Another way of kind of like another way of drawing this circuit that is why this term Hexverter came another way of drawing this circuit is something like this ok.

So, you see there are several ok. So, you can have 1, 2 and 3 this is the one AC system and the other AC system is like this ok. So, this is the same circuit these two are same circuit, but I am again drawing it in a different fashion. So, you can clearly see the A B C and A dash B dash C dash system connected through the converter that is why this is typically looking like a Hexagon. So, the author who had proposed first it called it as a Hexverter.

So, and you have a you see there is a there is a path for the circulating current here, this is the circulating current which will be flowing. So, this is the circulating current which is flowing through the six arms ok. So, this is also possible with such a converter three phase to three phase conversion.

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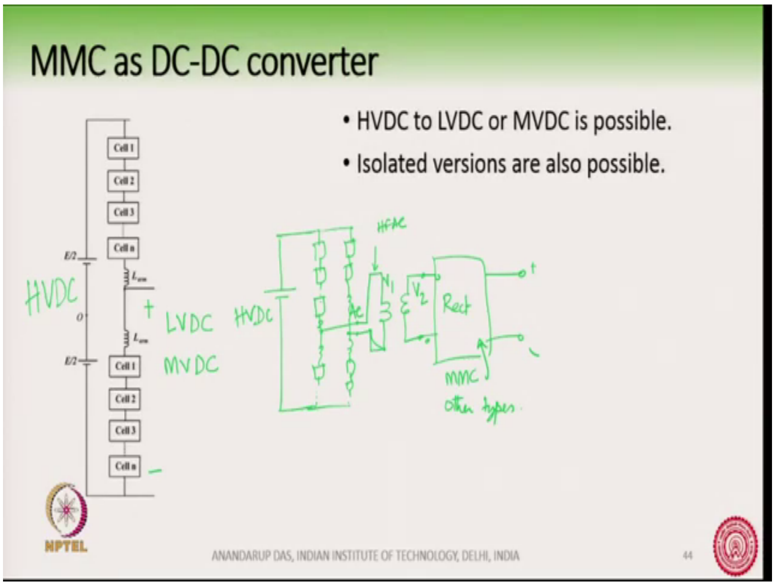

Now, what about DC to DC? In fact, yes MMC is considered to be a very promising solution for DC to DC conversion now why DC to DC? Because if you have something like an HVDC transmission system and you have some renewable energy sources which is close to this HVDC and suppose you want to inject the renewable energy source directly into the HVDC grid or you have a load and the HVDC line is going you want to tap, some little amount of power from that HVDC into the local load ok.

Often it we often it is found out that sometimes the HVDC lines are going through remote places where the grid is not so, means there are places where the power is flowing through HVDC line, but the local loads do not get the grid is far off from there ok.

So, in India it happens many times that the HVDC line is going through a remote area, where there is a possibility of lot of solar energy generation or hydropower generation. If we can directly integrate these energy sources into the HVDC grid something called as an HVDC tap, then it may be very very useful we can directly connect that energy source into the HVDC grid.

So, such a thing. So, then we need a DC to DC converter we need a DC to DC converter for suppose this side then becomes an HVDC and this is an LV DC or MVDC medium voltage or low voltage DC it is possible ok. So, again we use these controllable voltage sources or cells in such a way that as if like we are taking one let us say its very similar to the voltage divider circuit ok. So, we get. So, this is one HVDC and this is what we get a fraction of this one fraction of the DC voltage.

So, isolated versions are also possible. So, isolated versions means say suppose you have this HVDC and then you have a large number of cells and there is also. So, there is an arm inductor and then there are number of cells like this and you can have like this and you can have a high frequency transformer here, you can have a high frequency transformer and then.

So, what this is doing? This is doing this is DC and here you get a high frequency AC high frequency means say because this is at a very high power level. So, high frequency means instead of 50 Hertz we may go to 400 or 500 Hertz ok. So, because this will be producing a high frequency AC here 500 Hertz AC, which we pass it through a transformer get the isolation and here then we convert it back we will have a rectifier either we can. So, we will rectify it here and we get the DC here right.

So, this rectifier can be MMC, it can be other types of converter because the voltage here may be less it can be MMC or other types this rectifier here. So, and we got this this side voltage this is V 1 and this is V 2 these are also possible. So, you see here that what I want to stress yeah.

So, we will see this. So, what I want to stress here is that a large number of possibilities exist a large number of possibilities exist when the MMC blocks or MMC cells are used and the way to analyze it is to think like these cells working together are controllable voltage source and these controllable voltage are picked or controlled or manipulated in such a way we get in such a way that we get the desired output from the converter ok.

So, you can convert AC to say one AC frequency to another AC frequency convert from single phase AC to three phase AC, convert from AC to DC, DC to AC even DC to DC also. So, that is why the possibilities with this converter is huge and so, people are very much attracted to this topology.