High Power Multilevel Converters – Analysis, Design and Operational Issues
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Lecture - 24
Modulator Multilevel Converter – Fault Tolerant Operation and Commercial Production

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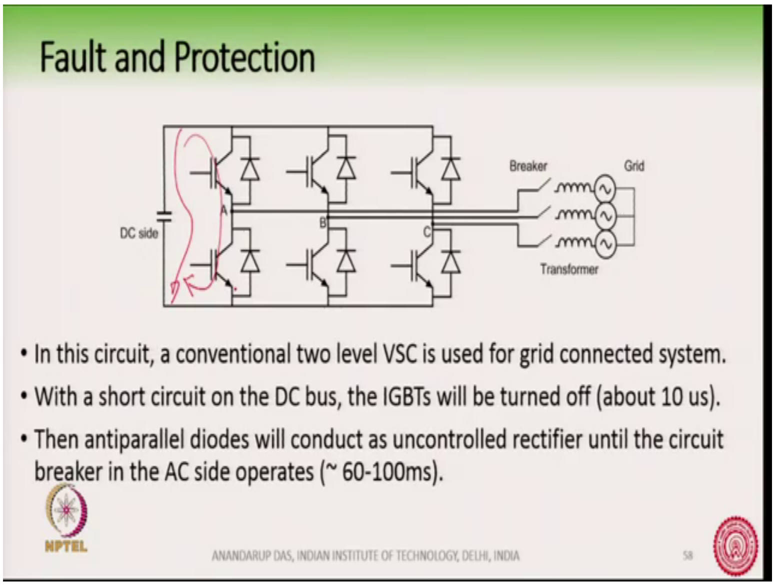

In today's class, we will talk about some aspects of fault in MMC and how we can protect it? There can be different types of faults in a converter ok. One of the faults, which we will be more concerned in MMC is a condition, where the IGBTs or the control switches are switched off. Now, as we understand there can be different types of faults in a converter. There can be electrical fault, there can be mechanical fault, there can be thermal fault for example, over temperature.

There can be mechanical fault, for example one device one rack the screw in a rack due to vibration has loosened and the cell has been displaced from it is original position for example, there can be also catastrophic faults. For example, capacitors may blast, because of some electrical faults because of something wrong capacitors may blast inside the cell.

So, these faults are so there can be different categories of faults. We cannot cover all types of faults, but we will cover only some very severe electrical faults in this discussion.

Now, one of the severe electrical force again under electrical faults, there can be several types of faults, you can have faults in the IGBT, you can have faults in diodes, you can also have fault in capacitor. You can have faults in an inductor, and it means you can have faults on the cable to in the cable you can have cable to ground fault, you can have line to line fault line to ground fault. Now there can be several types of faults.

But, one type of fault which we will focus more here is what is one of the most severe electrical faults, other types of faults for example, suppose this is what I have shown here is voltage source converter, typical voltage source converter. And, it is connected to the grid ok, three phase grid and in this converter which is connected to the grid; you can have many many types of faults, but suppose you can have a line to line fault on the grid side right.

So, for such a fault it may possible the converter should be protected during that time of fault. Remember that any fault can happen, but the Motto or as a designer as a designer or as design engineer, the main idea during fault condition is to protect your converter. So, that in spite of the fault, your converter is in a safe region of operation or it is shut down safely. Because, if there is a fault and your converter is also destroyed then it is a very bad design.

Any fault can happen at any point of time, but the converter should be able to protect itself from such an external fault. So, for example, if there is a such a in this example, if there is a line to line fault on the grid side, the converter breakers, the breakers at the output of the converter can operate and can isolate the fault. But, there can be some faults, which are very severe on the converter. And, the designer must ensure that the converter is protected during such severe faults.

So, one of the severe faults is what we will start with our discussion today and eventually we will progress to MMC. Now, one severe fault, which can be understood for example, let us take this voltage source converter here ok. These are typical voltage source converter ok, three phase voltage source converter there is a grid. And, there is a transformer, which I am representing through an inductor there is a breaker and there is a DC side. And, you can have other loads connected on the DC side we have not shown it here.

One of the severe faults is a short circuit on the DC bus. There can be many reasons for that short circuit or another fault that is also very severe is something like both switches have been turned on in this leg, this is also a very severe fault. I mean it will short circuit the DC bus here. So, that there is a path here. So, one fault that I talked was the short circuit on the DC bus. So, it means that you can have a fault like this here ok. A short circuit on the DC bus, you can also have a fault where you have by mistake these two switches have been turned on.

Why it can happen? Suppose, there is a miscommunication, there is a there is a false signal being sent to the two switches. Due to some unforeseen circumstance or unforeseen behavior of the gate drive circuit. So, then what will happen is that, if these two devices are turned on. So, current will flow like this here say dead short circuit. And, the whole energy of the DC bus in the capacitor will now be dissipated through these two transistors. It will flow and the current will rise very fast and this is a potentially destructive situation.

So, there will be local hotspots inside the transistor and then eventually it will burn out, the bond wires will lift off or it will come completely burn out. So, we generally shut off the transistors during this time. So, typically the one way of monitoring the fault is to monitor the collector emitter voltage of the IGBT or drain source voltage of the MOSFET. So, if you monitor the VCE voltage of the IGBT and if you remember the IC VC characteristics, it is typically the VCE will shoot up increase.

So, if typically the VCE voltage is around 1.5 to 1.7 volt and it may go up to 2.5 more than 2.5 volts during a fault condition, when the collector current is dramatically increasing. So, we sense that voltage and we understand that there has been a fault and we shut down or we will remove the gate pulse from the IGBT and causing the transistor or the IGBT to shut off. Typically, it takes 10 microseconds ok, within 10 microseconds this can be achieved.

So, if I see this circuit, we see that we will shut off the IGBT. So, what will happen now in this circuit once we have, once we have turned off the IGBT. So, we will turn off all the 6 IGBTs.

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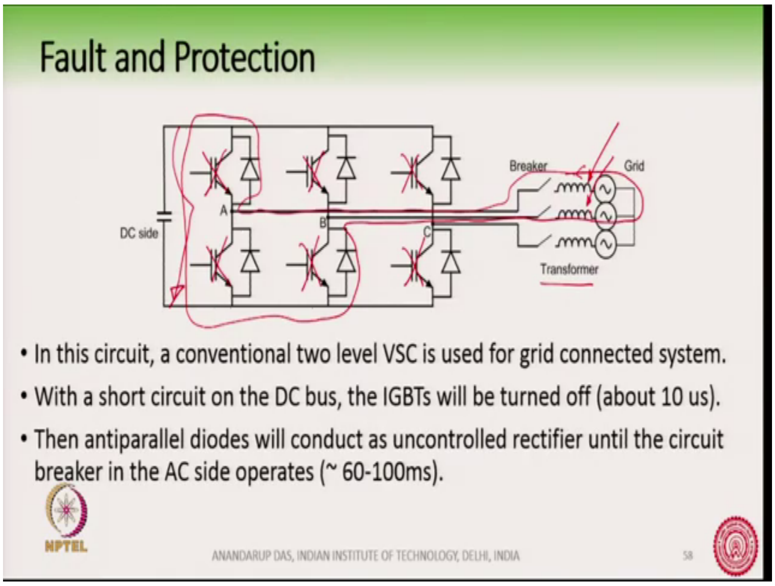

So, this is off, this is off, these are all off ok. Now, after 10 micro second how does this circuit look like? This circuit looks like an uncontrolled three phase diode rectifier ok. You see these diodes these are all present here and they are uncontrolled devices right.

So, therefore, what will happen they will conduct? And, the grid here the grid will see an uncontrolled rectifier feeding to the DC bus ok. The current during this time can be very high, there can be also a situation where suppose the DC bus itself is shorted ok. The DC bus itself is shorted due to some reason and also during that point of time, the situation can happen that the grid is feeding to an uncontrolled rectifier with it is DC bus shorted.

Now, this is a very dangerous situation and the current through the diodes and also coming from the grid can be very high and we expect the circuit breaker to operate, but circuit breakers typically take 60 to 100 milliseconds to operate mechanical circuit breakers. So, during this time of this 3 4 cycles of time is very crucial with regard to how the current is behaving during this point of time?

Remember that usually this grid is connected to such a voltage source converter through a transformer here. So, typically it is through a transformer and the transformer leakage inductance is the factor or is the element, which can control the rate of rise of current during such a fault condition ok. So, that is why I have represented the transformer by an inductor here ok. Because, it is the leakage inductance of the transformer, which will limit how fast the current is rising?

For example, you see if you see the path from this here. So, the current path will be like this say for example, you can take any of this goes through this rectifier, goes through the short and say comes back through this and this is how the current path is ok. So, the leakage inductance of the transformer with these elements, these are the electrical components which will limit. The rate of rise of current by the relation VA or V equal to L D i D t. So, there are two inductors. So, 2 L D i D t is equal to the line voltage VA B or VA C.

So, therefore, when you choose this transformer here, you must remember that the leakage inductance of the transformer should be something like 4 to 8 percent ok. You cannot make the leakage inductance very small ok. If, you make it very small during the fault condition it may happen that the whole VSC the diodes can be destroyed. So, the leakage inductance of the transformer has an important role to play during fault condition. And, it should be something people choose between 4 to 8 percent of leakage inductance.

Now, this was regarding the voltage source converter.

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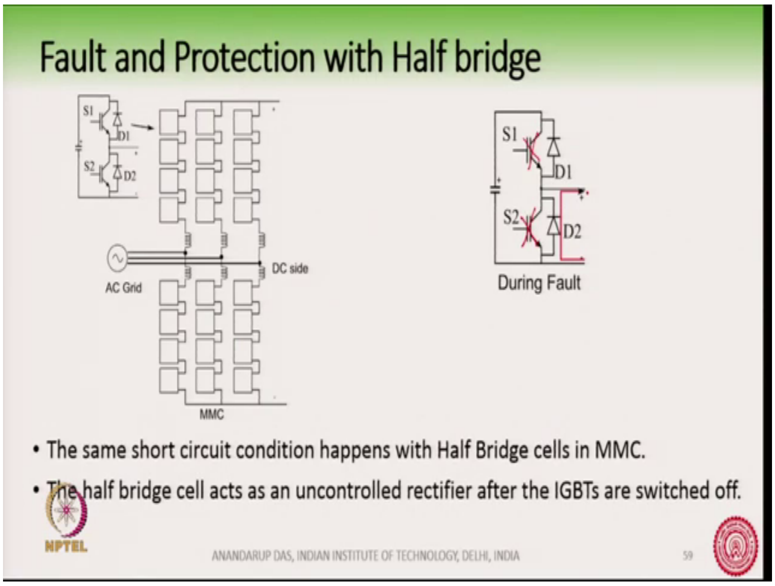

Now, let us take or look into a MMC and see what happens in an MMC. Now, as we have seen, we can have two versions of MMC; one is a half bridge and one is a full bridge. Let us start with the half bridge. So, here I have shown the MMC here many cells and these are all made up of half bridges ok. Now, one important property of half bridge is that, suppose there is a fault and fault means a very severe fault.

Let us analyze the behavior of a half bridge circuit ok. Suppose, we have a very severe fault and we have kind of we have like shut off the transistors of a half bridge, because we have seen a very severe fault happening in the circuit. And, for the sake of protection we switch off the transistors ok, within 10 microseconds for example, but you see one if you see the circuit of the half bridge here, you see the diodes, which are present are uncontrolled devices and they will continue to conduct ok, in spite of the transistors having been switched off.

So, depending on the polarity of the voltage, so, it may happen that the current is flowing through this diode D 2 here ok. It is flowing through this diode; it may also happen that the current may flow through D 1 and through the capacitor. However, the current flowing through the D 2 is a most more severe condition we will understand it a little bit later, that the whole half bridge now acts as a single diode and fully uncontrollable.

So, suppose now this MMC is acting as a rectifier ok. And, we have a very severe pole to pole fault in the HVDC line. So, suppose it is acting as a rectifier for an HVDC line there is a very severe fault.

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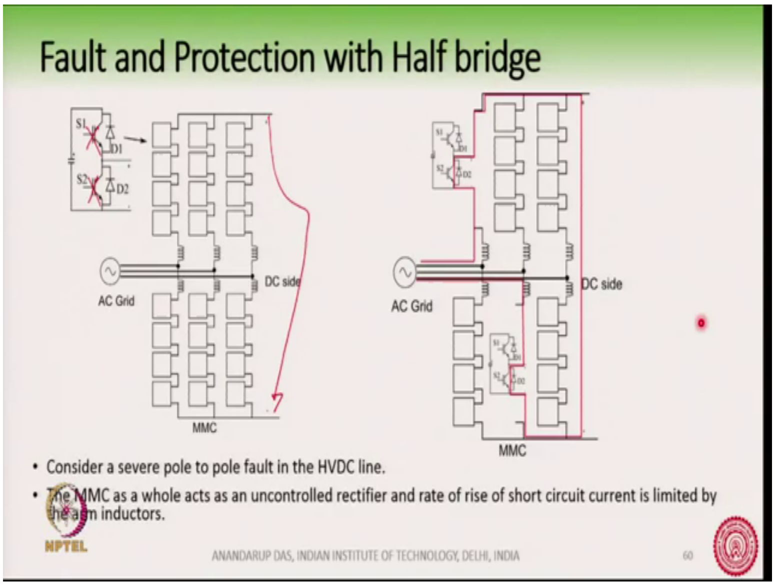

So, this is a very severe fault here and there is a pole to pole short circuit. Now, remember as a design engineer you have to protect the MMC, you have to protect your converter ok. Now, during this time you see that the current is rising very fast, because you have a pole to pole fault. And, so you shut off the IGBTs, but unfortunately what is happening?

So, you have shut down these two ones, but these diodes are conducting ok. So, how does the circuit look like, when the diodes are conducting? In order to understand this, I have drawn this circuit here ok. In this circuit the entire arm.

For any for this phase a for example, let us take this phase a we are representing the entire arm by a single half bridge ok, it is for the purpose of analysis the same thing. So, if you have more number of half bridges the same analysis will be valid. So, we are considering, the entire arm as if like composed of one half bridge. Similarly, in another phase in the lower arm the whole arm is as if like composed of one half bridge ok, here and here. So, here and here these are the two equivalent representation of the arm with one half bridge.

Now, there is a fault here as you can see there is a DC pole to pole fault and suppose we have sensing this fault we have shut down the IGBTs. However, the diodes are still conducting. And, you will see that there is a path for the current to flow ok. You see here this from starting from this point say a phase you go like this go through the diodes come here and go like this, and go through the short circuit here, and come here and go through this diode here, and go through this inductor and come back here through the B phase.

So, you can see therefore, that there is a path for the current to flow during this short circuit condition, which is provided by the diodes of the half bridges. The AC Grid so the line voltage across the line voltage in the AC Grid is impressed across the fault, if we neglect the voltage drop across the diodes. So, the rate of rise of the current will be determined by these two inductors, which are on the path ok, this inductor and this inductor here.

So; that means, the rate of rise of current say if this is given by D i D t, then VAB is equal to 2 L D i D t where L is the arm inductor. So, that is how the current will be limited ok. So, therefore, the inductors in the MMC is very important has a very important role to play during short circuit condition, because the rate of rise of the current during short circuit condition is controlled by the arm inductors ok. And, of course, the inductors should not saturate during that point of time.

Because, during a short circuit condition the current through the inductor is very high, it is going to be very high. And, so, the total MMF or the total flux, which is produced in the inductor can be very high n times I ok. The MMF, which is getting impressed is very high. And, so we usually these inductors are made air core, because air core inductors are very hard to saturate, because it is air. So, there is no iron there is no amorphous core, there is no iron involved or a ferrite core in case of a low voltage.

So, in case of a if we use amorphous core, it is very difficult, it is very easy to saturate it, but if we use air core it is very difficult to saturate ok. So, therefore, using an air core inductor, we get less amount of inductance per unit volume, but we can avoid saturation of the inductor, during this time. So, often these armed inductors are air core inductors to avoid saturation, but of course, the penalty is the size of the inductor is very big ok. With an air core inductor the inductance obtained per unit volume is much less than that when you use an amorphous core inside.

So, the size of the inductor is very big, but we can avoid saturation of the inductor, but anyway what I want to say here is that rate of rise of the current will be limited by the armed inductors and that is how, we should be kind of like choosing the inductance. So, that under worst condition also the current is limited.

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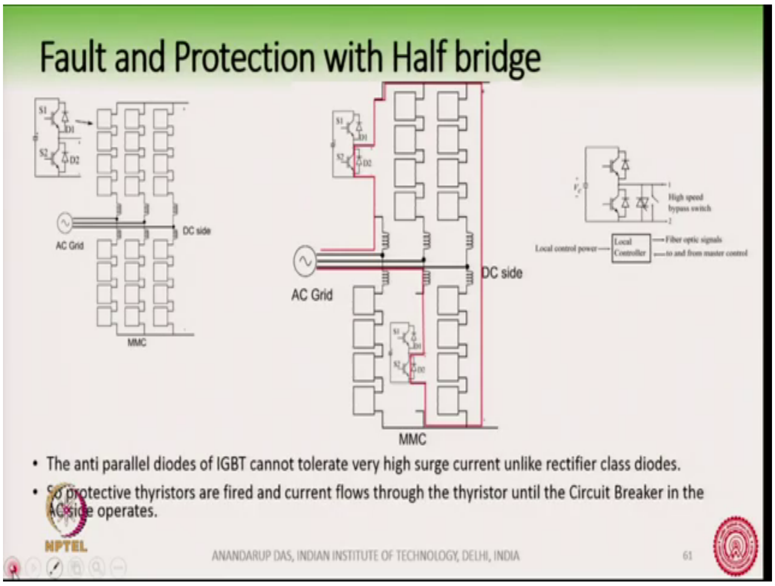

However, one more thing that also must be kept in mind is that, the anti-parallel diodes of these IGBTs, these are inverter class diodes.

Now, there is also a kind of like rectifier class of diodes, which we use in rectifiers. The rectifier class of diodes, the I square t rating of those are much higher, than the I square t rating of inverter class of diodes. These diodes which are anti-parallel to IGBTs, they have very good switching performance, that is a turn on turn of times are very less, but they are not designed to sustain very high, I square t rating or they cannot sustain very high I square t rating which a rectifier class of diode or thyristors can sustain.

If, we have seen earlier that often these half bridges are provided with anti-parallel thyristors or triax here at the output. So, when we have a huge surge current, which is flowing through these anti parallel diodes in order to protect the half bridge, we also fire the thyristors. Thyristors have enormous I square t rating ok. And, so what will happen is the current will now the flow through the thyristor until a point of time, the circuit breaker the circuit breaker is here in this region.

The circuit breakers until the circuit breaker opens that is about 60 to 100 milliseconds, the current will flow like this. So, the arm inductors along with the protective thyristors they help to they help to kind of like minimize the impact of the severe fault, pole to pole severe fault on the DC side. With this way you can see how the MMC can be operated during the fault condition with half bridge circuits.

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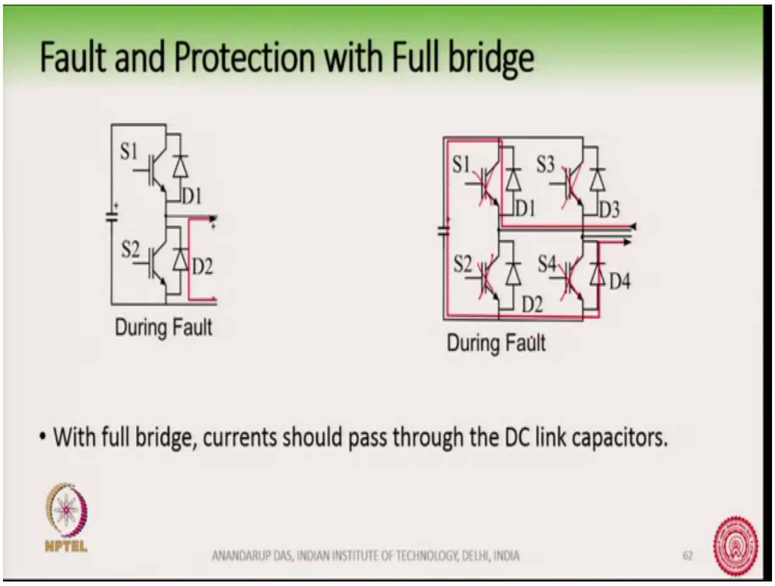

Now, what happens with a full bridge circuit? So, this is interesting ok. What happens if, we instead of using the half bridge if we use full bridge. Now, here you can see the behavior of the half bridge during the time when the IGBTs or the transistors have been switched off here. In case of a full bridge, when you turn off the transistors; that means, you have turned off the transistors here, then also this full bridge will act as an uncontrolled rectifier.

But, if you observe the path of the current, you will see that it will always flow through the DC link capacitors. See for example, the current the it comes through here flows through these diode and through these capacitor and comes out through these diode here ok. So, depending on the voltage polarity, but it acts as an uncontrolled rectifier; however, the path of the current always gets complete through the DC link capacitor right.

So, this is a behavior which is different from the half bridge.

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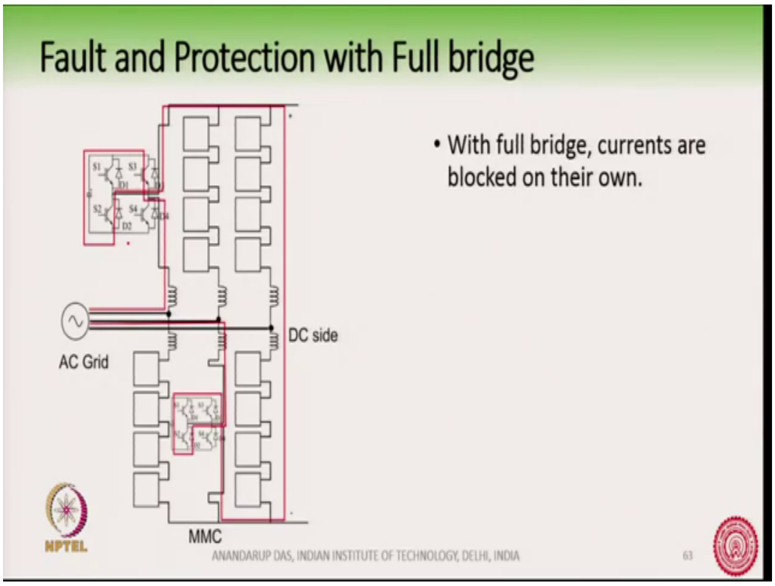

Now, just like the half bridge case, let us consider the pole to pole fault case with full bridge modules in the arms. And, let us again kind of like one arm you replace with one full bridge, for the sake of analysis. What will happen now? You will see that, the current flows like this and goes through the capacitor here, and goes through like this comes out of the full bridge, goes to the DC side. There is a pole to pole fault here, comes here and then again the path gets complete through this capacitor and then through this inductor and goes back to the AC grid right.

So, here also we see that the arm inductors are present in the circuit during fault condition, but additionally these capacitors in sub modules. All the capacitors in the sub modules are kind of like present inside the circuit right. And, these capacitors are very helpful, because when the fault condition will happen during that transient portion before the circuit breaker opens, what will happen is that, these capacitors which are in the part of the fault current will immediately charge up.

Because, it is a simple AC circuit with a RLC elements; R is present as part of the resistance of the inductor. So, it is an RLC circuit ok. And, you can solve to find out the fault current, the peak of the first peak fault current, second peak fall current and how it dies down, what are the time constants of dying down? All this can be found out, because it is a simple RLC circuit, which is fed from an AC voltage source. And, the capacitors will quickly charge up to the peak of the AC voltage.

Once the capacitors are charged up, then these diodes which were allowing the current to flow will now get reverse biased and the currents will be blocked. So, the full bridge circuit can help to minimize the current or block the current on it is own. Because, the capacitors will charge up to the peak of the AC voltage and the current will stop. So, this is the advantage of having a full bridge circuit instead of a half bridge circuit. A full bridge circuit, a full with MMC circuit has a better performance, than a half bridge MMC circuit during fault condition.

So, many of the commercially established MMC use full bridge instead of half bridge ok. Now, of course, in a full bridge circuit as you can understand the losses will be more, because instead of using two transistors we are now using 4 transistors. The losses will be more, but the fault performance is much better in a full bridge circuit. Some researchers have even gone one step ahead. And, have suggested not to even shut off the IGBTs during that fault condition.

This is also very interesting. Now, remember the full bridge circuit here. So, if there is a fault. So, the national the natural tendency when there is a fault here is to shut off the transistors, so, that you can protect the converter. So, that is the natural way of thinking.

However, it may be better under some circumstances to actually run the converter during fault condition, why? Because, you see the capacitor along with this full bridge circuit it is nothing, but a controllable voltage source. And, so the arm is a controllable voltage source.

Now, suppose the fault has happened and you modify your controllable voltage source, in such a way that it is kind of like a back EMF to this AC grid voltage sources ok. Remember that the controllable voltage source here and the controllable voltage source here, there is a control; there is a grid voltage source here and there is a controllable voltage source here ok. The full bridge is a controllable voltage source the arm is a controllable voltage source. The exchange of energy or the exchange of power between this voltage source and the voltage source here is governed by this inductor here.

So, we often use the formula v 1, if there is a 1 voltage source here 1 another v 1 and v 2 and there is an inductor in between. So, the power can be controlled by there is some formula which comes from basic circuit theory like v 1 into v 2 divided by x into sin delta. So, then that is how the power is exchanged where x is the inductance the impedance of the inductance and then delta is the angle between v 1 and v 2.

So, during fault condition, you can make sure that the controllable voltage source in the arms are kind of like are adjusted in such a way. So, that you prevent the current flow ok. And, so the short circuit current during this time can be drastically kept down by modifying the arm voltages.

And, so some researchers have suggested not to shut up, shut down the transistors and instead work them like a back EMF or the controllable voltage source, so as to prevent the rise of current during fault condition.

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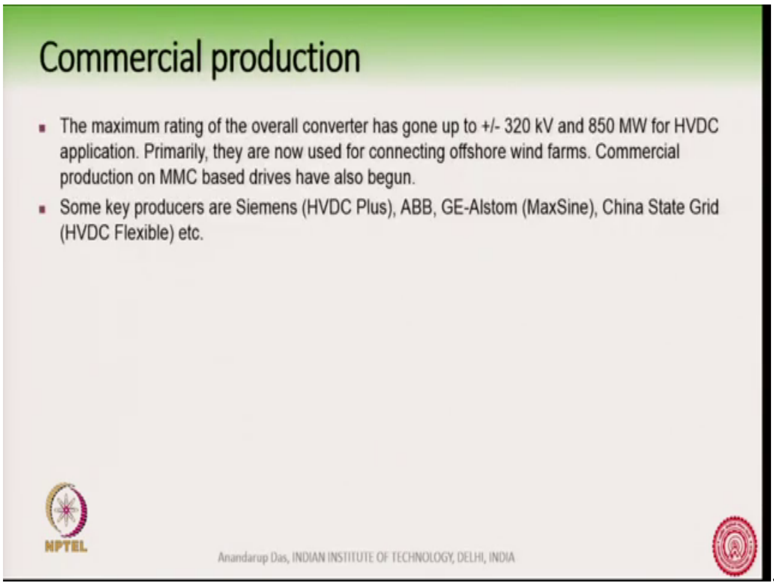

Now, we see some of the commercially manufactured MMC ok. Now, MMC as we had earlier said was introduced or was first proposed by professor mark worth around 2001 or 2000 or 2001. And, then the commercially produced MMC came to the market around the years of 2007 or 8. And, after the introduction by one manufacturer, that is Siemens, the converter was getting a lot of attention by other manufacturers and several producers now are producing MMC on a commercial basis.

But, generally it is relate or it is confined to HVDC application, High Voltage DC transmission. So, the maximum rating of the converter has gone up to like plus minus 320 kilo volt and 800 and 50 mega Watt for HVDC application. However, these numbers are continuously changing. So, as of like now we are around 2000 end of 2019 and beginning of

2020, but these numbers are continuously changing. And, higher power rated or higher voltage rated converters are either being built or are getting deployed.

So, various manufacturers in like, Siemens, ABB, GE-Alstom or China State Grid, so, these manufacturers are producing it on a commercial basis. So, they are used for connecting offshore wind farms, but commercial production on MMC base drives have also come to the market. So, the viewers or the students you are encouraged to look into the internet and search about these commercial manufacturers of MMC and you will get a lot of literature, as well as YouTube videos on who are making these products, what voltage rating?

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For example, you may also get information of how many cells are connected? Typically, 100s of cells are connected. So, a lot of information is available in the web. So, I thought of introducing or a sort of including some pictures of this converter, which you can see now. So, this is a kind of a converter MMC converter in an offshore wind farm.

Now, although this does not show anything about the converter, but I included this picture, which I have obtained from one commercial manufacturer, this picture is kind of like shows the environment in which such converters are used.

You see here the converter is this yellow one, they here inside this the converter station. The converter station is inside this and you can see, it is deep inside the sea, where large number of wind turbines can also be seen. So, you can see here that such converters are often used in a very harsh and very isolated environment. So, it is deep inside the sea and that is probably very few people, who are actually going there and managing the operation, it is very isolated environment very harsh and isolated environment.

So, the concept of fault tolerance becomes very important in this kind of an environment, where these converters are being used. You will not get easily the spares and also the downtown dying down time can be quite high. If, there is a fault inside the converter, because a replacement of course, a replacement may arrive, but it may arrive at a it is not such a frequent rate.

So, when designers make such kind of converters, which are going to operate in a very harsh environment, then they have to take particular attention to these kind of practical problems, which the converter face in real life. So, therefore, the fault tolerant feature of MMC the reliability high degree of availability. These are kind of like very useful in this type of environment, isolated environment, isolated and harsh environment. So, this is kind of like one picture of the whole converter.

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Now, here we see one picture of the half bridge and full bridge cells. Typically the size of the half bridge or full bridge cells is like this, like this much, and this much, and this much height. So, it is not difficult actually two kind of like, when it is running, not means, when it you it is fabricated it is easy to take it out or put it in ok. So, it is like this much size and can be handled by a person.

So, you can see this is the half bridge configuration on the right hand side this is a box here, which have these holes here. So, inside this box are several PCBs. For example, gate drive board and also the fiber optic board ok. Fiber optic board means you have fiber optic signals, which are going to the devices. So, the and additional power supplies. So, and communication boards communication PCBs these are all inside this box here and you can see some wires coming out here.

And, the main device is inside this. So, this is the half bridge and this is a full bridge very similar in structure. So, here also you can see the, there are control cards here and there is a mean IGBT there ok. In both these cells the capacitor is not shown ok. The capacitor has this kind of like separate box. And, then you can see here, there is one, there is one pipe kind of thing and through this pipe you actually the deionized water flows, through the, flows through the heat sink and helps in cooling of the cells.

Additionally, you can see for example, it is very clear here these are the two terminals of the cell. So, this is one cell and these are the two terminals of the cell. So, whether it is half bridge or which you can have that you will have the two terminals. So, here it is not very clear, but here it is also there the two terminals. In here this green colored this thing this is probably the thyristors ok, that anti-parallel the two theorist heirs back to back that is the triac which has this bypass feature, which helps in the bypass bypassing of the cell in case of a severe fault.

Also, you have the circuit breakers here inside these boxes. So, this arrangement whatever you can see on the picture. So, for example, for half bridge and full bridge, this is for one version of the half bridge and full bridge. And, other versions or other improvements are continuously made. Again, this is from one manufacturer, other manufacturers have slightly different designs, but the concept of modularity.

So, this is one cell and then you go, so once this cell is made you go on producing 100s of such cells in numbers and go on interconnecting them. So, how does this interconnection take place?

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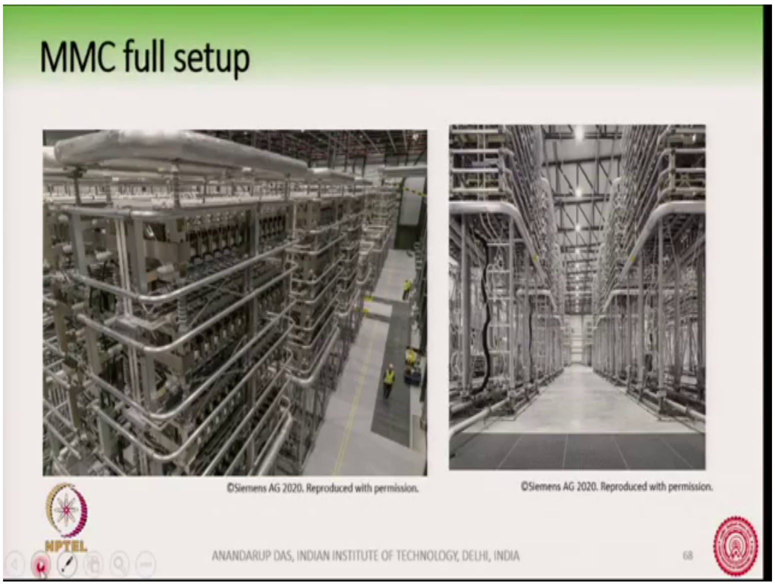

So, I have shown two pictures here. So, if you see here on the left hand side. So, usually these cells are connected together to form kind of a like a stack. So, you see here this is one stack ok. So, this is this may be, this may be, one arm or part of an arm of the converter.

So, here you can see, if you close look closely into this picture, you can see these cells this these are the cells, what we had shown you earlier, this is the back side and this is the front side of that cell. And, you can see these; however, they are stacked one over another or side by side. And, so, these forms one tower a tower of so the tower may be a part of the, tower may be a part of the arm of the converter. And, so this is a station converter station and the size of this tower or the size of the converter station can be understood by comparing it with the size of this person who is here?

So, you can understand how much long and how big is this converter station?. So, one another view is like this here, another view is like this. And, you can see that, the cells are substantially isolated from the ground. The height of the cell is maybe several meters above the ground ok, for isolation purpose. So, so this is one picture of the converter inside the current station, and this is the picture of the full converter station from the outside.

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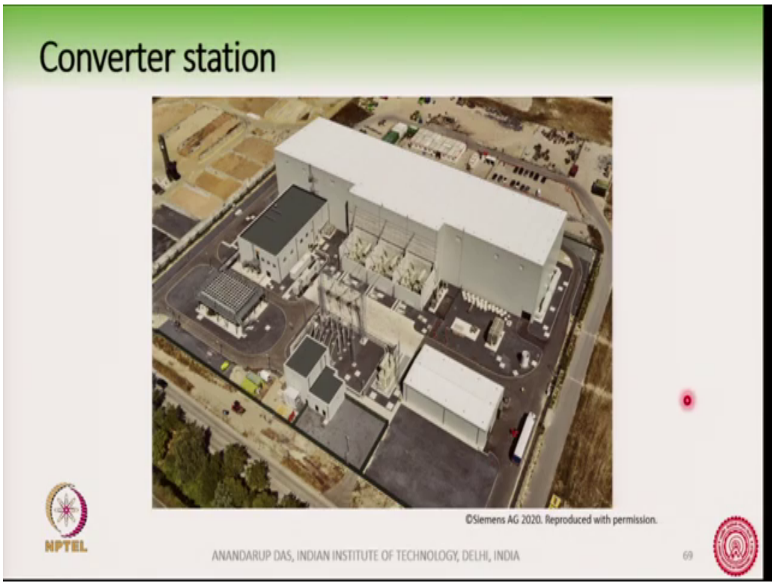

So, the size of this place can be understood by observing the size of the cars here. So, you can estimate how big is this size? So, this white color like this box here, this is where the converters are located, but additionally you can see, there are isolators there is a transmission line and there are transformers here ok. After, which the cables go inside this white box, where the converters are located.

Not shown here or it is not visible here. I do not see it is that, sometimes we can see from outside the inductors, the arm inductors, probably in this picture the arm inductors are inside the box probably. But, sometimes it is outside ok. And, you will see that these are cylindrical shaped and air core inductors. Generally, air core inductors are used because air core inductors are big in size.

Of course, that is a disadvantage it is big in size to produce the same inductance; however, it is very difficult to saturate an air core inductor ok. Because, the air because it is not iron inside and so it does not saturate. So, the arm inductors as we know that is very important it plays a very important role during short circuit of the converter. And, during that point of time the inductors should not saturate, high current is flowing through the through the coils of the inductor and should it should not saturate. During a short circuit, otherwise the value of inductance will fall down.

So, we use air core inductors ok. To prevent saturation, but having a penalty that the size of the inductor is big ok, as compared to an iron core inductor. The inductors are generally cylindrical in shape and it is not I am not able to see these inductors here, but if you search in the web with some other this, you will see many pictures are available and can see how these look like.