High Power Multilevel Converters – Analysis, Designs and Operational Issues
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Lecture – 18
Modular Multilevel Converter – Topology and Operation

Welcome to this lecture on Modular Multilevel Converters. So, we have earlier seen the cascaded H-bridge converter as the first multilevel converter we studied that and now, we are going to study the modular multilevel converters. In short this converter is called MMC – Modular Multilevel Converter.

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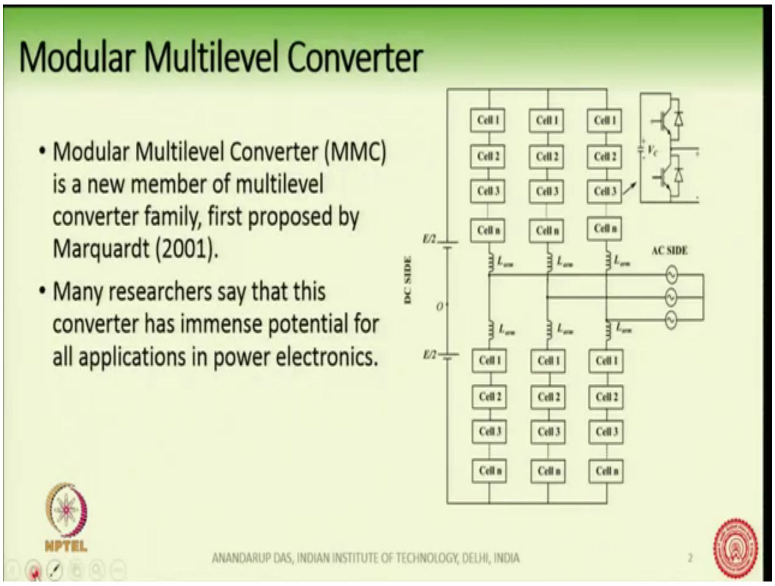

So, this right hand side picture is the circuit representation of MMC. And like the cascaded H-bridge converter also we can see that this converter has many cells which are connected in cascade or in series.

So, here you can see that for example, cell 1, cell 2, cell 3 up to cell n; these are all connected in series ok. So, the principle of this series connection of low voltage cells, in order to produce a high voltage is also applicable for the MMC. We will see this topology in details, but let us first see that the history of this converter.

It was first proposed by professor Marquardt in Germany in 2001 or around 2001. And thereafter, the kind of like the converter immediately was not so popular and there were hardly any publication or any research articles on this converter. However, one company it was in the process of they saw the potential of the converter and they started plans to commercialize it.

And, around 2007 – 08 during this time, based on this converter the first high voltage DC transmission was commercially launched and when it was launched then there was a lot of enthusiasm and there was a lot of activity on this converter. And, then people started realizing that there is a lot of potential and benefit of this particular MMC, a Modular Multilevel Converter and after that within a span of 7, 8 years or 9 year there has been a lot of work, which has taken place on this converter.

And, if we search for example, in some online say I triple E database we find a thousands of articles on MMC or its derivatives. And, it is not only confined to high voltage DC high voltage DC applications, but it is also used or it is proposed to be used in other grid connected applications for example, integrating PV or battery systems or it can be used also for motor drive applications and so on. So, this converter once we study we will understand that it has immense potential for many applications in power electronics.

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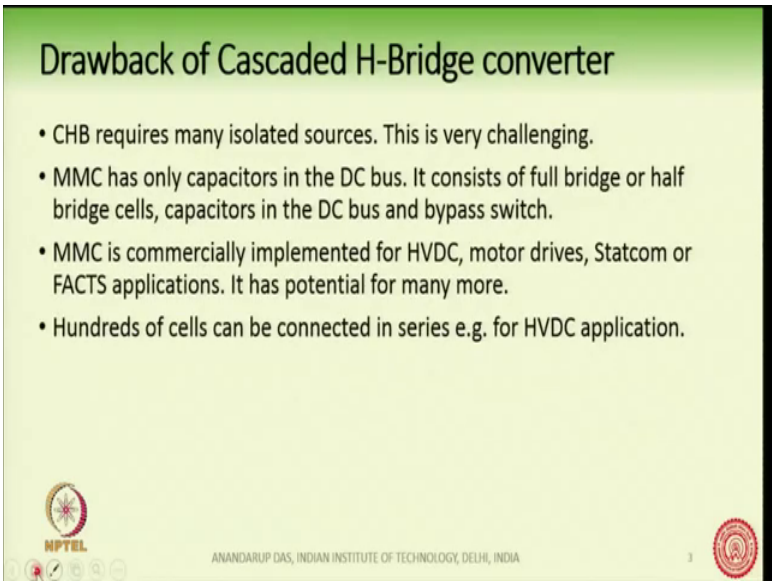

Now, before we go into the MMC, let us first understand that the drawback of the cascaded H-bridge converter. As we had studied earlier we found out that cascaded H-bridge converter is a kind of like quite it has many advantages, it has very unique features. For example, using low voltage devices we can connect many of these low voltage devices in series or in cascade and then we can reach a very high voltage. And by using proper PWM techniques we can achieve quite a nice sinusoidal waveform at the output.

And, also there was a fault tolerant feature; I mean you can bypass one of the faulty cells and can still run the converter. Although the cascaded H-bridge has these advantageous features, but there is a big drawback what is a big challenge? And the challenge is that, the cascaded H-bridge converter requires many isolated sources. The DC bus of each edge bridge is isolated from the DC bus of the other edge bridge. So, we had seen that we make a several transformer second bridge we use several transformer secondaries in order to make this isolated DC bus of cascaded H-bridge converter.

So, there was a need to remove the requirement of this isolated DC sources and here comes the MMC ok. So, MMC does not require any isolated DC source or these transformer fed DC sources. It has only capacitors in the DC bus. At the same time, it retains the advantages of modularity and scalability; which means that many cells many there are many identical cells in MMC like in CHB and all these identical cells are low voltage rating. And they are many of them are cascaded and they can produce a very high voltage.

So, the advantage of CHB is retained in MMC, but at the same time the requirement of this isolated DC sources that requirement is removed. So, MMC has only capacitors in the DC bus and the cell structure of the MMC consists of either half bridge or full bridge like the CHB also it has a bypass switch. So, if one of the cells is faulty it is possible to bypass the faulty cell and can still run the converter without shutting the shutting down the entire converter. You can bypass the faulty cell that is the faulty half bridge or full bridge cell; you can bypass it and can still continue to run with the. So, the fault tolerant feature is also present in the MMC like in CHB.

So, it is commercially implemented for HVDC, motor drives, Stat com or other types of FACTS application. And, as I told you many researchers and people in the industry say that it has potential for many more applications in future.

Now, in cascaded H-bridge, we have seen cells being connected. Now, when we talk about HVDC application for which MMC is very suitable we are now talking about hundreds of cells connected in series ok.

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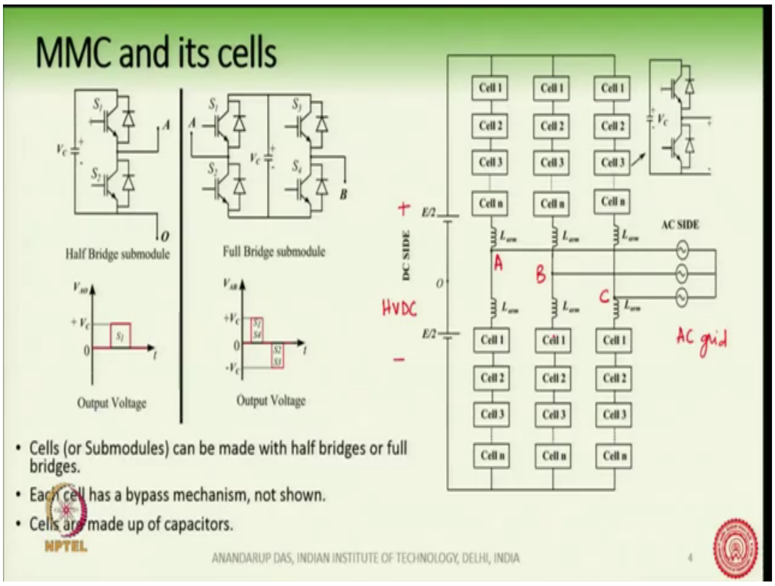

So, in HVDC application for example, at plus minus 400 kilo volt and say 800 mega Watt of HVDC application, we can connect hundreds of cells in cascade in an MMC converter. So, we can now see that this arrangement of series connection of cells is not limited to just a few cells connected in series. We can have hundreds of cells connected in series and so, the concept of modularity scalability is very much applicable for the MMC application.

So, let us now see what is the converter structure and before we go into the converter structure we first see the cell. So, MMC, the basic structure of MMC is made up of cells ok. There can be hundreds of cells working together. So, what is there inside one cell? Inside one cell you can see here the cell can be two varieties of cell. Usually there can be two varieties of cell –one is this half bridge sub module, another one is full bridge sub module. Cells are also called sub modules, they are interchangeably used. So, you can say half bridge sub module or you can say half bridge cell.

So, this is one cell structure one possible variety or variant of the cell structure. So, this is half bridge and this is full bridge ok. This is the full bridge cell. Now, so, in case of a half bridge cell we see that there are 2 IGBTs like this which of course, are complementary in nature otherwise it will short the DC bus. And, there is a this DC bus is formed of capacitor.

So, there is only one capacitor here ok. So, there is no isolated DC source which is connected to the DC bus of this cell. In a similar fashion for the full bridge sub module we have a capacitor here and there are four such switches. In the half bridge sub module this point A and O are the two ports of the cell. Similarly, in the full bridge variant A and B these two are the two ports of the cell or two terminals of the cell.

Now, if we see this half bridge module sub module, we can see that if we turn on S 1 the output voltage is that is v AO if we see the terminal voltage as v AO or the it is called the output voltage v AO. If I turn on switch S 1 then v AO is equal to v c; if I turn on S 2 then v AO is equal to 0 and this is shown here in this waveform that v AO if I turn on S 1 then I get v AO as v c that is the capacitor voltage is obtained at the output v AO. When I turn on S 1 and the of course, if I turn on S 2 then I do not get any voltage.

On the other hand, for the full bridge sub module if I turn on these two diagonal switches S 1 and S 4 then the voltage v AB is equal to the DC bus voltage positive DC bus voltage that is plus v c. On the other hand, if I turn on these two diagonal switches here, then I can get a negative vc minus vc voltage on the output. And, if I turn on the S 1 and S 3 or if I turn on S 2 and S 4 then I get 0 voltage at the output. So, this MMC the cell can if it if we use half bridge cells, then we get two levels of voltage that is 0 and v c. Whereas, if we use the full bridge cells full bridge variety then we can get three levels of voltages at the output plus v c 0 or minus vc.

Now, each cell what is shown here also has a bypass mechanism. It is not shown here right now. We will discuss this bypass mechanism sometime later. What is the bypass mechanism?

The bypass mechanism is like there is a bypass switch like this which will be activated when we want to bypass the cell; if there is a for example, a very severe fault inside the cell and it is no longer usable then we can bypass that cell and without shutting down the whole converter. This bypass mechanism is not shown here, but we will discuss it sometime later.

Now, so, this half bridge and full bridge sub modules are present in half bridge, either half bridge or full bridge variety can be used. So, inside this inside this cell 1 or cell 2 or cell 3 inside these cells either the half bridge or the full bridge is used ok. When do we use half bridge and when do we use full bridge, we will understand it a few slides later. But, let us take the simpler case let us take the half bridge.

So, if we take the half bridge variety so, each cell like this is made up of half bridges ok. So, many of these cells so, there are n number of cells and the total n number of cells this number n can be more than 100; for example, for high voltage DC transmission. So, in the plus minus as I told you plus minus 400 kilo volt, the number n can be more than 100 ok.

If we look at the structure of this converter now, we see that these n number of cells are connected in series and 6 such ah. So, this is called one arm of the converter where suppose we take the half bridge variant. So, n number of half bridge cells are connected together to form one arm of the converter. Similarly, we have we have an upper arm and we have a lower arm for any phase. So, suppose we have the AC side here. So, this is A phase, this is B phase and this is C phase.

Say for example, this is A phase, this is B phase and this is C phase. So, the AC is AC A phase, B phase, C phase is connected like this and. So, in each phase we have an upper arm and we have a lower arm and in each arm we have n number of half bridges. So, B phase is like this and C phase is like this and here we get the DC ok. For example, this converter if I think of an HVDC application, then this side becomes HVDC, here this is the plus and this is the minus of the HVDC and then this is the AC grid here. Is the AC side – A phase, B phase, C phase and the converter is connected in this fashion with 6 arms A phase, B phase, C phase we six such arms and each face has two arms upper arm and lower arm.

Now, there is also something which is called the arm inductance present here. Here you can see there are 6 arm inductors corresponding to each arm of the convertor. The arm inductor has a lot of functions. It can control the circulating current inside the arms and it can also limit the short circuit current in the event of a short circuit on the DC side. We will talk about the arm inductors little bit later ok.

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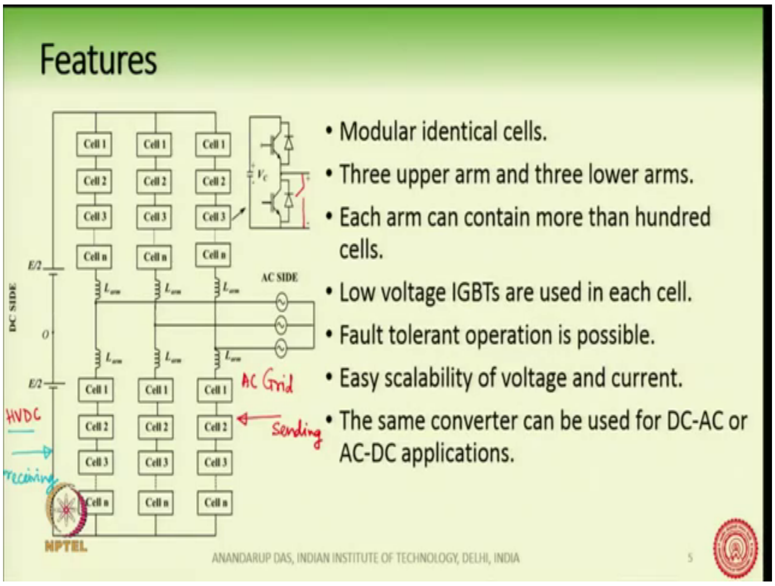

So, if I now see the features of this converter, we can see that the converter has many modular identical cells. So, each of this cell is a half bridge which is one of the most simplest structure in power electronics and each cell has a DC bus which is made up of a capacitor. So, there is no need for any isolation. Switch – each cell has its own capacitor. It has two switches and it has a bypass feature which is not shown. Actually in this particular diagram we have not shown the bypass feature, but the bypass feature is present here.

Now attractive feature of MMC is that we can have low voltage for example, low voltage transistors or low voltage IGBTs, they can be used in each cell. So, as I said that if the DC side here is plus minus 400 kilo volt, then we may use many many low voltage IGBTs inside these cells. For example, 3.3 kilo volt or 2.5 kilo volt IGBTs, but many of them inside each cell say this cell has 2 IGBTs. So, and each IGBT can be rated for say 3.3 kilo volt ok, but since many of these cells are connected in series. Therefore, we can get to a very high voltage ok.

And, the other feature of this is the fault tolerant operation, where the faulty cell can be bypassed. And also we see one of the attractive features of this converter is the easy scalability of voltage and current; which means that say if I want to have a higher voltage we can connect more number of cells in series so as to get a higher voltage. For example, we have a plus minus 400 kilo volt application and then we use certain n number of cells, but if another in another application if we have plus minus 200 kilo volt requirement, then we can reduce the number of cells.

Another unique feature of this converter is that it can be used as a DC to AC or an AC to DC application. So, for example, as you can see here in this circuit diagram you can see that the if this is the grid available to me then with the help of this converter I can HVDC side here ok. So, then the power will flow from the grid into the HVDC line. From the AC side suppose we suppose want to send power from the AC grid over a long distance via high voltage DC transmission we want to send the power to another grid.

So, then the power flow is happening from this AC grid here through the HVDC line. On the receiving end this is the sending end topology on the receiving end we get the HVDC so, this is the sending end. So, this is the sending end, but on the receiving end we have the DC voltage available from which we would like to get back the AC. And so, the same converter so, in the on the receiving side we have the HVDC available to us and we can use the same converter to connect it to the existing grid on the receiving side and then the power will be flowing from here to here ok.

But, you see the same converter same converter can be used. So, we can send power from the AC side to DC side say at the sending end and an identical converter can be used at the receiving end. So, this is the receiving end, the identical converter can be used, which will convert that DC into AC and the power will flow from the DC to AC. So, this is one of the advantages of this converter.

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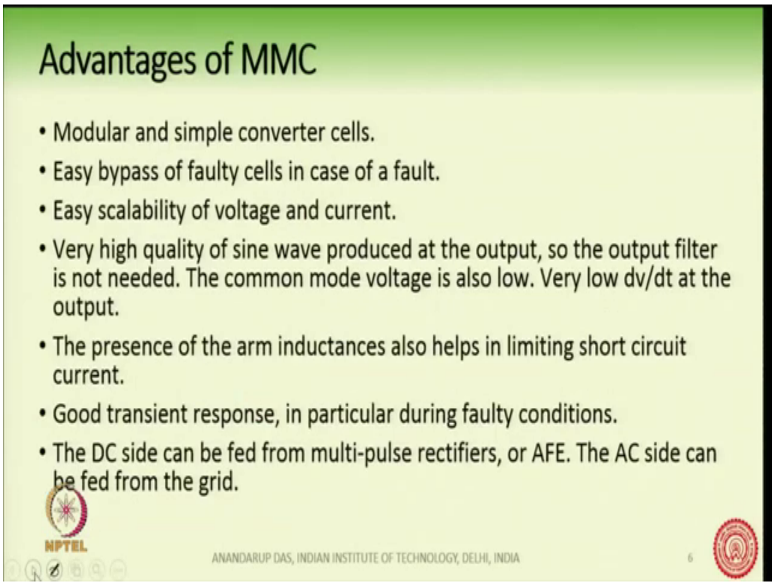

So, just summarizing the advantages of the converter. It has modular and simple converter cell like a half bridge bypass of faulty cells is possible easy scalability of voltage is possible and very high quality of sine wave is produced at the output. This we will see in the next slide how the sine wave is produced.

So, if it if we are making say AC to DC converter or a DC to AC converter then a very high quality of AC waveform can be used by using these cells in with the help of pulse width modulation. The common mode voltage is also very low and very low dv dt at the output because now the step size on the voltage waveform is very very small because we are using hundreds of cells. So, the step size so, each cell I mean the step size on the waveform AC waveform becomes very small, we will see that.

And, the presence of arm inductance also helps in limiting the short circuit current. So, this is very advantageous because suppose we are converting AC to DC and the DC we know that DC circuit breakers are not easily available it is very difficult to make a DC circuit breaker. So, the arm inductors actually help in limiting the rate of rise of current when there is a fault on the DC side; because the when there is a fault on the DC side the current will flow from the AC side and will feed into the DC faulted DC and at that point of time the arm inductors help in restricting the rate of rise of the current from the AC side into the DC side ok.

It has good transient response; the MMC is a good transient response during fault condition also and so, the DC side can also be fed from a multi pulse rectifier in case we are going for a DC to AC application. For example, for motor drive application if the DC is available that DC can be generated from a 12 pulse rectifier and then there can be several cells and we get an AC output which can be fed to a motor drive application ok.

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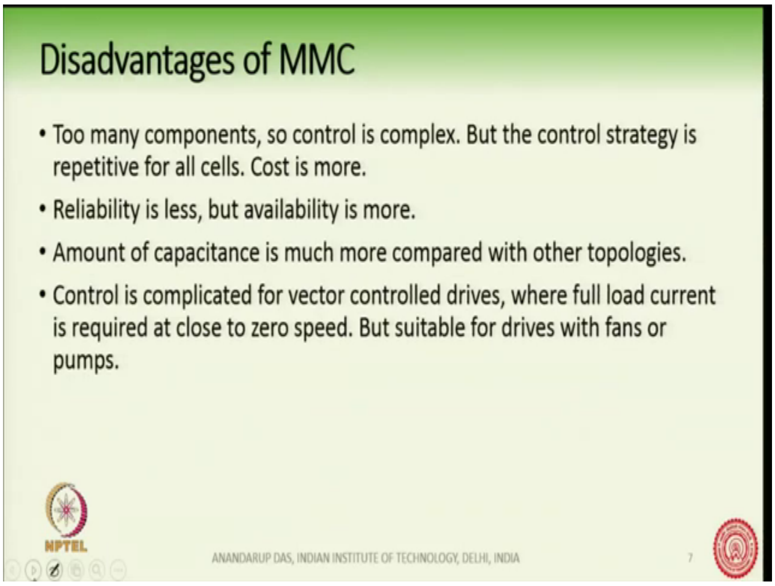

Now, although MMC has many advantages which we discussed. There are in fact, certain disadvantages there are too many components ok. So, the control is complex however, the control strategy is repetitive for all cells ok. So, same control strategy gets on repeating for all the cells and of course, the cost is more because now we are using many many half bridges. Each half bridge has it is own gate driver has it is own protection mechanism and so on.

But, this cost is something which we must be careful; because whenever we talk about cost there is of course, something like a running cost and something like an initial development cost or initial cost. Now, MMC has a very high initial cost because the converter building the converter testing it and making it working so, it is a very high initial investment. But, at running condition the efficiency of MMC which is you may be surprised to know is very close to or even more than 99 percent the running efficiency of MMC.

So, the running cost or the losses are less in MMC and so, it is advantageous when we talk about the operational reduction of losses. Reliability is less in MMC definitely because we have many many components and so, with many components the reliability goes down, but availability is more. So, if we have many cells then the availability so, if we can bypass some of the cells then availability is more.

The other disadvantage of MMC is the amount of capacitance. The although each cell has it is own DC bus and it is made up of capacitance, but the magnitude of capacitance required in MMC is much more compared to other topologies. We will see one more topology later for example, Neutral Point Clamp Converter NPC; as compared to NPC the amount of capacitance required in MMC is 3 – 4 times or even more. So, that is one of the drawbacks of MMC.

The control is also complicated for vector control drives where full load current is required at close to zero speed. This is one of the drawbacks, but there is an active research going on when the motor is running at zero speed how do you control the converter with full torque on the motor, but MMC is quite suitable for drives with fans or pumps which do not require full load torque at start at start up.

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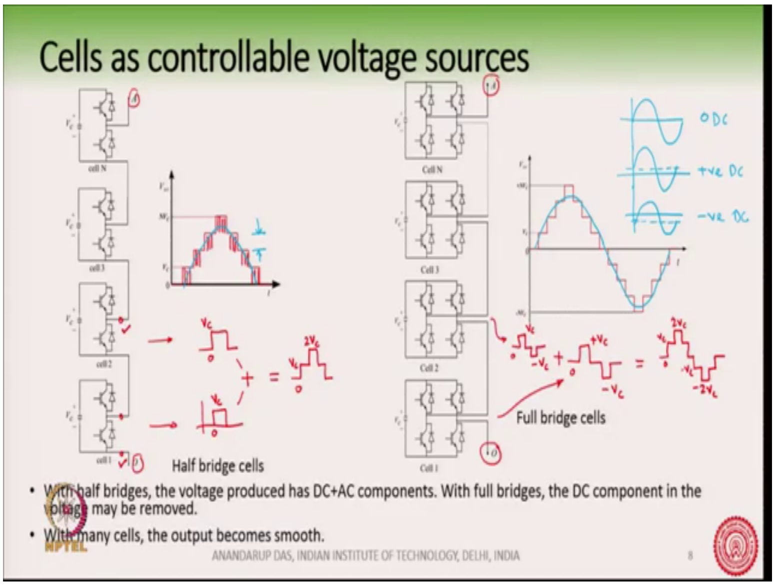

Now, we see how we can understand the operation of the converter and how can we analyse because you see with so many cells connected it becomes a little bit tricky and difficult to understand like how all these cells are going to be controlled it little bit challenging. But, fortunately if you understand the operation of the cells and how they are connected in series it is not a difficult task ok. So, let us see how we understand this.

So, here on the left we show you that one arm of the converter with n number of cells in half bridge configuration, on the right hand side we show the n cells in an arm of the converter, but they are now connected in full bridge configuration. So, we will analyse both of them together ok. So, for example, if we take let us take the half bridge configuration first it is easier to understand.

So, with one cell let us with this one cell here as we told you the output of the cell can vary between 0 or v c; 0 means when the lower switch is on so, then we get 0 voltage at the output 0 voltage here and this is the output of one that is cell 1. So, if the lower switch is conducting then we get 0 if the upper switch is conducting then we get a voltage of vc.

So, the output of the first cell can be kind of like written like this drawn like this ok. Similarly, the output of the second cell can be drawn like this also independent of the first one. So, the output here will change from 0 to v c and here again 0 to v c assuming that all the all the cells have the same DC bus voltage vc.

Now, when we series connect them that is when we cascade them so, the two voltages get added up and so, these two voltages get added up what we get like this 0 v c and 2 v c ok. This much this voltage we will get between this point here and this point here between these two points we will get a voltage which is going like 0, v c and 2 vc. So, similarly if we have n number of such cells connected in series then we get a voltage which is something like this here 0 v c, 2 v c, 3 v c going up to n v c ok.

So, of course, so, therefore, by using these low voltage devices and low voltage cells we can get to a high peaky the peak voltage in v c can be quite high if n is very high if there n is for example, 100 then we can go up to 100 v c that is quite a high voltage which can be obtained between the point A and O, there is the arm the arm voltage can be quite substantial in magnitude when the number of cells is quite large ok. Of course, we can also control this voltage by using pulse width modulation here this is not shown, but by using pulse width modulation it is possible to minutely control or vary the amplitude of the v AO voltage.

In fact, with n very large we can get a nice sine wave from the arm of the converter ok. See very nice and quality of sine wave can be produced because if n is large this step size here this is the step size of each the size the height of each step in the waveform, when n is very large the size becomes very small for a fixed magnitude of the AC voltage. So, if n becomes very large, then the wave form automatically approximates to a sine wave ok. So, that means, suppose this is the sine wave, we are we are actually getting very with large value of n; we are actually very close to a perfect sine wave as you can see here.

A very nice quality of sine wave can be produced if n is very large ok. So, this is one of the advantages of the converter. Now, in this particular case, we can see that between A and O the voltage that can be produced can vary between 0 and n v c; that means, the voltage produced has both DC and AC component ok. There is a DC component here because the voltage is between 0 and n vc there is a DC voltage inside it and whatever AC we want to produce can also be embedded inside that. So, this is what happens with a half bridge.

On the other hand, if we see the full bridge full bridge as we have earlier said can have full bridge can have three levels of voltage that is 0 each cell can be plus v c and minus vc. So, suppose this cell produces this voltage here this cell here can produce the same voltage independent of the first one. So, it can also produce 0 vc and minus vc ok. Now, if you add both of them when you are cascading them, then what you can get? You get something like thi,s 0 v c, 2 v c and then again minus v c and minus 2 v c ok.

So, therefore, if you have n cells in cascaded fashion then you can get such a kind of wave form at the arm. Now, this wave form of the arm voltage for a full bridge configuration which is coming between the point A and O here, this waveform can have 0 DC ok. The DC component can be 0. As you can see from the waveform itself the full bridge variety or the full bridge variant can have 0 DC and a full AC. So, the AC waveform is embedded here. So, this is the AC waveform embedded here ok.

The full bridge can produce a DC, it is not that the full bridge cannot produce a DC it can produce a series DC, but that DC magnitude can also be 0. So, the full bridge variety can produce a voltage waveform which is like this ok. But, it can also produce a voltage waveform which is like this with a DC value which can be positive or negative also. So, it can also produce a voltage like this depending on the rating of the arm. So, this is a DC, this is a positive DC and this is a negative DC ok.

So, the full bridge variety is more flexible in that regard, but this DC is definitely present in case of a half bridge, we cannot avoid the DC in case of a half bridge. But, we can avoid the DC in case of a full bridge or we can have the DC in case of a bridge variety. So, whatever may be the case whether we go with a half bridge or full bridge what we understand is that with many many cells connected in series, it is possible for us to approximate the arm voltage as very close to a sine wave within very large value ok.

We can see here from the even with like 4 or 5 steps in the waveform that I have shown on this waveform, even with 4 or 5 steps we can see that we are approaching closer and closer to a sine wave ok. The sine wave can have a DC component the sine wave will must have a DC component in case of a half bridge, but in case of a full bridge it may have a DC component ok.

So, with this understanding of the arms, arm voltages let us analyse the converter.

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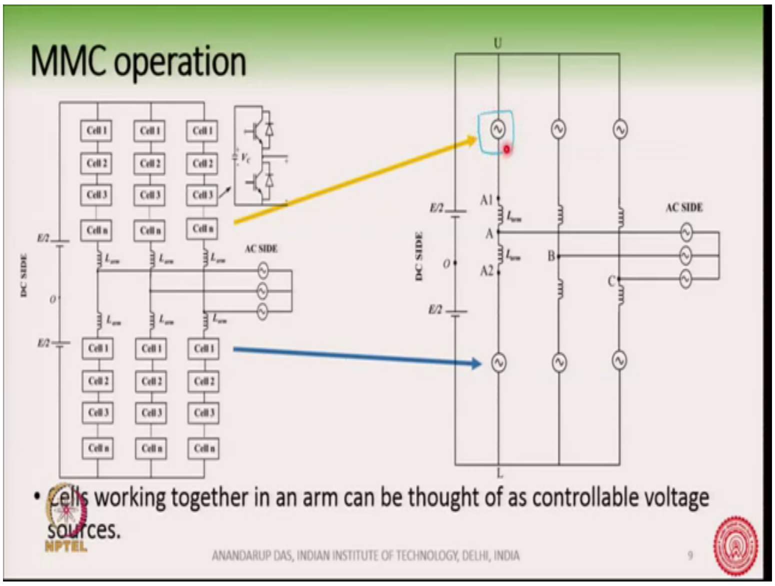

So, what we do here is that suppose we take again the simpler case we take the half bridge variant. Let us start with the half bridge and see how the MMC circuit can be modelled ok. So, you see here this all these cells as I told you when all these cells are connected they just like the previous we can say that this arm voltages can be assumed to be a controllable voltage source ok. Depending on how you place the cells how you place the waveforms we are basically generating a controllable voltage sources. So, the arm voltage is a controllable voltage source.

And, the control algorithm will decide what type of a controllable voltage source we are producing. In fact, we are producing a sinusoidal controllable voltage source from this converter. And, so, this arm here this arm is now replaced by this controllable voltage source here ok. So, this voltage source is representing the arm voltages. So, they are now you can see there are six such controllable voltage sources which are these are the six controllable voltage sources which are working together ok.

This these six controllable voltage sources are completely independent of each other. So, this is something which is unique for this converter like there are six controllable voltage sources which can be controlled independent of each other and of course, we will see how to control them so as to create AC or DC ok. So, on this side we have the AC and we on this side we have the DC.

Now, in case we use a half bridge in this controllable voltage source must have a DC component as we had seen in the last slide. The controllable voltage source here in case of half bridge will have a DC and an AC component whereas, in case we use a full bridge, we may have the DC component and we may not have or we may not have the DC component we can make the DC component 0.So, let us see only the half bridge configuration.

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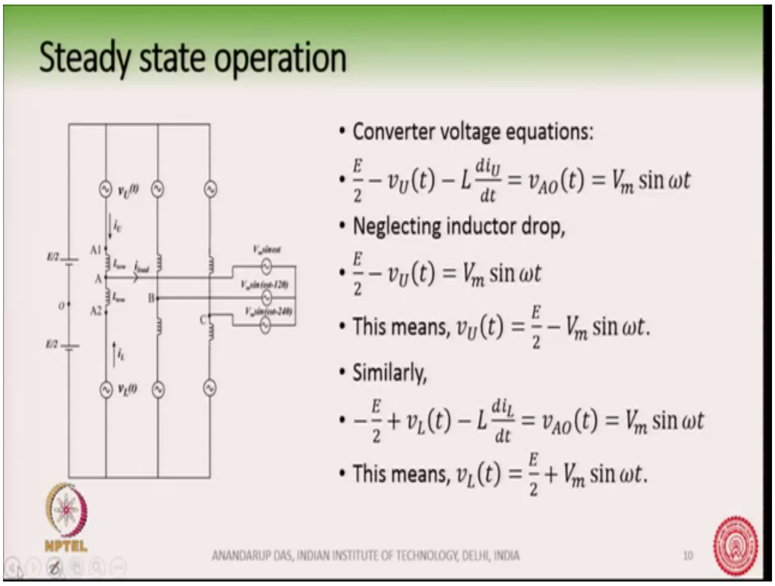

So, when we see the half bridge configuration then we can. So, we can we this controllable voltage sources we can now write the Kirchhoff's voltage law and can find out what is the magnitude of this controllable voltage source ok. What is it is magnitude, how is it related to the AC side and the DC side voltages how they are related with the controllable voltage source magnitude. So, this is shown by this mathematics here. It is easier to understand if we have a DC and we are trying to convert it into AC ok.

So, we will start with the DC to AC converter analysis and later you will see that it is the same analysis when we can do from AC to DC side. So, suppose we assume that we have the DC available here and we are trying to produce an AC here, balanced AC ok. So, we have the DC and so, this is a DC to AC converter so, if I if this is a DC to AC converter I have we have the DC voltage available here, where the total DC bus magnitude is E and O point is the imaginary midpoint of the DC bus. In some cases for example, in bipolar HVDC transmission the O point can be physically excisable also, but for this analysis let us assume that O is an imaginary point here.

Now, from this circuit we can write the converter voltage equations. So, I can write it here say so, if I go Kirchhoff's voltage law. So, E by 2 minus v U so, if I put this as the plus here. So, E by 2 E by 2 minus v U minus L di dt is the points voltage a with respect to point O this is what is written here E by 2 E by 2 minus v U that is the upper arm voltage v U stands for the upper arm controllable voltage source v U is the upper arm controller voltage source. So, E by 2 minus v U minus L di dt L di dt is equal to v AO t ok. So, for phase A, fine.

And, let us assume that this v a voltage AC voltage which we want to produce is given by V m sine omega t ok. So, we are talking about a DC to AC converter where the DC is available to us and we are trying to produce a controllable AC at the AC side. So, this is the governing equation here which is written here. So, if then if I neglect the inductor drop then I can simplify this equation and write E by 2 minus v U t is equal to V m sin omega t, I just neglect the L di dt drop.

Now, this is a fairly good approximation. We will see some example later where you will see that the inductor size is pretty small and the energy stored in the inductor is under steady state it is pretty small. So, it is a fair approximation to have this L di dt under steady state to be quite small ok. So, neglecting this inductor drop, we can write E by 2 minus v U t is equal to V m sin omega t ok. So, then this means that v U t is equal to E by 2 minus V m sin omega t ok. So, this is the equation of the upper controllable voltage source ok.

So, as I said this is the upper controllable voltage source which is like made up of like this many cells connected in series and this is what we had made the upper controllable voltage source is made like this. So, its mathematical representation is given by this equation here v U t is equal to E by 2 minus V m sin omega t right. So, this is the equation of the upper controllable voltage source in phase A. In a similar way, like we have shown for upper arm of phase a we can also write for the lower arm of phase A and then we see that minus E by 2 plus v L. So, I should write this plus v L here.

So, minus E by 2 so, this is what the equation says minus E by 2 plus v L minus L di dt is equal to v AO t going from the bottom side and then it is also equal to V m sin omega t, the A phase voltage. And again if I neglect the inductor drop here, we can say that v L t that is the lower controllable voltage source can be written as E by 2 plus V m sin omega t ok. So, this is the expression for the lower controllable voltage source, this is the expression for the upper controllable voltage source ok.

Now, you should note that the upper controllable voltage source where is v U and v L both of them have a DC component and an AC component ok. You see here there is a DC component and there is an AC component; here also there is a DC component and there is an AC component ok. So, this is consistent with our previous analysis saying that a half bridge as an arm which is made up of half bridges that arm will be generating a DC plus an AC and you can see here it is generating a DC plus and AC.

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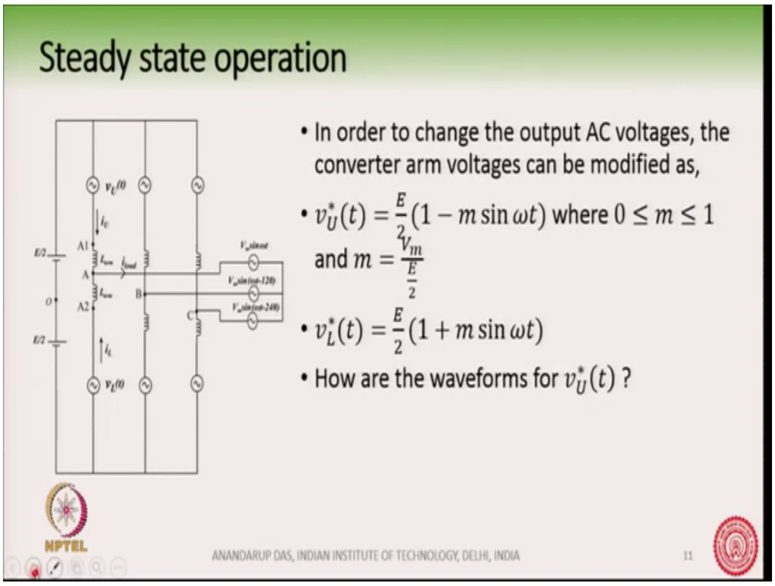

So, if we so, this is the controllable voltage that can be generated by the upper arm and the lower arm voltages. Now, how can I change the voltage here how can I change the voltage here? Of course, v U and v so, that V m voltage which is being produced by at the output of the converter has to be changed because we want to change V m ok. We want to get a variable output from the converter variable output voltage from the converter. For example, for motor drive application this is very much necessary and if we are going for say V by f application both the voltage and the frequency will also change.

But, anyway, if you want to change the voltage output then that V m which we were producing has to be changed and how do we do that, we say that the converter arm voltages can be written as v U star that is the control which is given to this converter voltage is E by 2 1 minus m sin omega t, where m is defined as the modulation index and is given as V m by E by 2. So, here there was a V m. So, we have taken V m as a fraction of a by 2 and it defining a new term modulation index m for the converter which is V m by E by 2.

And, this is what the upper and similarly the lower one the lower voltages are will look like. So, the earlier equation was something E by 2 minus V m sin omega t and we are defining a modulation index m as V m divided by E by 2; so that we write this equation here where m is a factor which is possible to change ok; m can change from 0 to 1 ok. And, so, the upper and lower voltages from the converter these two here can be changed. So, it is very easy to understand from waveforms.

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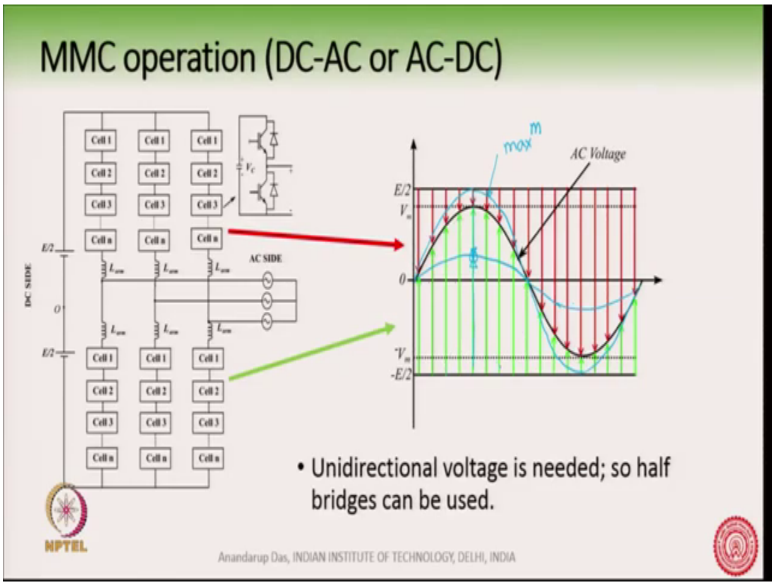

So, let us see the waveforms ok. Now, in this waveform whatever mathematical analysis we did has been now shown graphically. So, suppose this is the AC voltage which we are trying to produce this is the AC voltage you can see the peak of the AC voltage is V m here V m; the peak of the AC voltage is V m. On this curve, we also are showing the E by 2 and minus E by 2 with respect to this O point here. Here O point is here, E by 2 and minus E by 2 this is a zero point which has been assumed E by 2 here and E by 2 down there.

Now, if you see the voltage to be produced by the upper arm because it has to satisfy the Kirchhoff's voltage law. So, what it will do? See, the voltage produced by the upper arm is shown by the red arrows here. The red arrow denotes the instantaneous voltage produced by the upper arm ok. Why these red arrows are instantaneous upper arm voltage because if you see here you start from here you go E by 2 minus v U and of course, neglecting this L di dt. So, E by 2 minus v U is equal to V m sin omega t.

So, if you go on this waveform you go from 0 E by 2 minus V is what you get V m sin omega t here. So, this means that this red arrow is indicating the voltage which is produced by the upper arm ok. And, the magnitude is the instantaneous magnitude is changing with time here the arrow length is small whereas, here the arrow lengths are big ok. So, big in size here and this is exactly or this is consistent with the equations that we had written earlier, but this is just a diagrammatic representation.

What about the lower one? What about the lower controllable voltage source, this v L? v L also follows the Kirchhoff's voltage law and so, minus E by 2 plus v L is this without this neglecting the L di dt minus E by 2 plus v L is the V m sin omega t. So, if I go from 0 I go minus E by 2 and then this green arrows, these green arrows indicates the instantaneous magnitude of the lower arm voltage ok. It is varying with time it is minimum here and it is maximum here ok, fine.

So, this means that the lower controllable voltage is denoted by the green arrows and the upper controllable voltage is denoted by the red arrows. Now, one thing to note is that the AC output voltage can be changed in magnitude by changing the length of the arrows. So, for example, the AC output can be made like this also. Of course, under that condition this red arrow here will no longer be of such a length, but will increase up to this point and similarly, the green arrow will be up to this point ok.

So, therefore, we understand that the magnitude of V m magnitude of V m can be changed. And that is exactly what I was talking about the modulation index in the previous slide; that the modulation index is something which is in our hand ok; that means, the upper and lower controllable voltage sources can be adjusted in such a way that the AC voltage which is produced at the output of the converter at any point of time can be changed can be modified. So, it can be even made 0 you can make the voltage to be 0 also.

Now, how much voltage you can produce the maximum voltage that can be produced from the converter? The maximum voltage that can be produced is this much here, the maximum voltage can be produced like this here. So, this is the maximum voltage that is the maximum voltage which can be produced and at that point of time you can see that some of the arrows a few arrows are almost 0 in magnitude while some arrows here are getting to the peak or the length of the arrow is coming up to E ok.

So, the length of the arrow is E when the maximum voltage is produce and V m is touching this E by 2 ok. So, when this maximum happens that is the maximum voltage needed to be produced; maximum voltage of E needs to be produced from the arm under the condition when V m touches E by 2 here which I have shown by this curve. There is also one thing to note and that is all the arrows are unidirectional. So, all the arrows for example, for the red arrows are all pointing downwards.

You can see here all the arrows are pointing downwards well all the green arrows are pointing upward ok. So, the arrows are unidirectional in nature. So, half bridges can be used because in half bridge we only produce unidirectional voltage. So, we have seen now that the unidirectional voltage with the arms are producing unidirectional voltages and so, half bridges can be used.

Now, so far I was talking about MMC being used as a DC to AC converter. So, that is how we have analysed this waveform. But, now it is interesting to observe that if suppose I have an AC to DC application for example, the MMC is used as a rectifier in an HVDC application; then what do I need to do? In case I have to make or operate this converter as a AC to DC rectifier, then the AC side or the grid is available to me or available to us and I would like to produce a DC right.

So, therefore, in this waveform this AC voltage is available, it is present as the voltage from the grid; whereas, you would like to produce this DC voltage. And, during that condition what we have to do? We have to just flip the direction of the arrow, it is very simple. We just flip the arrow direction. So, in this waveform all the arrows are downwards.

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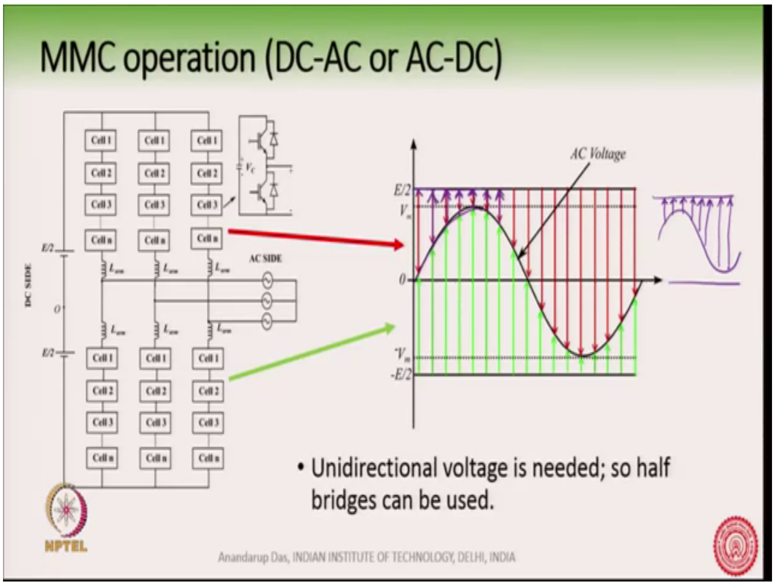

So, if I if I if this if this arrow waveforms are if the arrow wave arrow directions are made like this the opposite part like this, then if this AC voltage is available then it is possible that the DC voltage will be produced at the output of the converter. So, if we can flip the direction of the arrow, which means the controllable voltage source in the arms the controllable voltage source in the arms are now commanded to produce a voltage like this like this here.

So, it has now the reference has become opposite. So, since the AC waveform is available here and we are trying to produce a DC. So, the arm voltages are now commanded to produce such a voltage ok. Again, this is perfectly consistent with the equations of the arm voltages it is perfectly consistent you can check it up. So, this v U it is just that the polarity is reversed. And, still so, the advantage is that we are now producing or we can use this converter as a AC to DC converter and the same half bridges can be still used; because again the arrows are all unidirectional ok. So, the half bridges can be used.

So, the same converter; so, what I want to say is that by change of the control logic, the same converter can be used for AC to DC conversion or from DC to AC conversion as we can see from the graph. This is very advantageous and therefore, for long distance DC transmission where at the sending end you will convert the AC to DC and at the receiving end you will convert the DC back to AC and so, both at the sending end and the receiving end we can have the same MMC converter same MMC.

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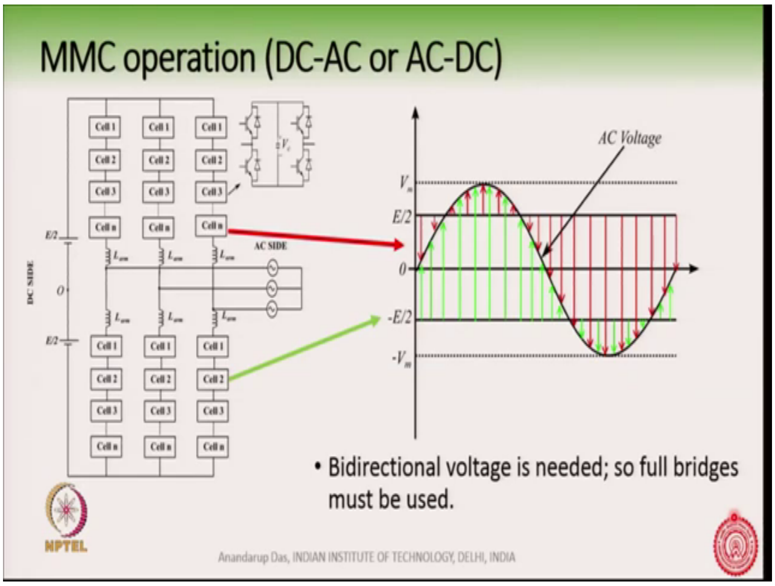

Now, an interesting thing that comes up next is what happens if the DC voltage suddenly becomes lower ok. Now, why can or when can this happen? This can happen for a variety of reasons. For example, if the MMC is used as a rectifier and due to some disturbance on the DC side the DC voltage has been reduced ok.

Now, if the DC voltage is reduced we have shown a waveform here. Now, if you observe this waveform here then you see that now the AC voltage is here and the DC voltage has a magnitude which is lower than the peak AC voltage right. Now, we observe the arrows ok. Now, when the DC voltage is here and more than the AC voltage, then the arrows are downward ok. What is this arrow indicating? The arrow indicating, the instantaneous arm voltage the red arrow is indicating the upper arm voltage and the green arrow indicates the instantaneous lower arm voltage.

Now, the upper arm in during this portion the arrow direction is downwards whereas, when the AC voltage is more than the DC, then the arrow direction is reversed. And, then again here the arrow direction is downward here the arrow direction is upward. For example if you observe the red coloured waveform the upper arm voltage. So, therefore, when the DC voltage becomes lesser in magnitude than the AC voltage, then we need bidirectional voltage from the arm ok. So, the arm voltage here is bidirectional in nature, sometimes it is positive sometimes it is negative right.

In this particular waveform, the magnitude of the upper or upward arrow and the magnitude of the downward arrow they are not same ok, but in any case we see that we need bidirectional voltage from the converter or from the arm of the converter. And, so, we must use full bridges in this arms; because a full bridge the difference between a full bridge and a half bridge is half bridge can produce only unidirectional voltage ok. So, if there are in half bridges so, 0 vc, 2 vc, 3 vc up to n vc that is what the half bridges can produce.

But, a full bridge can produce plus vc, 0 or minus v c; that means, a bidirectional voltage capability is present in a full bridge. So, if there are n number of such full bridges it can produce plus n vc to minus n vc. So, in this case we see that in this waveform, we see that the bidirectional voltage capability of the arm is needed when the DC bus has a magnitude less than the peak AC voltage. Again, this is again consistent with the equations that we have derived earlier v U t and v L t; if you put there, you will see that during this condition v U t has a bidirectional component ok. So, it can be plus or minus positive as well as negative.

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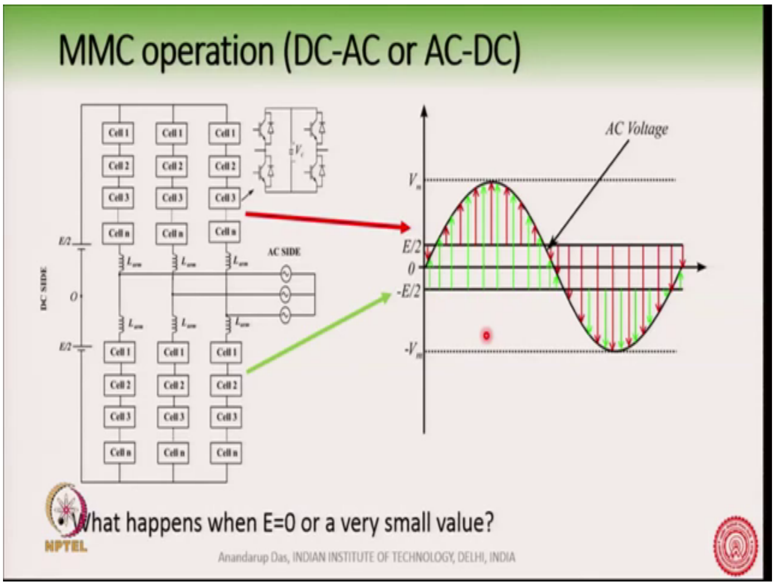

Now, what happens, if they go on reducing the DC voltage? This is something very interesting. If you go on decreasing the DC voltage like you can go up to E equal to 0 or a very small value, it is a possibility ok. You go on in decreasing what happens now? You see that the arrows of course, are changing in magnitude, if you compare this waveform with this waveform, the positive magnitude of the arrow and the negative magnitude of the arrow they were kind of like different in magnitudes and unequal.

Now, when as E becomes closer to 0, then these two magnitudes of the arrows are becoming almost equal and the converter can actually still work right. The converter the arm voltages can still or support this condition ok. Now, when does this condition happen that is E becoming 0 or a very small value when will it happen? It will happen during the during a short circuit on the DC bus ok.

Say for example, we have an HVDC line and we have a pole to pole fault bipolar HVDC line, we have a pole to pole fault, this is a condition where E becomes 0 or a very small value ok. So, this is the condition but, during this short circuit fault when E has become close to 0, then also this converter can support in fact, the armed voltages during this condition are shown here on this diagram. And, you can see that the converter can still work during this short circuit condition.

And, it is as if during this time the armed voltages are as if you can think of it something like a back emf ok. So, the grid is available there is a short circuit here the AC side is available and the armed voltages are basically the armed voltages basically are able to sustain this condition by generating an AC voltage here ok. And, this AC voltage which is being generated by the arm is kind of like a back emf to the AC grid and it prevents the very high rate of rise of current during this short circuit condition.

So, the arm voltage is here you can see the arm voltages you can command the arm voltages to produce a voltage here at this point which is directly opposing this AC voltage which can pump in energy into the short circuit condition. And, during this time the waveforms can be made like this here which it has been shown. Of course, so, therefore so, what is the advantage? The advantage is, the short circuit current because this is a very severe fault you have a pole to pole fault, but the short circuit condition can be tolerated at least for certain duration of time ok.

But, we will of course, need the full bridge. Definitely, we will need the full bridge converter in order to have something like this, but of course, this condition cannot be sustained for a long time. Definitely, it cannot be sustained because remember that the cells have capacitor ok. So, there is some stored energy in the capacitor and if we have to if we have to operate the converter during this time, what we are utilizing basically is the stored energy of the capacitors in the cells, which are helpful in creating this back emf and this energy will quickly dry down. It will quickly get exhausted and then we have to immediately shut down the converter.

But, at least for the time when this short circuit happened and the time for which the AC side breaker opens during this time say about 3 – 4 cycles 80 to 100 milliseconds. During this time when the circuit breaker has not opened on the AC side during this time it is possible for the converter to kind of like prevent a very high rate of rise of current during a short circuit condition. So, such a condition is shown in this graph here.