High Power Multilevel Converters - Analysis, Design and Operational Issues
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Lecture – 16
Fault Tolerant Operation of Cascaded H-bridge Converter: Part I

Today we will talk about the Fault Tolerant Operation of Cascaded H Bridge Converter. So, one of the very important feature of a cascaded H bridge converter is its fault tolerant feature. What do you mean by fault tolerant?

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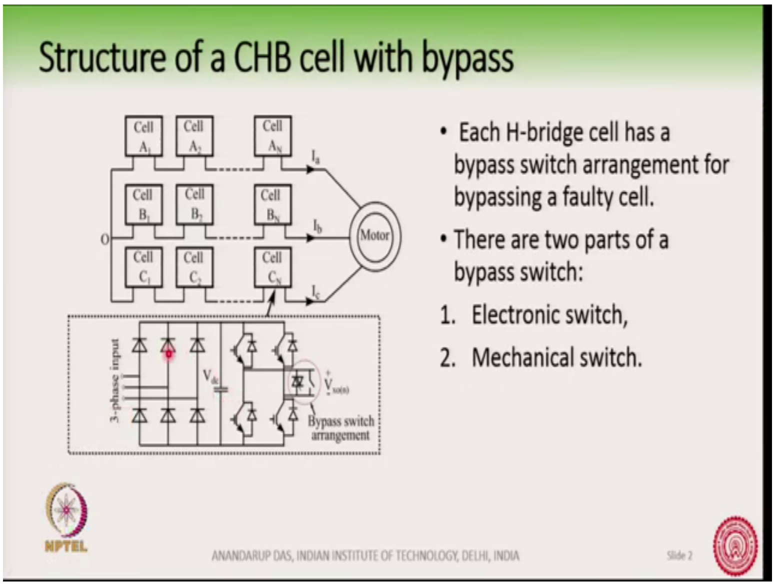

Now, there can be several types of faults in a converter. The fault may be for example, in the device, the fault can be in the gate driver circuit, the fault can be in the interconnection of two cells. For example, here there are two cells and there is an there is a fault or there is a disconnection of the wire which is connecting two cells. There can be other types of faults for example, you can have fault outside the converter like you can have a fault on the cable which is taking the power from the converter to the motor.

There can be non-electrical faults for example, you can have a thermal over trip. So, one of the converter component is heating up to temperature which is more than the permissible limit, there can be mechanical faults also some part may be broken due to vibrations. So, there may be several types of faults. Now, we are here mostly concerned with the electrical faults, now electrical faults can again happen in a number of places.

We are again focusing more on the converter, the faults inside the converter. Now, fault inside the converter can almost likely to happen inside one cell ok. So, inside the cell one IGBT may be damaged that is one fault, the capacitor may be damaged. The dc bus capacitor here inside the cell you have rectifiers, you have capacitors and you have transistor IGBTs. So, again capacitors in particular this type of electrolytic capacitors are very prone to failures ok.

In fact, they are the one of the least reliable component in a power electronic converter. So, there can be several types of faults. Now, often this type of fault and you remember this is a big converter and there are many many components, there are many cells and inside each cell there are many components like that. So, often it this type of converters are used in mission critical applications. What do you mean by mission critical application? Say one of the application for such cascaded H bridge converter is for motor drive applications.

And, where do the where do use this motor drives? For example: for running pumps and these pumps are used for extracting oil from the mines ok, this is one of the application. So, this kind of converters are used in the oil and gas industry. There are many other places where these kind of converters are used, where the continuity of service is essential. I mean the because there are many components in this converter and since there are many components each component has a probability of failure. And so, the chances of failure is quite high in this current of a converter.

But, you do not want the whole converter to shut down because of failure inside one single component, inside one cell ok. For example, the gate driver board in one cell, one gate driver board for one IGBT inside one cell there can be a small fault in that gate driver board. And, because of that if you say that will shut down the whole converter because of that single fault, then it defeats the purpose. Because you have so, many components and because of a single fault in one single component inside the converter you are basically shutting down the whole converter.

And, this may not be acceptable for many mission critical applications because if you shut down the converter of course, then the motor shuts down and then the pump also shuts down. And, the whole process will be disrupted and the cost of downtime or the cost of shutting down the whole process in terms of money can be enormous. So, we do not want the whole process or the whole converter to shut down because of a single failure inside one converter. So, we have to think of developing some kind of a fault tolerant feature inside this converter.

In fact, this cascaded H bridge converter has an inherent fault tolerant feature which we will discuss today. So, the idea here is that if you have a fault inside one cell then you can bypass that cell and can still continue to operate the converter, but with a reduced rating ok. So, this is the idea that you have a fault inside one cell, you bypass that faulty cell, but still continue to run the converter with the remaining healthy cells. Of course, some compromise regarding the rating of the converter has to be done.

Once this is done when the faulty cells has been bypassed then at the next scheduled maintenance you can take out that faulty cell and then can repair it and again insert it back. Or, you can if the fault cell is faulty to the extent that you cannot repair it then it is possible to insert a new cell. So, what do we gain from this is that at least the service is continued ok. You have you can run the motor, but for example, you can run the motor, but maybe at a slightly reduced voltage and a slightly reduced power.

But, at least some production the whole production is not stopped because of a failure in or a single point failure in the converter. Now, our discussion today is to have a glimpse of how can we achieve this in this cascaded H bridge converter. If you look into the cell structure of the converter then you can see that each cell we have discussed it earlier, we have shown it each cell has a rectifier and you have a capacitor and then there are transistors. What we did not show early earlier was that each cell output has a bypass switch arrangement ok.

So, you can see here there is a bypass switch arrangement, the bypass switch arrangement is used to bypass the cell in the event of a fault ok. So, it consists of there are two parts in this bypass switch and one part is an electronic switch which is you can see here is a back to back thyristor or a Triac arrangement and there is a mechanical switch ok. So, the bypass switch consists of two parts: an electronic switch and a mechanical switch. So, suppose we turn on the mechanical switch then this whole cell is completely bypassed of course, when we do that we also turn off the IGBTs.

We also turn off the transistors inside the cell so, that the whole cell is completely bypassed, but the converter can still continue to operate.

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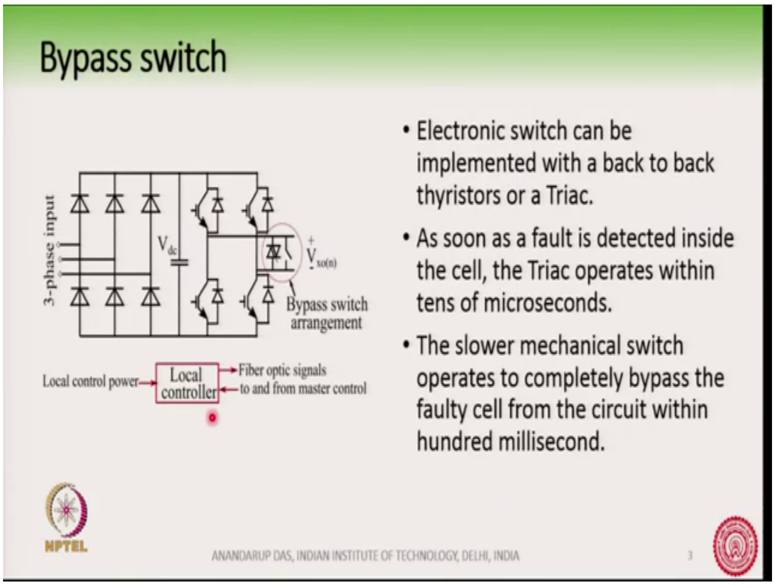

Now, why there are two switches? So, if you see here a little bit this diagram of a cell you can see that there are two switches: one is an electronic switch and a one is a mechanical switch. Now, electronic switches are faster ok, electronic switches made of semiconductors. For example, the Triac here or the back to back thyristor, this is faster as compared to the mechanical switch. So, when a fault is detected at first this back to back thyristor the Triac is fired and within 10s of microseconds then this thyristors starts to conduct.

So, the current will be bypassed. So, at first the transistor is switched off. So, if you detect that there is a fault severe fault inside one cell then you can first switch off the transistors. And, then you can fire the thyristors or the Triacs, but since this is a semiconductor it has some on state loss which we would ideally do not want because this is a bypass cell and we do not want additional losses to happen. So, eventually we will bypass the whole circuit with a mechanical switch ok. Typically, a circuit breaker which operates in the range of hundreds less than hundred milliseconds, say 3 to 4 cycles maybe 60 to 80 milliseconds it will take.

So, after this hundred millisecond then a mechanical switch fully isolates this cell ok. And then the cell is for example, outside the circuit and probably with some necessary precautions it can be taken out of the converter with during a scheduled maintenance operation. The mechanical switch takes more time say in the order of 100 millisecond close to 100 millisecond and that is why the electronic switch, there are two switches; one is a fast switch and one is a slow switch. The fast switch is the Triac, while the slow switch is the mechanical switch.

And, there is also on this each of these cells have a local controller and this local controller basically gets its power from the dc link of the converter of the cell, from this dc link this local controller is powered. And it is it communicates with the main controller which runs the whole converter and it communicates through fibre optic signals; so, that necessary electrical isolation is maintained. The local controller has several sensing circuits for example, you can sense the current flowing through the terminal out.

It can also sense the gate driver board can also sense the V ce, the collector emitter voltage of the transistor and by checking the saturation voltage V ce it is possible to identify that whether for example, an IGBT is short circuited ok. Normally, the V ce sat or the saturation voltage of the IGBT is around 1.7 volt, but it will drastically increase 2.5 to 3 volt when there is a fault or in the high current passing through the transistor or IGBT. We can sense that V ce sat voltage and can detect there is a short circuit in the IGBT and the local can controller can take a quick decision that shut off the pulses to the IGBT.

At a later point of time if there is a severe fault say in the cell, then it is possible for the main controller to also bypass the whole cell with the help of the bypass switch arrangement ok. So, once we have bypass of the cell then we do not have those cells available. So, they are completely bypassed from the circuit. Now, how does the circuit look like when there is a bypass?

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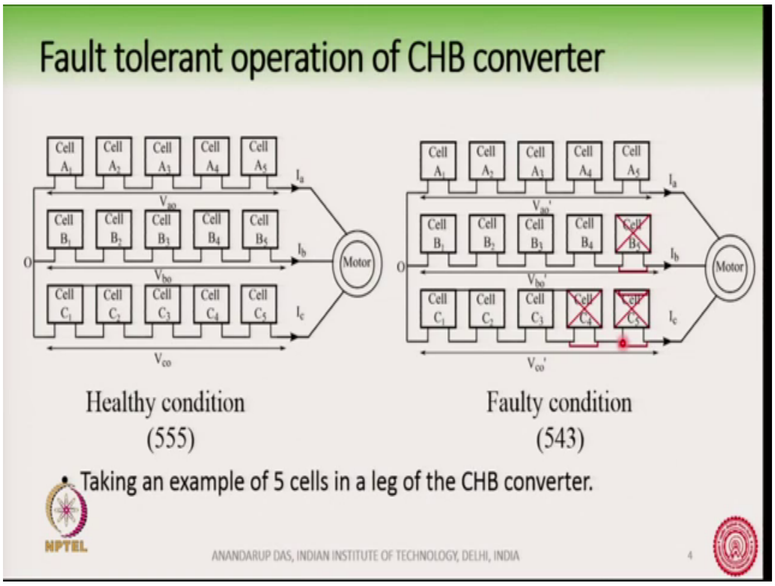

So, on the left hand side we have shown a cascaded H bridge converter with 5 cells in each leg or in each phase. So, you can see here cell A 1 to A 5 here, 5 cells. Now, this is a healthy converter since there are 5 cells in each phase; so, we denote this combination as 555 here, 5 in A phase, 5 in B phase and 5 cells in C phase ok. And, all of them are perfectly healthy and so all of them are in the circuit. Now, suppose we have fault condition and there may be kind of like several faults over time ok.

And, in such a case we are taking a general case here and suppose the faulty condition is denoted by 543. What does 543 mean? 543 means that there are 5 cells in A phase, 4 healthy cells in B phase and 3 healthy cells in C phase. And, this is diagrammatically shown in this picture, you have 5 cells in A phase, 4 cells in B phase that is cell B 5 is faulty and has been bypassed ok. And, in C phase we have 3 cells working and 2 cells bypassed, they are faulty and have been bypassed. So, a faulty condition in this converter is denoted by this 543 combination ok.

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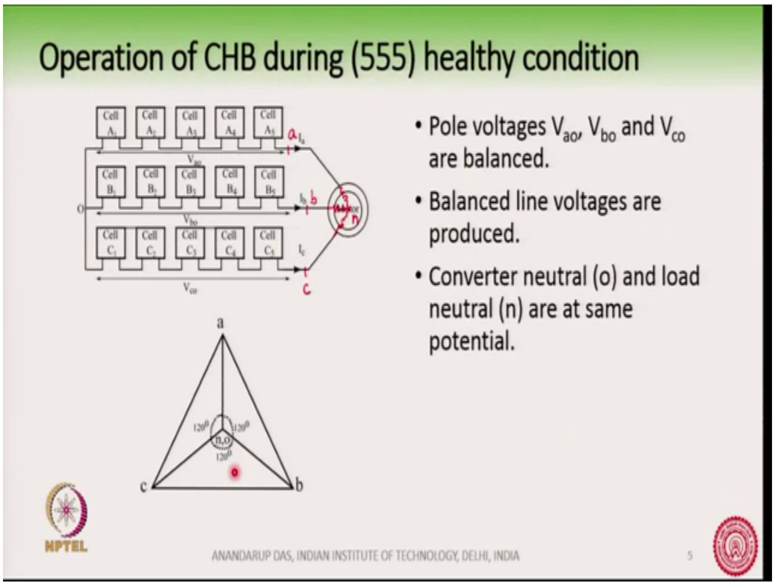

Now, when there was all cells where were working and all of them were healthy that is this 555 combination, how does the pole voltage and phase voltage look like? That is shown by this triangle here, the voltages are all balanced during 555 condition. So, the ao bo and co, that is ao means the pole voltages this point is a here. So, this is the a b and c and there is a neutral point of the motor.

So, the motor if it is start connected there is a neutral point here in. So, the ao bo and co voltages are equal in magnitude and they are 120 degree phase apart. So, the line voltages ab bc and ca are equal and 120 degree apart in time and so, the we get an equilateral triangle because it is a balanced system ok. And, the converter neutral that is this point o, the potential at point o and the potential at point in they are at they are same ok. So, o and n points are coinciding with each other during this condition of 555 with the cascaded H bridge converter.

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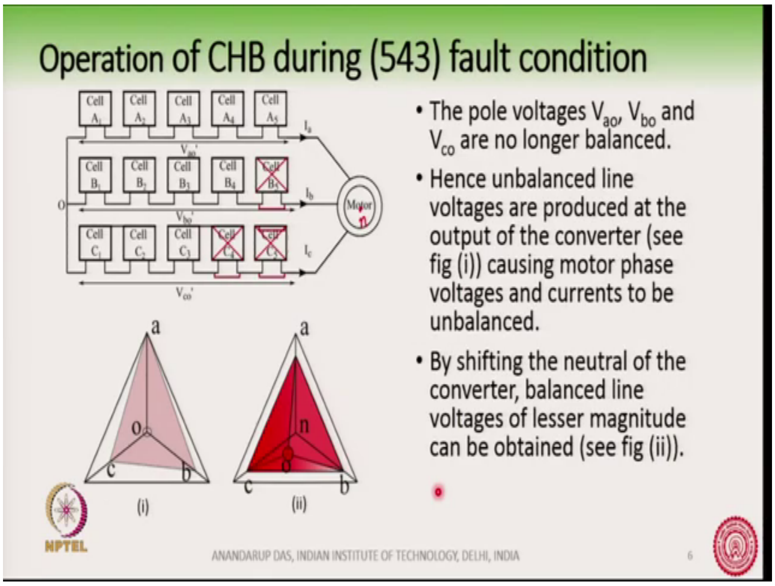

Now, what happens when there is a fault? Suppose, we take this 543 combination. Now of course, we understand that the pole voltages V ao V bo V co are no longer balanced ok. We cannot produce the same voltage magnitude from A phase B phase and C phase any further. Of course, you can argue that if we increase the voltage on the dc bus of the cells of course, you can do that you can increase the dc bus of say if you can increase the dc bus of cells in phase B. In this case you have lost one cell.

So, if you increase the dc bus of each cell of phase B by 20 percent you can get the same voltage from 4 cells. But, this is not a good practice because of simply because of the reason that all these cells are designed for a specific voltage. So, for example, suppose let us take an example, if this dc bus of the voltage is designed to be 1000 volts then you may choose an IGBT of 1700 volt rating ok. Voltage rating of the IGBT can be taken as 1700 volt keeping a safety factor of 1.7. Now, why this 1.7? Because, there may be several reasons why the designer can keep 1.7 as the safety factor.

For example, why they why 1.7 has been or why one someone takes 1.7 as the safety factor? Say for example, 1000 volt is on the dc bus, the first thing is this 1000 volt is not a constant value. It will have a ripple and under some circumstances, it may be possible that there is a regenerative operation from the motor where, the motor is acting as a generator and pumping back energy into the dc bus.

Now, on the input of the dc bus is a diode rectifier. So, it cannot take the energy back into the supply. So, whatever is the energy coming from the motor will be again dumped into the capacitor, the dc bus of the capacitor. So, its voltage which is normally designed at 1000 volt will increase, say it will increase to 1200 volts. The regenerative operation can take place, during that point of time that IGBTs have to withstand this voltage.

Secondly, when there is a switching happening in this IGBTs, there is always a voltage overshoot on the terminals always. Unless, you I mean its a matter of how you design the gate driver board, but there will always be a voltage over shoot at the collector emitted terminals. And, this voltage overshoot can easily be 15 to 20 percent under some circumstances.

So, we have to keep a certain margin for that. So, there may be several such considerations which must be kept for deciding this safety factor ok. So, if the nominal voltage of the dc bus is 1000 volt, transistor of 1700 volt may be taken or a transistor or a IGBT of 2300 volt may be taken. Compromising on this safety factor is actually not a good idea. So, we must keep this safety factor otherwise if you increase the dc bus of these cells, then it may happen that you lose all the cells.

Because, you have compromised on the safety factor, voltage safety factor then you can over a quick time you may lose all the cells; so, that you do not want. So, you do not want to compromise on the safety factor which has been kept there by design. So, increasing the dc bus voltage on these cells is not a good option. So, now so if you have a cell, if you have a bypass of this cell B 5 and you have a bypass of cells in C 4 and C 5, then the pole voltages will automatically get unbalanced ok.

Now, there is also another option which is possible, the option is that in order to get balanced voltage there is one more option possible that you also by; suppose you have lost two cells in C 4 and C 5. Then what you can do in order to get balanced voltage is that you can also bypass two healthy cells in phase A and one healthy cell in phase B. For example, in order to get balanced voltage you have lost two cells in C 4 and C 5 and you have three healthy cells in C phase here.

What you can do, is you can say fine in order to get balanced voltage, I will only operate three healthy cells in B phase and three healthy cells in A phase, that is a possibility. And, I get a balanced voltage that is definitely a possibility, but what we will see in the analysis is that the magnitude of voltage that is obtained by this process will be less as compared to the case, where we use all the available healthy cells. So, if we bypass some of the healthy cells, then actually we are losing on the voltage ok.

So, that is not a very I mean bypassing a healthy cells is not something which is very much advisable. Because, we have this healthy cells available, why not use them to get the maximum voltage possible from the converter. So, we want to use five healthy cells from A phase, four healthy cells from B phase and three healthy cells from C phase. Now, then but the pole voltages V ao V bo V co will become definitely unbalanced ok. So, you can see here ao bo and co these three phasers have become unbalanced here.

So, if this become unbalanced definitely the line voltages become unbalanced ok. And, if the line voltages here become unbalanced then unbalanced current will flow into the motor which is not at all advisable and not recommended. So, what can we do? The strategy that we adopt is that if we change; so, this diagram here you can see the unbalance is produced and because the angle between ao bo co is 120 degrees. But, if we change the angle between them which is shown by this red colour equilateral triangle.

Here you can see that ao bo co they are unequal and the angle between them that is the phase shift between the pole voltages ao bo co, they are not 120 degree anymore; they are different angles ok. If you make those angles different from 120 degree, then it may be possible again to get back this equilateral triangle. The equilateral triangle corresponds to the balanced line voltages. So, it means that in spite of having unbalanced pole voltages, it is possible to get back balanced line voltages which is shown by this red coloured diagram.

This is the balanced line voltages and this is the these are the three unbalanced pole voltages. And, their magnitudes are different and the angle is no longer 120 degrees so, different angle. If we get a balanced line voltage; that means, at this point here we get a balanced line voltage, then the motor will not see any difference ok. Because, the motor will not even understand that there is a fault inside the converter, because the motor phase voltages will become balanced again.

As soon as the line voltages become balanced, the motor phase voltage will also become balanced and balance current will flow. So, the load will never understand that there has been a fault inside the converter, as long as we can ensure that the line voltages are balanced at the output of the converter. Now, when we do this of course, you can see that there are two things happening. First is the balanced voltages produced during a fault condition, the balanced voltage produced has reduced in magnitude ok.

So, you can see that earlier we were able to produce this much of length of the equilateral triangle, but now we are able to produce only a smaller magnitude equilateral triangle. So that means, the magnitude of voltage available to the load has reduced. Secondly, we also note that there is a pole potential difference now coming up between the point n and o ok. The point o is here and point n is the neutral point of the load on the motor.

So, between this points n and o, this point and this point n and o; we will now see; we will now see a potential difference coming up and that is shown in the phasor diagram here V n o ok. This is a common mode voltage because this voltage is existing in all the phases, it is there. So, V a n plus a o is V a o, V a n plus V n o is equal to V a o and also V b n plus n o is equal to V b o and V c n plus V n o is equal to V c o.

So, which means this is a common mode voltage which is present in all the three phases and this common mode voltage will cannot allow a current to flow because the points o and n are isolated from each other ok. But, we are able to produce a balanced line voltages and of a lesser magnitude and so, the motor can be run with a lesser voltage magnitude, this is possible.